Addressing Traffic Congestion and Throughput Through Optimization

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Declaration

The research described in this dissertation was performed at the University of KwaZulu-Natal under the supervision of Dr. Brett van Niekerk. I hereby declare that all material incorporated in this dissertation are my own original work, except where acknowledgement is made by name or in the form of a reference. This dissertation has not been submitted in part or whole for a degree at any university.

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As candidate's supervisor, I have approved the dissertation for submission.

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Declaration – Publications

The following publication emanated from this dissertation:

M. Z. Iyoob and B. van Niekerk, "CAUDUS: An Optimisation Model To Reducing Port Traffic Congestion", 2021 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), 2021, pp. 1-7, doi: 10.1109/icABCD51485.2021.9519354.

Signed:

[redacted] ……………………………………

Dedication

To my Mother,

who *always* believed in me,

and to my Wife and Kids,

who *always* believe in me.

Acknowledgements

First and foremost, infinite gratitude and appreciation to my Creator, Who has given me the will to start studying again and the endurance to see this through in a time when the world was turned on its head. My perseverance, accomplishments and very being are only by *Your* will.

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Abstract

Traffic congestion experienced in port precincts have become prevalent in recent years for South Africa and internationally [1, 2, 3]. In addition to the environmental impacts of air pollution due to this challenge, economic effects also weigh heavy on profit margins with added fuel costs and time wastages. Even though there are many common factors attributing to congestion experienced in port precincts and other areas, operational inefficiencies due to slow productivity and lack of handling equipment to service trucks in port areas are a major contributor [4, 5].

While there are several types of optimisation approaches to addressing traffic congestion such as Queuing Theory [6], Genetic Algorithms [7], Ant Colony Optimisation [8], Particle Swarm Optimisation [9], traffic congestion is modelled based on congested queues making queuing theory most suited for resolving this problem. Queuing theory is a discipline of optimisation that studies the dynamics of queues to determine a more optimal route to reduce waiting times.

The use of optimisation to address the root cause of port traffic congestion has been lacking with several studies focused on specific traffic zones that only address the symptoms. In addition, research into traffic around port precincts have also been limited to the road side with proposed solutions focusing on scheduling and appointment systems [25, 56] or the sea-side focusing on managing vessel traffic congestion [30, 31, 58]. The aim of this dissertation is to close this gap through the novel design and development of Caudus, a smart queue solution that addresses traffic congestion and throughput through optimization. The name "CAUDUS" is derived as an anagram with Latin origins to mean "remove truck congestion".

Caudus has three objective functions to address congestion in the port precinct, and by extension, congestion in warehousing and freight logistics environments viz. Preventive, Reactive and Predictive. The preventive objective function employs the use of Little's rule [14] to derive the algorithm for preventing congestion. Acknowledging that congestion is not always avoidable, the reactive objective function addresses the problem by leveraging Caudus' integration capability with Intelligent Transport Systems [65] in conjunction with other road-user network solutions. The predictive objective function is aimed at ensuring the environment is incident free and provides an early-warning detection of possible exceptions in traffic situations that may lead to congestion. This is achieved using the derived algorithms from this study that identifies bottleneck symptoms in one traffic zone where the root cause exists in an adjoining traffic area.

The Caudus Simulation was developed in this study to test the derived algorithms against the different congestion scenarios. The simulation utilises HTML5 and JavaScript in the front-end GUI with the back-end having a SQL code base. The entire simulation process is triggered using a series of multi-threaded batch programs to mimic the real-world by ensuring process independence for the various simulation activities. The results from the simulation demonstrates a significant reduction in the

duration of congestion experienced in the port precinct. It also displays a reduction in throughput time of the trucks serviced at the port thus demonstrating Caudus' novel contribution in addressing traffic congestion and throughput through optimisation. These results were also published and presented at the International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD 2021) under the title "CAUDUS: An Optimisation Model to Reducing Port Traffic Congestion" [84].

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Glossary

4IR	Fourth Industrial Revolution
4PL	4th Party Logistics
ACO	Ant Colony Optimisation
ADM	Architecture Development Method
AGO	At Gate Out or Pre-Exit point
AI	Artificial Intelligence
API	Application Programming Interface
BGI	Before Gate In
BPN	Business Partner Network
CC	Customer Collaboration
DITS	Distributed Intelligent Traffic System
DOS	Disk Operating System
eqp	Equipment
EqTime	Equipment Time
Fch	Fetching
FIFO	First In, First Out
GA	Genetic Algorithm
GDP	Gross Domestic Product
GI	Gate In
GO	Gate Out or Exit point
GUI	Graphical User Interface
ITS	Intelligent Transport Systems
$\mathrm{LastMove}_{\tau}$	Last truck movement in a period of time
LB	Loading Bay or service area
LD	Loading
OFLD	Offloading
OMTA	Optimization Model for Truck Appointments
ORT	Open Road Toll

PSO	Particle Swarm Optimisation
POC	Proof of Concept
PSFFA	Pointwise Stationary Fluid Flow Approximation
PTM-SBB	Predictive Traffic Management SBB
SA	Staging Area
SBB	Solution Building Blocks
SQL	Structure Query Language
ST	Straddle Carrier
STFetch_StackTime	Straddle Carrier (Equipment) Cargo Fetch/Stack Time
STLoad_OffLoadTime	Straddle Carrier (Equipment) Cargo Load/ OffLoad Time
TOGAF	The Open Group Architecture Framework
TQIn	Truck Queue In: No. of Trucks entering the Queue
TRC	Travel Route Chain
TTT	Truck Turnaround Time
UoM	Unit of Measure
ρ	percentage
$\mathrm{GI\tau}$	Gate In Time
$\mathrm{GO\tau}$	Gate Out Time
TOn	No. Of Trucks Turned Out
TrvlRt	Travel Route
$\mathrm{V\tau i}$	Time of Varying Activities
$f(x) = eqp \times \theta Rs \times x$	No. of Equipment X Service Rate of Each Equipment X the no. of minutes per shift = No. of Trucks Serviced
$g(x) = (eqp \times \theta Rs \times x) + (eqpnew \times \theta Rsnew \times x)$	No. of Trucks Serviced by old Equipment + No. of Trucks Serviced by New equipment
$\mathrm{\theta Rq}$	Rate of trucks entering queue over a period of time
$\mathrm{\theta Rs}$	Rate of the trucks being serviced over a period of time
$\mathrm{\theta q}$metres	Length of the Road (metres)
$\mathrm{\theta qCap}$	Truck Queue Capacity
$\mathrm{\theta qCong}$	Truck Queue Congestion
$\mathrm{\theta qLength}$	Truck Queue Length

θqtr	Truck Queue Threshold limit
$\theta queue$	Truck Queue
$\lambda m\tau$	Move to Loading Bay Time
$\lambda plus$	Additional Loading Bay and Equipment
$\lambda s\tau$	Loading Bay Service Completion time
τ	Time period
τact	Time duration for a specific action to be performed
$T_{\beta ptn\_max}$	Maximum truck capacity at Bottleneck Point n
βpt_n	Capacity at n^{th} Bottleneck Point

Chapter 1: Introduction

1.1. Background

Solving a problem through optimisation requires identifying the issue to be addressed then modelling the problem in an algorithmic format with variables and constraints. The output of the algorithm is the target result that is required, also defined as the objective of the function. The objective functions can then be used to identify target ranges providing for upper and lower limits or boundaries. Problems addressed in this manner can be considered optimisation problems [15].

Queues are a reality in nearly every aspect of one's life. Whilst queues bring order to chaos, sometimes it can also be seen as a form of organised chaos as in the case of queue congestion. As a result, the need to formally look into optimising this organised chaos became evident as far back as the early 1900s [16] using queuing theories. Depending on the impact of queues, addressing the pain-points against the risk-to-reward ratio may not always be practical. However, when the impact of overflowing traffic queues and congestion affects economic and environmental factors, then the prudency in addressing the problem is undeniable. Notwithstanding the availability of other optimisation techniques discussed in the literature of this dissertation, the case for traffic congestion and throughput through optimisation makes for an ideal optimisation candidate using queuing theories as the foundation.

Optimisation and queuing theories are employed continuously to address the issues of traffic congestion in studies across the globe. While in some instances traffic is managed through dynamic and optimised traffic light control solutions [81], these do not address the root cause and therefore the benefits of these systems will at some point dwindle [82]. Aging or stagnating infrastructure that cannot accommodate the excess road vehicle capacity, traffic light interruptions, accidents and construction work are just some of the root causes [79].

In ideal situations, when road infrastructure (size of motorways, number of lanes etc.) and supporting systems (traffic lights, stop signs, traffic circles) are aligned to the number of vehicles, congestion would hardly be experienced. This is evident during off peak periods and weekends when road usage is at a minimal. During peak hours, when traffic increases nationally for specific reasons such as the start and finish of work times, lunch times, school runs times, etc. [17], the supporting systems can be dynamically optimized to manage these situations as well [18, 19]. However, in exceptional cases such as accidents, breakdowns, influx of traffic for specific reasons e.g. organized event or business requirement, bottlenecks are created resulting in congestion. In order to address these varying root causes, specific solutions are needed.

Traffic congestion experienced in port precincts have become prevalent in South Africa and internationally [1, 2, 3] with the Port of Durban contributing to an estimated 15% of its GDP. This has an adverse effect on the country's environmental and economic factors [21]. Managing congestion in dense truck volume areas requires focusing on the root cause to the problem. Some of these root causes, particularly in port and industrial areas, are attributed to operational inefficiencies due to slow productivity and lack of handling equipment required to service the vehicles [4, 22]. These inadequacies compel the trucks that are entering the precinct to wait until the ones ahead of them have been serviced. This allows for the next truck in line to leave the queue as an opening in the service process has become available [23]. Through the use of some intuition, which is normally acceptable in queuing theories [24], traffic queue congestion and overflow therefore results when the rate at which the trucks enter the port precinct grows at a faster rate at which the trucks leave. Also, since the truck will only leave the queue when there is a spot available at the server, leaving the precinct becomes dependent on the rate at which the trucks are serviced. Therefore, the rate of trucks serviced must be better than the rate at which trucks are entering the queue in order to alleviate congestion.

This principle is not exclusive to port areas alone but extends to any area that provides a service. Example, a queue at a takeaway or retail outlet grows as the number of people that enter the queue exceed the number of people that leave the queue in the same period, and the people will only leave once they are served. Therefore, the queue length increases in proportion to the time taken to serve the people eventually resulting in congestion.

CAUDUS is a novel smart queue system designed and developed in this study to specifically address traffic congestion and throughput through optimization. The name "CAUDUS" is derived from a Latin composition of words representative of its purpose.

1.2. Problem Statement

Traffic congestion in the Port of Durban is a common occurrence due to the influx of cargo vehicles entering the precinct to fetch or deliver cargo, with existing operational inefficiencies exacerbating to the situation (Figure 1.1). South Africa is not a unique case in this global challenge as road traffic congestion in ports are the basis of several studies [5, 25, 26].

Figure 1.1: Example of Traffic at the Terminal In Gate [86]

The Port of Durban is also in the process of diversifying its business by developing a 4th Party Logistics (4PL) [27] solution [28], that will see added burden to its port operations and road capacity constraints. The application will present business opportunities to other smaller private third-party logistics companies to transport cargo to and from the terminals, in addition to the contracted shipping lines' and cargo owners' service providers. Furthermore, plans to develop the Port of Durban as a hub for the African continent has already been announced [29]. With the current 60% dominance of South African import/ export cargo-handling by the port, these added traffic commitments will further exacerbate the existing traffic congestion around the port precinct.

The problem of traffic congestion in port precincts is likely to increase, especially given the lack of infrastructure to expand, limited capital resources and time constraints. This study intends to provide an optimisation solution aimed at reducing traffic congestion experienced in port precincts.

1.3. Aim and Objectives

The aim of this study seeks to address the truck congestion challenges around port precincts. This is achieved through the following objectives:

1. Formulation of the optimisation algorithms that will address truck congestion in port precincts;
2. Design and develop a smart queue solution, Caudus, using a multi-objective function approach viz.:
   - 2.1. Preventive – To prevent congestion of the truck queues around port precincts
   - 2.2. Reactive – To alleviate the congested truck queues around port precincts through counter measures
   - 2.3. Predictive – To predict situations leading to congestion and prescribe rectification measures to avoid congested truck queues

3. Evaluate the proposed solution through the novel simulation developed for this study.

1.4. Methodology

Queuing Theory is a common optimisation technique used to address traffic problems [35]. This study leverages the principles of Queuing Theory to identify the causes and symptoms related to traffic congestion around the port precinct. It also forms the basis for some of the derived algorithms to address these traffic congestion problems.

The approach used to address traffic congestion in the port precinct is to first identify the causes and then to define solution building blocks to those causes. This is achieved through the use of tools from the TOGAF framework [71]. TOGAF, further elaborated on in **Section 3.1 Solution Architecture**, is an architecture framework developed by the Open Group [71] and is used to address business problems through a structured approach by identifying business and technology solution building blocks. The defined solution building blocks are then translated into derived algorithms. Finally, the algorithms are tested, and the effectiveness of the solution demonstrated through Caudus, the smart queue solution developed specifically for this study.

A variety of development tools were used in developing Caudus. These include HTML5 and CSS for the frontend GUI, JavaScript and SQL Server for the middle layer and backend logic processes, respectively. The simulation is executed using batch processes for its multi-threading capabilities to mimic the nature of independent activities in reality.

The results of the simulation are used to demonstrate the effectiveness of the solution through the derived algorithms in this study.

1.5. Significance of Study

1.5.1. Contributions

While previous studies look at traffic optimisation localised to the area of interest, focusing on the symptom to address the problem, this study focuses on a holistic approach to traffic congestion in the port and inter-connecting areas acknowledging the inter-dependencies and its influences. Caudus approaches traffic congestion by resolving the root cause to the problem that is the imbalance between supply and demand, which contributes to a more dynamic and sustainable solution in comparison to other traffic optimisation studies. It also uses the *cause-and-effect* relationship to monitor the effects of traffic in the areas of focus in order to identify a problem in preceding areas. Previous studies only focused on remedying the area in which the congestion is found. This route to addressing traffic congestion through optimisation is a novel approach as previous papers researched primarily focus on localised congestion areas specific to the sea-side or inside the terminal and not the port inter-connecting areas [25, 30, 31].

From an 4IR perspective, Caudus has Big Data capability to gain insights in areas of its application that can promote economic growth through efficient operations, health safety benefits through driver pattern recognitions as well as peak traffic patterns and related driver behaviours and mental state, among others. An endorsement of this contribution is evident in its acceptance for presentation at the International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD 2021) under the title "CAUDUS: An Optimisation Model to Reducing Port Traffic Congestion" [84].

1.5.2. Potential Impact

Potential impact of this study includes environmental benefits, operational efficiency and cost savings. The application of Caudus extends well beyond the port precinct into other areas such as warehousing and storage precincts. Further expanding on its influence, although the use case focuses on traffic, the application is not limited to traffic. In general, any environment that has a queuing model and an underlying operational dependency can utilise Caudus to optimise output dynamically. This effectively reduces the cost of business by ensuring additional capacity is only available in peaks and disengaged during troughs. Case in point is the banking sector [32] that uses queuing theory to predict peak periods for customers and plan for the activation of additional tellers. If the influx of customers does not materialise and the queues are relatively quiet, then the overheads of the additional staff, equipment and operating costs are already spent. Caudus waives the need for planning as optimisation would be dynamic with the allocation and de-allocation of existing resources taking place in real time.

Contributions to an integrated traffic management solution is also evident. Caudus' integration capability with ITS in future works will add to the greater network of traffic awareness and support providing for benefits in road safety objectives, health safety objectives, and enhanced road user experiences providing for a healthier mental state [33]. With an integrated view across the travel route, road users are more likely to arrive alive in a less frustrated condition.

1.6. Limitations of the Study

This study was limited to the terminal layout and operational activities of the Durban port. Also, the number of equipment used in the simulation were based on a scaled ratio of the average equipment used across a single shift in the Durban port terminal. These limitations may suggest a constrain to the functionality of Caudus due to its applicability to the Durban port only. However, the algorithms derived are generic in nature and attempts to circumvent this limitation.

Also, in order to demonstrate the cause-and-effect attributes of congestion in areas beyond the control of the port, this study was limited to the algorithms derived for the identification and theoretical implementation of the CC-BPN (Figure 3.2), ITS [65] and DITS [49] systems integration. Therefore the level of Caudus' effectiveness beyond the port precinct can only be complemented by the successful implementation of these supporting systems.

1.7. Structure of the Dissertation

Chapter 2: Literature Review delves into some of the studies relevant to optimisation, traffic optimisation and vessel traffic optimisation. Chapter 3: Methodology discusses the approach taken in identifying the problem areas and defining the building blocks and algorithms used to develop the solution to those problem areas. Chapter 4: Design and Implementation unpacks the Caudus simulation built to test and confirm the algorithms used in addressing traffic congestion through optimisation. The Caudus optimisation module is further dissected in Chapter 5: Implement Results and ensuing discussions covered in Chapter 6: Implementation Discussion. The dissertation concludes with Chapter 7: Conclusion summarising the discussions and outcomes as well as areas for further studies in future works.

Chapter 2: Literature Review

"True optimization is the revolutionary contribution of modern research to decision processes" [34]

This chapter explores the various optimisation studies conducted to provide context of this dissertation. Section 2.1 provides a background on optimisation with specific focus on Queuing Theories. Section 2.2 delves into the different types of Traffic Optimisation works pertaining to freeway and urban roads. Section 2.3. looks at the various studies conducted into Traffic Optimisation for Ports and Section 2.4 summarises the varied traffic optimisation topics discussed highlighting the need to address port traffic congestion in this dissertation.

2.1. Optimisation

Indeed, true optimisation is revolutionary, especially when the smallest contribution has the potential to yield exponential benefits in every facet of existence. It is therefore most appropriate to use this revolutionary approach to address an equally impactful pain-point of everyday life, *queues*. Queues are inevitable in almost every aspect of one's life, from minor queues encountered at home to the major traffic queues, shopping queues, getting into work queues, printing queues, even the workload queues everyone needs to tend to.

Optimisation is certainly not an infant topic for research with various studies yielding results from Genetic Algorithms (GA) [7], Ant Colony Optimisation (ACO) [8], Particle Swarm Optimisation (PSO) [9], among others. Although several optimisation approaches can be employed for addressing congestion, Queuing Theory is a widely used technique to addressing traffic related problems [35].

2.1.1. Queuing Theory

Queuing theory is a mathematical study used in addressing queue delays [24]. Queuing Theory forms the basis of several optimization problems with its origins dating back to the early 1900s when mathematician Agner Krarup Erlang first introduced the concept [36]. He sought to address the problem of excessive waiting times on the Copenhagen Telephone Exchange. Looking at the period customers waited to get access to a telephone connection, his aim was to determine the number of telephone circuits that would be required to reduce the waiting times for the customers [37]. This work became the foundation of several queuing theories thereafter.

Following the principles of waiting in queues, a queuing model can be formed showing common components such as Arrival Time, Service Time, number of servers, queue length and Queue Discipline. The Arrival Time can be based on the probability model with Poisson's distribution being most often used to determine the input into the queue [24], although Kendall suggests additional input types such as the Deterministic input type as well as the Erlangian input type, which tends to both Poisson and Deterministic input types given certain properties [38]. The Service Time is the time taken to address the queue. The Number of Servers refers to the number of processes that are used to address the queue. The Queue discipline refers to the manner in which the queue is addressed i.e. whether the queue follows a First In, First Out (FIFO) or Last In, Last Out (LILO) or a random service model.

2.1.2. Kendall Notation

David G. Kendall, a mathematician known for his works on probabilities and queuing theories, suggested that queuing systems can be simplified using Markov Chain [39] on single-server queues and this can then be applied to multi-server queues [38]. Employing this rationale, the operational model of trucks serviced at the ports is similar to single-server (Figure 2.1) and multi-server (Figure 2.2) queues, thus further supporting queuing theories as a fitting approach to addressing traffic congestion.

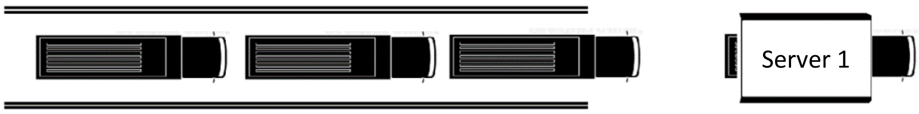

Figure 2.1: Single Server Trucks Queue

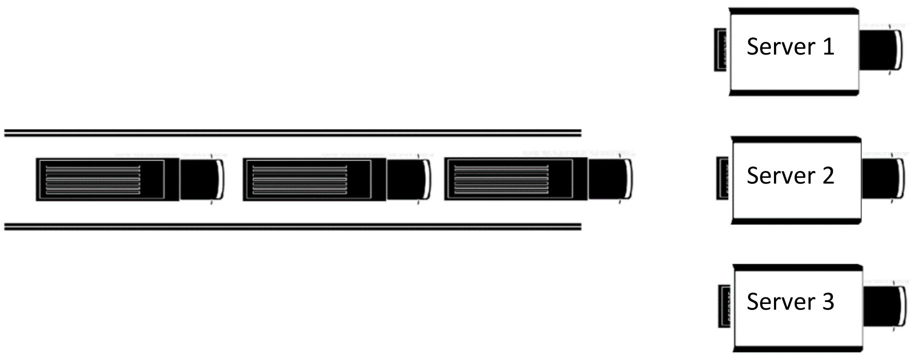

Figure 2.2: Multi-Server Trucks Queue

Using the common components of a queue, Kendall developed the notation to depict each of the 6 components being of the form A/B/c/K/m/Z [40]. The Arrival times A can be given using a Markovian process (M), Discrete or Deterministic process (D), or General distribution (G). These processes can also be used for the Service time processes (B). The number of servers addressing the queue is a constant (c). The queue capacity (K) is a finite number of entrants in the queue from a population size (m). K and N are usually omitted if the source is unlimited. The queue Discipline (Z) informs the type of approach that is used to service the queue i.e. First Come First Serve (FCFS), Last Come First Serve (LCFS), SIRO (Service in Random Order), PQ

(Priority Queue) and PS (Process Sharing). Every queue studied can be defined as a combination of Kendall Notation.

2.1.3. Little's Theorem

John Little further simplified queuing theory with Little's Theorem that states that under normal conditions, the average number of entities in a queue is given by the product of the average rate of arrival of the entities and average time spent in the queue[14] i.e.

$$L = \lambda W \tag{2.1}$$

where L is the average number of entities in the queue, considered the Queue Length,
λ is the Arrival Rate of the entities in the queue,
W is the average Waiting times for the entities in the queue.

Unpacking the theorem a little further, the queue length increases as the waiting time increases for a consistent arrival rate. The waiting time will only increase if the time taken at the servers (Figure 2.1) increases, since there is no room for the entity from the arrival queue to move to the server queue. The speed at which entities are processed at the servers can be seen as the rate of service at the servers. So, this effectively means that in order to ensure an ideal queue length or prevention of overflow, the rate of arrival must be less than or equal to the rate of service i.e.

$$\theta Rq \leq \theta Rs \tag{2.2}$$

where $\theta Rq = \lambda$ and θRs is the rate of service for each entity in the queue.
Conversely, the queue length will continue to grow if:

$$\theta Rq > \theta Rs \tag{2.3}$$

With this simplistic manner in addressing queues, the queue length can always be determined at a specific point in time given the current rate at which the queue is being filled and the average waiting times across the current queue capacity. In general, given any two known characteristics of Little's theorem [14], the third unknown for the queue can always be derived. Of particular interest of the theorem, and for this study, is the arrival rate as this is directly proportionate to the length of the queue for W >0.

2.1.4. Summary of Queuing Theory

Queuing theories have been studied in several industries to improve customer service, operational and cost efficiencies, environmental impacts etc. Applications of queuing theories are not exhaustive and extend to the medical and healthcare [10, 41] sectors, airports transportation [11], food services [42], banking industries [32, 43], transportation [12] and freight logistics [13], to highlight a few. Although the benefits include a better understanding in the prediction of queue behaviours for better queue management, the approach in majority of the studies do not address resolutions to the dynamic nature of the birth-death [44] process of queues or the root cause behind queue congestions. For example, in the case of the restaurant [42], peaks are pre-empted based on queuing theories. However, due to unexpected or exceptional circumstances, even though a peak is expected, there may be a lull in attendance and the underlying overhead costs are already spent; or if an influx of customers is experienced over a particular period that was not anticipated, the reputational damage due to extensive customer delays and loss of customers altogether [78] may be detrimental for the un-prepared establishment. Similarly, in the freight example [13], optimizing business processes are used to circumvent congestion and waiting times. However, intuitively this method only leaves room for the competitors to increase fleet presence in the supply chain and does not address the underlying cause behind the congested queues or increased waiting times.

In several queuing theory applications identified, the dynamic nature of a continuous birth-death process has not been addressed with an equally dynamic birth-death solution as in the case of Caudus. The primary objective of Caudus is to ensure queue congestion is minimized as well as identifying and managing unexpected or exceptional congestion causes while minimizing its impact.

2.2. Traffic Optimisation

An increase in the population of a country also sees an increase in its Gross Domestic Product [83]. By extension, this also leads to additional employment opportunities as well as an increase in travel and transportation. Expanding infrastructure and resources alone cannot address the increase in traffic experienced over the last few decades. Also, with limited infrastructure space available in addition to the years of chaos experienced with this type of remedy, this approach is not the most practical or cost-effective method in addressing the problem.

With ports being a major location for a country's import and export of goods, cargo transporters also add to the congestion problems (Figure 2.2 and 2.2). These cargo transporters range up to 22m [45] in length thus suggesting that each truck displaces approximately five cars i.e. traffic volume increases five times for every stationary truck.

Figure 2.3: Example of Traffic inside the Terminal [2]

Figure 2.4: Example of Traffic in the Port Precinct [46]

Advancement in technology and the Fourth Industrial Revolution (4IR) [47] have provided more cost-effective ways for addressing real world challenges with technological solutions. With infrastructure and resource limitations, formulating solutions through optimisation and leveraging technology as an implementation mechanism provides for a more efficient method to address traffic related problems.

The route normally travelled for cargo transporters and haulers are from warehouse districts followed by freeways or urban roads before finally reaching the port precinct and eventually into the port terminal. The operational activities ensuing in the port offloads the cargo before the haulers exit the terminal, following a similar return route to the warehouse or the next pick up point. Therefore, the same transporters will tend to experience the same congestion and bottleneck points created at each intersection along the route.

This dissertation seeks to address traffic congestion and throughput through optimisation. Congestion notably occurs across all traffic zones and therefore solutions to specifically resolve each zone's traffic problems must be developed and work as a collective to sustainably alleviate traffic congestion across precincts.

Figure 2.5 depicts the typical travel route for cargo haulers and transporters noting the key traffic zones travelled. Several traffic optimisation studies have been conducted for each of these zones with only a few that focus on the highlighted port precinct zone (Figure 2.5), which is the focus of this study. Although the list is not exhaustive, the literature review touches on some of the studies conducted for the different traffic zones showing that only a few contribute in port precincts and are constrained to a limited scope.

In recent years, optimisation and algorithms have been the basis of addressing traffic problems in freeway and urban road areas. Some of these are further reviewed below including *Traffic Flow Optimization on Freeways* [48], *NetLogo implementation of an ant colony optimisation solution to the traffic problem* [49], *Optimization of urban road traffic in Intelligent Transport Systems* [50], as well as congestion issues around ports such as *Optimization Model For Truck Appointment In Container Terminals* [25]. In order to collectively alleviate traffic congestion across the travel route of the transportation ecosystem, solutions developed across each traffic zone must work to complement each other. As in the case of the chain being as strong as its weakest link, the weak links in the travel route chain is each congested bottleneck point.

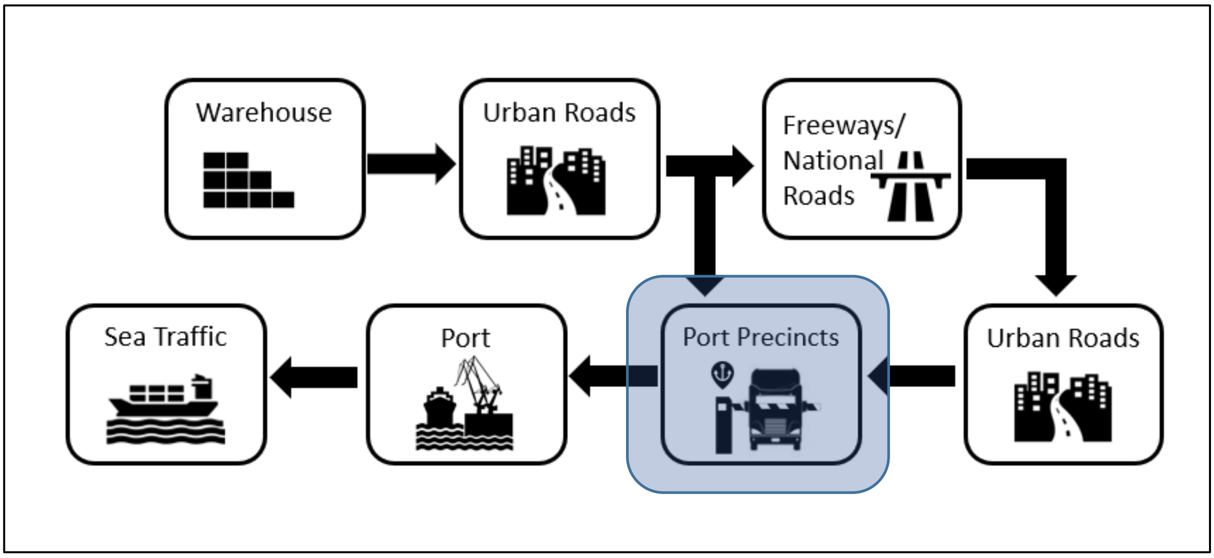

Figure 2.5: The General Travel Route Chain (TRC) for Transporters

2.2.1. Freeway Traffic Optimisation

2.2.1.1. Traffic Flow Optimization on Freeways [48]

Taking a closer look into studies on freeway traffic congestion, some have already identified toll collection points as a huge contributor to congestion on freeways primarily due to its manual collection methods [48]. The study suggests that theories on traffic flow is based on the flow, density and speed of the traffic and uses fluid dynamics applied to traffic to derive a mathematical model to test the different toll collection scenarios that impact throughput.

[48] uses three scenarios to demonstrate the success of the preferred solution. The first scenario uses the current situation where there are six lanes, with four Telepass and 2 Cash Collection lanes. It is apparent that the Cash Collection lanes provides a number of constraints, particularly the vehicle requires slowing down, then stopping for payment, waiting for the payment receipt, before moving again. Each of these constraints compound delays in the process of passing through the toll collection point. The second scenario applies the model solely to the Telepass lanes and these too have some limitations in their designs. This solution requires each vehicle to have the Telepass system installed, which serves as a constraint on this solution being the most efficient since not all road users may opt for it [48]. An additional constraint includes requiring the vehicle to reduce its speeds from the average motorway/ freeway limits to 30km/h in order for the Telepass toll collection to work.

The third scenario involves having an Open Road Toll (ORT) design where there is no reduction in speed, since slowing down for tollbooths is one of the major causes in the congestion problems on freeways [48]. The model demonstrated that the best throughput time across the three scenarios is the ORT.

Although [48] contributes to the alleviation of congestion in the greater ecosystem of the TRC, its application extends mainly to areas of disruption caused by toll collections and therefore the algorithms used does not extend to the port precinct problem.

2.2.1.2. Freeway Traffic Management and Control [51]

Freeway Traffic Management and Control [51] is a study done on managing freeway traffic dynamically. It employs a collection of tools, procedures and methods used to manage traffic flow on freeways.

The study shows that most of the inefficient traffic flows are a result of bottlenecks, wrong travel route choices and blocking. Bottlenecks, also relevant to congestion in the port precinct, are typically caused by ramp traffic, bridge and tunnel traffic, difficult steering areas such as curves and grades areas as well as merging and diverging traffic areas [51]. Traffic jams caused by bottlenecks are more serious as it can impact traffic flow by up to 30% of its capacity compared to other reasons whose impact ranges between 0%-15% [59, 60] of the traffic capacity. In the case of blocking, this type of congestion is a result of another congestion where the traffic build-up blocks intersection points. A typical example of blocking is when on-ramp traffic bottlenecks block the exit point for off-ramp traffic – Figure 2.6.

In order to minimize the impact of bottlenecks, route choices and blocking, tools to measure and control traffic can be employed in the relevant areas of concern. These control measures include Ramp Metering, Dynamic Speed Limit, Route Guidance and Lane control measures.

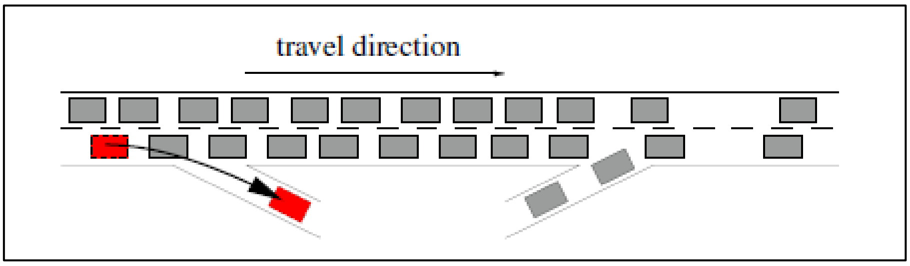

Figure 2.6: Blocking - Traffic build-up from on-ramp bottleneck blocks the exit of the off-ramp traffic, adapted from [51]

Ramp Metering is a control that allows a limited number of vehicles to enter a freeway during the Green phase of the traffic control signal. The control is enforced through the use of a speed camera for Red phase offenders (Figure 2.7). Some of the benefits of Ramp Metering include traffic gridlock prevention [61], route choice influence based on drivers anticipating travel delays due to ramp metering [62], and localising traffic jams [51].

Ramp metering uses different strategies to determine the timing such as Traffic-Response versus Fixed-Time. The Fixed-Time strategy uses historic data to determine the ramp meter timing. Due to this reason, it lacks the dynamism required to address the ever-changing traffic situation. The Traffic-Response strategy addresses this shortfall by monitoring the traffic situation in real time and adjusting the flow accordingly. [51] proposes the Demand-Capacity algorithm [80] given by:

$$Qramp\ (t) = \begin{cases} Qcap - Qin\ (t-1) \ldots if\ Qocc\ (t-1) \leq Qmax \\ Qmin \qquad\qquad\qquad \ldots else \end{cases} \tag{2.4}$$

where *Qramp (t)* is the vehicle flow allowed from the ramp into the freeway at time *t*, *Qcap* is the freeway capacity, *Qin (t-1)* is the vehicle flow from the ramp entering into the freeway at time *t-1*, *Qmin* is the minimum allowed vehicle flow on the ramp, *Qocc (t-1)* is the ramp occupancy at *t-1*, and *Qmax* is the maximum occupancy. This method cannot identify freeway congestion alone and suggests that if the ramp occupancy is not at maximum limit ($Qocc\ (t-1) \leq Qmax$), then there is no congestion, else congestion exists, and the minimum allowed vehicles should enter the freeway.

Figure 2.7: Example of Ramp Metering on freeways [51]

Dynamic speed control measures allow for changing maximum allowed speeds based on the traffic flow or environmental and weather changes. Although used to manage congestion and traffic flow, the primary reason for dynamic speed control is due to safety factors as speeding is more likely to lead to a crash [63], which then has a domino effect on traffic flow.

Route guidance and Lane control measures assist drivers with real-time lane closures and alternate route recommendations based on the current traffic situation. In recent times, these recommendations have also been built into GPS navigation systems to better manage the drivers' arrival time and condition. Figure 2.8 gives examples of Route Guidance controls on national roads.

Figure 2.8: Example of Route Guidance Control Measures [85]

While the control measures are quite effective in its area of application, the study also places reliance on a network-oriented control system for traffic management. This is to ensure one area of application of the traffic control measure does not negate the efforts of another. The requirement of an integrated view of the various traffic management systems is becoming increasingly evident [48, 51, 64] in order to ensure a practical approach to eradicating congestion and traffic related problems. In addition to [51] displaying the benefits of an integrated view between Route Guidance and Ramp Metering, [48] also affirms the advantages of integration with ITS and Vehicle Ad-hoc Networks (VANET), a computer network of road infrastructure and moving vehicles, as a contributor to improving bottlenecks, safety and better traffic performance. [64] further highlights the benefits of an Integrated ITS with a multilayer and multilevel system where the layers refer to the processes, controls, schedules, planning, management and coordination of the system and the levels refer to various transportation networks.

Not all traffic control measures covered in this example could add value to the port precinct challenges. The Dynamic Speed Limit solution is used to control the flow of traffic and is relevant to freeways. Ramp metering may add some value by allowing a limited amount of trucks into the port precinct. The downside to this would be the congestion effect experienced beyond the port precinct when the metering system only allows the minimum trucks given by (2.4). This could possibly result in a blocking scenario (Figure 2.6). The Route Guidance solution could also provide some value added to port areas as it could allow for re-direction of traffic away from the port precinct during incidents and high traffic gridlocks. However, emphasis has been placed on ITS and VANET for an effective application of this solution.

2.2.1.3. Model Predictive Control for Freeway Traffic Networks [53]

While [51] highlighted various control measures to manage freeway traffic, several studies focus on ramp metering as an area of great benefits to reducing traffic congestion through the use of Model Predictive Controls (MPC) [52, 53, 54]. Developed in the latter part of the 1970s [52], MPC is a control mechanism that predicts the optimal control action based on the inputs. The control input can be the current state of the traffic situation, which can then be used to compute the optimal signal changes required to change the traffic situation for the better. The results of the computation are generally a series of control signals with the first control used.

The current commonly used control system uses a linear and local control loop. The linear nature of these control systems suggests the input is a single variable function that is used to determine the timing of the control signals. These control systems are also implemented local to a particular site and set to repeat the control pattern in a loop. This mechanism is limiting since traffic conditions change dynamically. In exceptional situations such as accidents, or weather conditions, the local control loop is not flexible enough to change with the change in traffic situation. MPC aims to address this shortfall in traditional control systems by applying a non-linear, centralised control system that computes the output online given the current situation. The drawback in the centralised MPC model is that computations increase for larger traffic networks adding to processing time and making it inefficient in a real time environment. [53] proposes different MPC models for a practical solution in larger traffic networks.

In order for MPC to be efficient in large traffic networks, the study proposes options of distributed MPCs for ramp metering and a hybrid model MPC using a Genetic Algorithm [7] for variable speed limits (VSL). In addition, the MPC needs to be a high-speed module as it needs to provide signal outputs based on accurate and reliable predictions whilst online. The high-speed capability is not as intensive as would be required for a centralised MPC solution.

The distributed MPC model is one that uses inputs from a distributed network of MPC and attempts to find the optimal output using its parallel processing capabilities. While the distributed MPC may not be as effective as a centralised one, [53] shows that it reduces total time spent by a further 14% from the current status quo. The centralised MPC for Freeway Traffic Networks is considered not practical as the computation time in a large traffic network is too costly.

Figure 2.9: Example of variable speed limits (VSL) on freeway [51]

The hybrid MPC is proposed for use in managing VSL (Figure 2.9). The first option of the hybrid solution proposes approaching VSL as a discrete set of values for optimisation as opposed to a continuous set. The system will exhaust the options based on all the discrete values to derive an optimal solution. The study found that performance in approaching VSL in this manner is more efficient than using continuous values [53]. In instances where the discrete value computation time is excessive, a genetic algorithm is used as the alternate option of the hybrid solution to minimize processing time and return a near equally favourable response.

2.2.2. Urban Traffic Optimisation

2.2.2.1. NetLogo Implementation of an Ant Colony Optimisation Solution to the Traffic Problem [49]

Ant Colony Optimisation (ACO), a study based on the behaviour of social insects such as bees, termites and ants, aim to address urban road traffic congestion in areas with traffic lights using Distributed Intelligent Traffic Systems (DITS) [49]. While traditional methods of managing congestion around traffic lights use historical data to control the timing of traffic signals, ACO uses collected information from the road vehicles and shared on DITS. DIT is an extension of intelligent transport systems that includes a distributed multi-agent network working together for a common purpose.

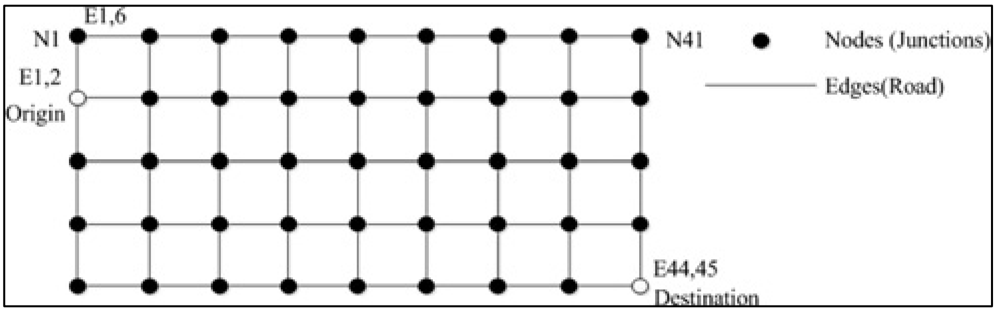

Figure 2.10: Road Scenario used in ACO solution, adapted from [49]

The ACO algorithm approaches the traffic congestion problem in a dynamic manner and uses probability in selecting a desired route [49]. As the route is travelled, information is received in real time on the existing route as well as other candidate routes to identify traffic situation. Based on the algorithm, the best possible route is selected. Each time, options are provided based on the distributed network until the final destination is reached.

The algorithm to determine the probability of the selected route being the quickest to the destination is achieved by scoring the different routes and finding the best route based on the condition:

$$\text{BestScore (route)} = \text{Score at min } (x_{ij}\ T_{ij})$$

where *ij* is the route taken between junctions or nodes (Figure 2.10) *i* and *j*, x_{ij} is the distance of the route taken and T_{ij} is the traffic along the route taken. Given this as the basis for decision-making, the probability of the selected route being the quickest or best scoring is given by the formula:

$$P_{ij} = \frac{T_{ij}^{\alpha}\, x_{ij}^{\beta}}{\sum_{h \in \varrho} T_{ih}^{\alpha}\, x_{ih}^{\beta}}$$

where P_{ij} is the probability that the chosen route given by *ij* is the best scoring route, T_{ij}^{α} is the traffic influence along route *ij* and α is the rate at which vehicles enter and leave each route; x_{ij}^{β} is the distance given along the route ij and β is the distance of each route solution while ϱ is the route not yet chosen. The traffic influence is aided through information retrieved from DITS.

The disadvantage in this solution is due to the cost of processing time involved in determining the best route for every node in the route for every vehicle in the network, in addition to the integrated requirements with DITS. Another disadvantage is that the traffic only considers congestion and excludes accidents and breakdowns in when calculating the traffic influence [49]. However, the benefit to the port precinct study is that it is a plausible solution to addressing traffic flow in areas leading to the port precinct.

2.2.2.2. Optimization of Urban Road Traffic in Intelligent Transport Systems [50]

[50] seeks to address congestion in urban roads through the use of optimizing traffic signals. The study affirms the issue of an ever-increasing presence of road traffic and the need to develop and upgrade infrastructure. As a complement to the capital investment, ITS [65] provides several benefits including a reduction in accidents, alleviation of traffic congestion as well as environmental benefits. In addition, optimization of the semaphore cycles at traffic intersections is proposed, particularly through the use of new equipment that can cater for more complex traffic modification strategies, semaphore synchronization for addressing traffic volumes dynamically, integration across semaphores for real-time management and automated control, removal of superfluous semaphores, modification of semaphore timings and cycles for different phases and the implementation of traffic optimization and analysis software.

2.2.2.3. A Global Optimization Approach to Solve the Traffic Signal Synchronization Problem [55]

The approach of addressing traffic signals as a means of addressing traffic flow and delays in urban areas is an oft-studied topic. [55] looks at the different models that are used in traffic signal control with the most common ones being the traffic assignment model and the signal optimization model. The traffic assignment model refers to fixed traffic signal controls and uses traffic assignments as objective variables to address the problem, while the signal optimization model aims to use the signal controls. The signal optimization model has two main objectives i.e. increase in green signal timing and a reduction in a multi-objective function including number of vehicle-stops, fuel consumption and CO emissions. The signal optimization model provides for a more predictable result set to find an optimal solution. The study uses TRANSYT [66] to analyse delays in the traffic network and derive an improved algorithm for optimal signal synchronization to achieve its objectives.

2.3. Traffic Optimisation for Ports

Various studies have been done for port traffic. However, the studies are generally focused on the sea side traffic and very few looks into the effects of port operations on the traffic in the inter-connecting port precincts. The following sections highlights some of the port traffic optimization models that have been done thus far.

2.3.1. Vessel Transportation Scheduling Optimisation Based on Channel-Berth Coordination [30]

Related to the seaside traffic of the port, Vessel Transportation Scheduling Optimisation Based on Channel-Berth Coordination [30] provides insights into the scheduling of vessels in a more efficient manner using the vessel scheduling order, vessel direction of travel, the distance to a berth and a mathematical model to determine the minimum waiting time. Suggesting that several studies primarily focus on either channel efficiency or berth operations and rarely use both, the study proposes a simulated annealing and multiple population genetic algorithm (SAMPGA), which uses both channel *and* berth operation coordination. The objective is to provide a more efficient vessel scheduling process, which inadvertently reduce vessel waiting times and channel congestion. Figure 2.11 depicts an example of a vessel scheduling.

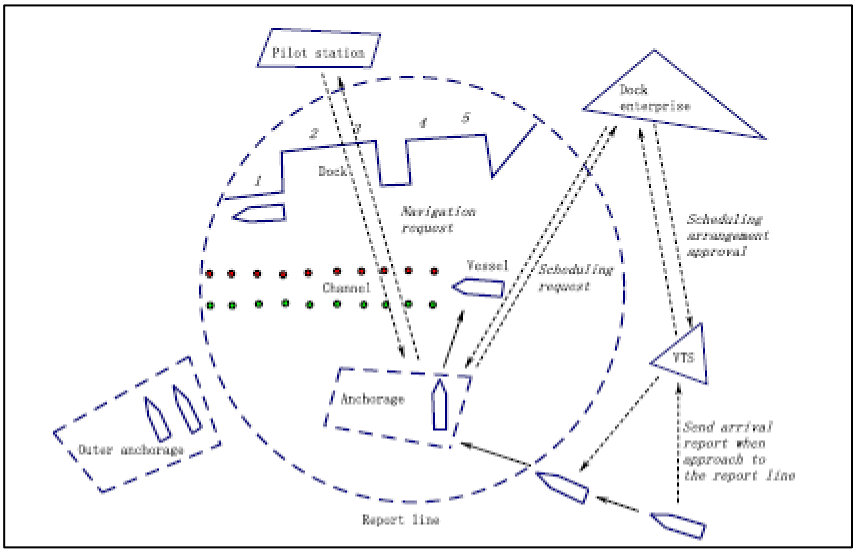

Figure 2.11: Example of a vessel scheduling in a port, adapted from [30]

This study focuses on vessel traffic optimisation in the Sea Traffic zone (Figure 2.5) and does not contribute to the port precinct traffic optimisation. The review has been included to highlight the number of Sea Traffic zone studies conducted in comparison to studies on traffic optimisation in the port precinct.

2.3.2. Vessel Traffic Scheduling for Restricted Channel in Ports [31]

Limitations around channels leading to multiple ports (Figure 2.12) have also been addressed. [31] focuses on optimizing traffic in a restricted channel which otherwise can serve as a safety hazard in addition to vessel traffic delays and costs. The study suggests three options to the channel problem viz. widening of the channel, which is not practical, both financially and time to implement, given the oft-changing market demands; regular channel dredging, which does not address the problem in its entirety in addition to the dredging process having geological and environmental effects due to the seafloor dumping [67]; scheduling of vessels based on a multi-objective optimization algorithm, which is the proposed solution. The solution uses the number of vessels, the vessels' navigational mode and direction, and basin and berth locations to determine each vessel's sequence and schedule for navigating the channel. This is achieved using the Non-dominated Sorting Genetic Algorithm II and Tabu Search (NSGA-II-TS) [31].

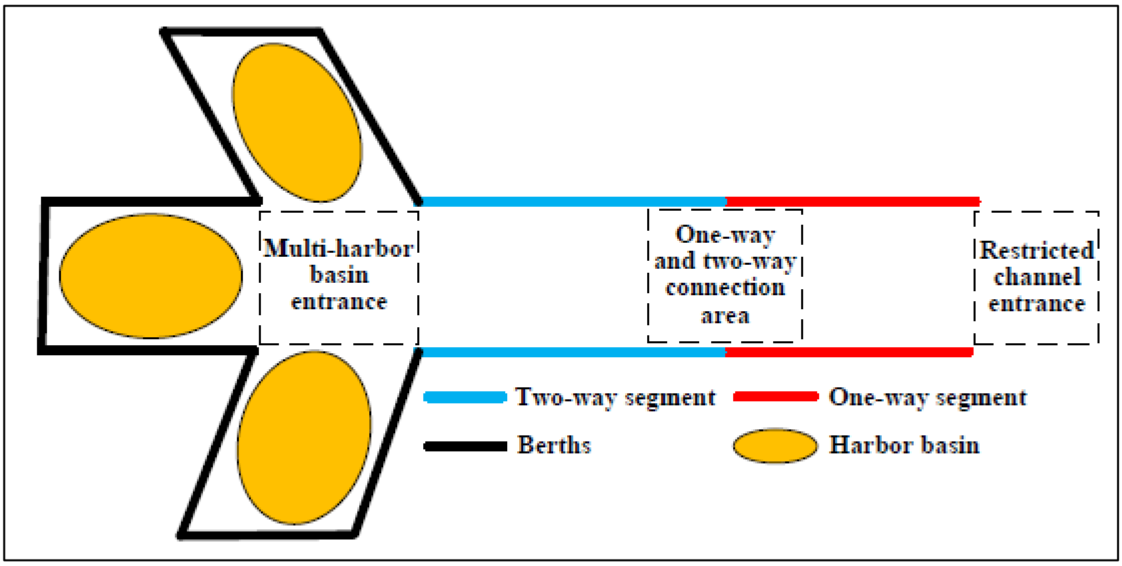

Figure 2.12: Example of a restricted channel [31]

Here too, focus is on vessel traffic optimisation in the Sea Traffic zone (Figure 2.5) and does not contribute to the port precinct traffic optimisation but has been included in this review to emphasize the number of studies conducted for Sea Traffic zones compared to the port precinct.

2.3.3. Berth Scheduling Problem Considering Traffic Limitations in the Navigational Channel [58]

The berth scheduling problems for traffic in navigation channels [58] yet again looks at optimizing vessel traffic in navigational channels. The proposed solution uses the mixed-integration linear programming (MILP) algorithm that is specifically applied to one-way ship traffic in channels, in addition to the Hybrid Simulated Annealing (HSA) algorithm for a dual-direction traffic solution to optimize berth utilization. The study looks at increasing efficiencies in port resources to accommodate the increase in vessel sizes and loads. These inadvertently impact on the efficiency of channel navigation due to its limited width and depth, which causes bottlenecks in the channels. Expanding the channel width and depth through dredging cite similar disadvantages as in other studies [68]. The alternative is optimization through algorithms. The objective of MILP and HSA is to address a variety of vessel sizes and loads to reduce departures times. This in turns increases throughput while reducing fuel consumption and emissions.

Here too, vessel traffic optimisation in the Sea Traffic zone (Figure 2.5) is in focus and does not contribute to the port precinct traffic optimisation except as an indicator of the number of studies prevalent for Sea Traffic zones over port precinct traffic optimisation.

2.3.4. Designing Container Trucks Arrival Schedule Using Truck Turnaround Time Method at Terminal [56]

While there are a number of vessel-traffic related studies, only a few have been identified to address vehicle traffic related to the port precinct with many of these only focusing on a scheduling system to address the problem. One area of improvement identified is truck waiting times and [56] implements a truck arrival scheduling system to reduce waiting times for the container trucks based on the truck turnaround time (TTT) in the terminal. TTT is given by the average time the vehicle takes to complete its process and the trucks average travel time across the process [57]. The model in this study uses historic data to determine average turnaround times for trucks causing low, medium and heavy congestion and formulate an arrival schedule for the trucks. Since the congestion levels were attributed to the number of vessels that were being worked at the time, the new truck arrival schedule will be a benchmark for the number of vessels that are forecasted for operations.

Although the benefit of this study reduces the truck waiting time in the terminal, it does not add value to the throughout time of the cargo entering and leaving the port. This solution is reflective of addressing the symptom i.e. the long waiting times of the trucks, and not the cause which may be related to the inefficient operational activities that exist within the port. This is a clear example of scheduling systems not adding the required benefit in addressing traffic congestion and throughput in the port precinct.

2.3.5. Optimization Model for Truck Appointment in Container Terminals [25]

The Optimization Model for Truck Appointments (OMTA) [25] focuses on truck extended waiting times in container terminals. The study analyses the truck waiting times in the queues that lead to the terminal gates proposing an optimized truck appointment model to reduce the excessive delays with the intention of curbing terminal congestion. The appointment system allocates a pre-determined number of trucks to different periods in the day that are allowed into the terminal to perform their duties. In this manner, the truck queue leading to the terminal is limited based on the trucks allowed to call at the terminal thereby managing the congestion. OMTA pre-determines the optimal truck quota through a model derived using Pointwise Stationary Fluid Flow Approximation (PSFFA) and Genetic Algorithm (GA). The optimal quota for the truck appointment system is the ideal number of trucks per appointment period that will result in the minimum waiting time across the gate and yard i.e.

$$min\, Z = \frac{(\sum l_t^g + \sum l_t^y)}{P} \qquad (2.5)$$

where *min* Z is the minimum waiting time of total waiting times for the trucks at the gate defined by $\sum l_t^g$ and yard defined by $\sum l_t^y$ per appointment period P. The model estimates the average yard and gate waiting times given by:

$$w_t^g = \frac{l_t^g}{\sum_i d_{it}^g}\ \forall\, t \quad \textit{and} \quad w_t^y = \frac{l_t^y}{\sum_j d_{jt}^y}\ \forall\, t \qquad (2.6)$$

where w_t is the average waiting times across the gate (*g*) and yard (*y*), l_t is the queue length across time periods at the gate (g) and yard (y), and d_t is the truck departure across time periods from the gate (*g*) and yard (*y*). In order to determine the best quota for the appointment system, the model uses GA and PSFFA to determine the optimal quota tested against (2.5) and (2.6).

Although this model is particularly effective in ensuring congestion is not experienced through the use of appointment systems, it only addresses the symptoms of congestion. Intuitively, based on an appointment schedule, operational activities are drawn out over a longer period to accommodate the fixed number of appointment periods P. In contrast to OMTA, this dissertation seeks to address the root cause of traffic congestion in the port precinct, which is also expected to improve throughput.

2.4. Summary

It is evident that increase in traffic across the globe is a growing concern. This is the natural order of growing economies. Nothing can be done to stop the growth thus leaving the option of academics and scientists to address the problem scientifically. As a result, optimisation studies are being continuously conducted in order to devise a method of managing the different traffic situations taking into consideration the various constraints such as time, cost and environmental impacts.

Most of the traffic optimisation studies encountered address the problem of a specific traffic zone, depicted in LR1, with little attention given to inter-connected traffic zones. For example, the limitation in the MPC solution is that although freeway congestion at onramps may be averted, the impact can be felt further down the ramps [54] leading into minor roads. This could potentially lead to urban road congestion, which have separate, siloed solutions.

Similarly, with traffic optimisation around port precincts only focusing on the roadside traffic outside the terminal [56] or on the sea-side traffic [30, 31, 58], attention is not specifically given to the optimisation of operational activities for which both port precinct as well as sea-side traffic are dependent on. The truck appointment system could possibly work well in most cases. However, there are some underlying drawbacks. For example, [25] has a limited number of slots available for scheduling trucks, yet the cargo imported can potentially be unlimited. So, in order to despatch all cargo from the terminal, the scheduling will extend over days and possibly weeks. These delays in turn impact on the transport logistics schedules and speed to market [69]. The storage costs are also compounded, as the goods remain in the terminals for a longer period, which is passed down to consumers. Operational inefficiencies within the terminals also pose a risk to congestion and further frustrations due to reneging on commitment [70], even with truck appointment. Hence, truck appointments are not a guaranteed solution and perhaps the risk to reward ratio of this solution could be examined in future works.

While ITS provides for a more integrated solution to traffic management, it is still a supplementary solution to the problem and while a specific integrated solution across the ecosystem is yet to be developed, this dissertation acknowledges the inter-dependency across traffic zones and attempts to address the underlying root cause to traffic congestion in port precincts or any warehousing precinct through Caudus. Although not as relevant to this research, perhaps for future works, non-port traffic optimisation solutions' relevance exists in their inclusion into ITS together with Caudus, which provides for an all-encompassing solution to the traffic ecosystem.

Chapter 3: Methodology

Due to the nature of the problem, Queuing Theory, above others such as GA, ACO and PSO, is the commonly used optimisation technique in addressing traffic congestion [35] and throughput. The solution does not lie only in alleviating congestion but also aims to complement throughput in the logistics chain. As a result, this solution has a multi-objective function viz. preventive, reactive and predictive objective functions.

In order to address the multiple objective resolution to the problem, it has to be approached in a structured manner. This chapter articulates the method involved in addressing the problem. Section 3.1. Solution Architecture delves into the discipline of system architecture and the tools from the TOGAF [71] framework used to define building blocks to resolve the current problem as well as additional building blocks to be explored in future works. Section 3.2. Algorithms provide insights into the heuristics used in implementing the preventive and reactive objective functions and Section 3.3. Exceptions Algorithm delves into the derived algorithms to address the predictive objective functions of the solution. The algorithms have been included in this section as they provide for the solution building blocks identified to address the problems in the solution architecture.

3.1. Solution Architecture

3.1.1. Solution Domains

The Open Group Architecture Framework (TOGAF) is an architecture framework that provides methods and tools for developing Business, Data, Application and Technology architectures [71]. The TOGAF framework consolidates addressing business problems through the Architecture Development Method (ADM). The ADM breakdowns down the approach into different domains and categories for use independently or collectively. Since this study focuses on the systems solution to traffic congestion, components of the ADM's Solution Domain (Figure 3.1) is used to develop the reference model and high-level architecture of the business challenges and relevant Solution Building Blocks. SBBs are potentially re-usable components of a solution that can be combined together to design the target state of the required solution [71]. The resulting reference model displays additional building blocks that can be used in potentially advancing this project in future studies.

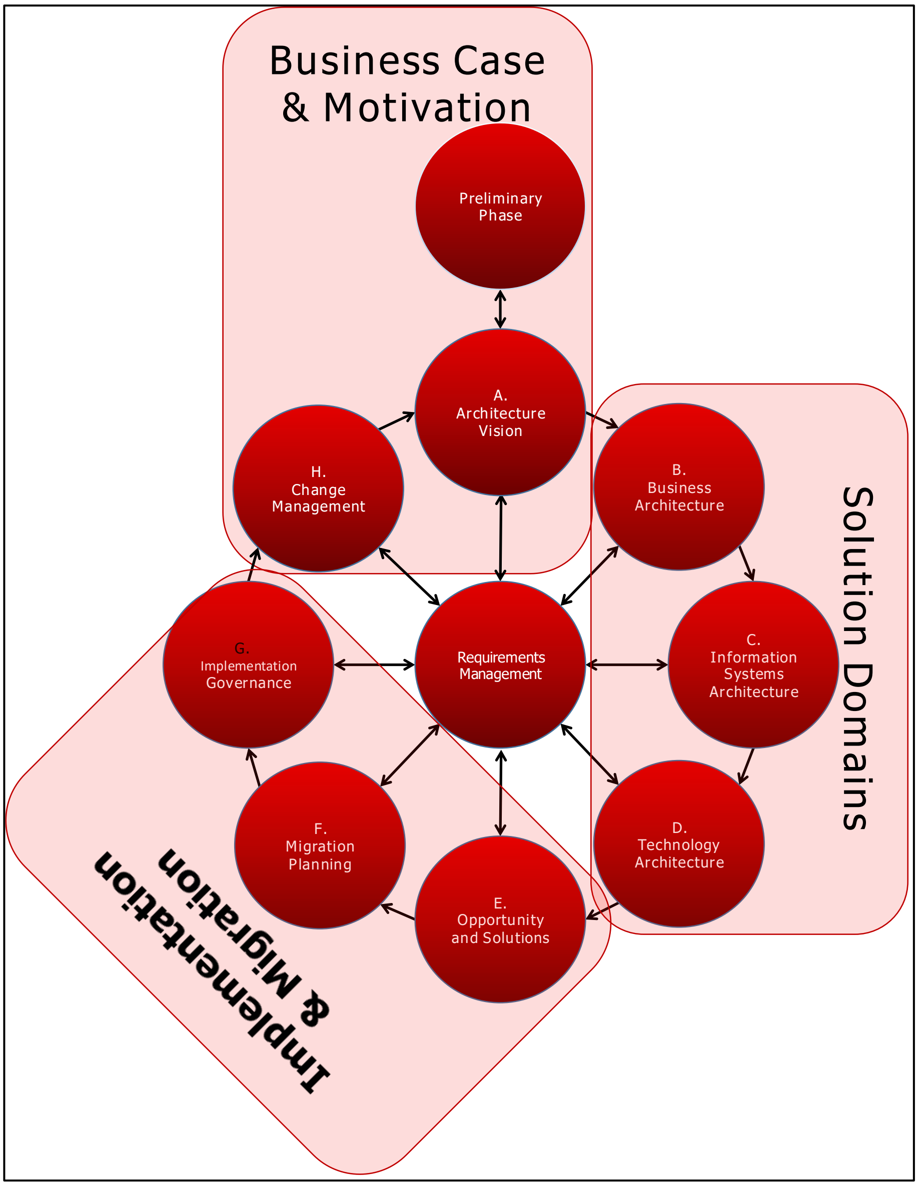

Figure 3.1: ADM Domain Categorization, adapted from the TOGAF Architecture Development Method (ADM)

3.1.2. Architecture Reference Model

The Architecture Reference Model (Figure 3.2) depicts the complete high-level solution architecture to address the congestion problem. The reference model is compiled by decomposing the problem statement into smaller pain-points. Solutions to the pain-points are then usually determined through brainstorming and engagement sessions with subject matter experts resulting in the Business and Systems SBBs.

Figure 3.2 decomposes the overall solution into Business and System specific solution building blocks. The Business Solution Building Blocks refers to the non-system related activities that need to be resolved in order for the complete solution to work. Some of these activities include creating Customer Collaboration (CC) and Business Partner Network (BPN) with the relevant trucking company owners and customers to support the technology solution as well as preparing the terminal's underlying yard and equipment facilities, and to up-skill the personnel to support the technology change.

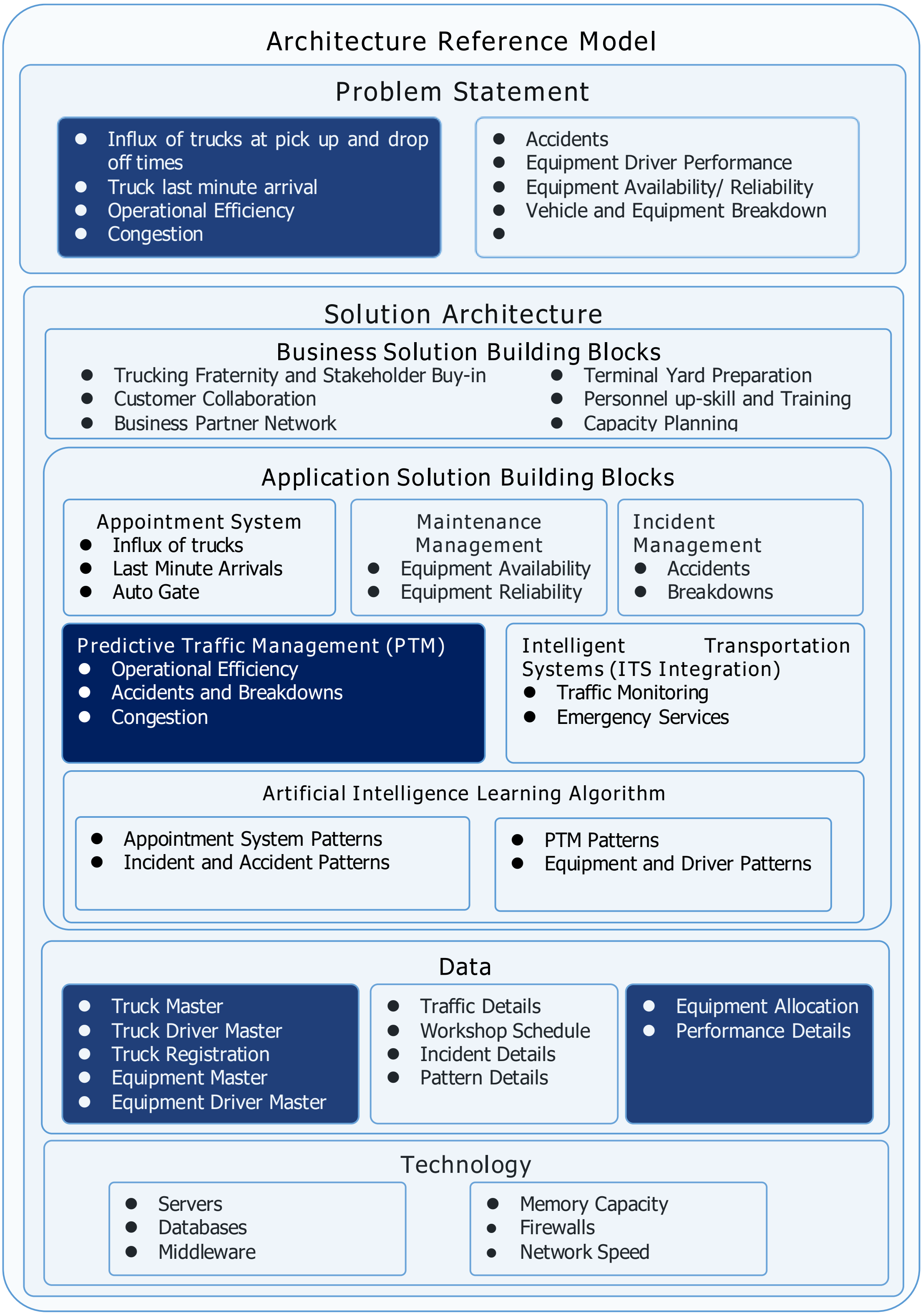

Figure 3.2: High Level Solution Architecture

3.1.3. Solution Building Blocks

The Application Solution Building Blocks (Figure 3.2) is a collection of building blocks directly related to the technology required to support the overall solution in addressing the congestion problem. The Appointment System SBB, for example, has already been addressed in previous studies [25] as well as Incident Management through the use of ITS and DITS. These have been included in the reference model as previously developed building blocks and act as solution components in the *TRC*. The Predictive Traffic Management (PTM) SBB highlight building blocks needed to address congestion through optimisation. The Artificial Intelligence Learning Algorithm SBB, a 4IR solution building block for possible future works to support PTM and other solutions, focuses on pattern recognition and predictions based on data collected across the ecosystem. Future building blocks developed in response to growing congestion problems may be included in this domain to support progressive developments in this area.

The Data and Technology Solution Building Blocks relate to the underlying data compositions and infrastructure to support the application solution. The Data SBBs is composed of the related database structures such as tables, procedures and database triggers used in the solution as well as the data collections and its relationship across structures. The Technology SBBs refers to the network, security and underlying infrastructure required to realise the solution.

Developing the solution to address congestion using the Architecture Reference Model allows its application to any environment that has similar parameters and constraints. Based on the requirements to address each problem, extracting the relevant building blocks from the reference model guards against reinventing the wheel in each situation. The reference model can be seen as a high-level blueprint of the solution to the problem at hand. The scope of this dissertation focuses on the shaded areas of the reference model (Figure 3.2).

3.1.4. Predictive Traffic Management (PTM)

The Predictive Traffic Management (PTM) SBB is a collection of building block within the Application Solution domain used for identifying operational inefficiencies, exceptional contributors to bottlenecks and potential congested situations, and provide relevant remedies. The PTM-SBB is composed of solutions that validate the operational performance of supply against demand in order to predict whether required needs are met, if there are possible incidents hindering demand requirements or if the problem exist within the confines of the operational control areas. In order to achieve this, attributes of the operational performance and traffic queue limits need to be defined.

3.1.5. The Solution Scope

The success in alleviating congestion across the transportation ecosystem lies in each congestion point finding its own solution. The literature review touched on congestion in the travel route of the ecosystem. Each cargo transporter travels this route from the point of origin e.g. warehouse districts before joining freeways or urban roads, thereafter entering the port precinct and finally reaching the point of destination i.e. the port terminal. Figure 3.3 depicts the Travel Route Chain of the truck's route to the terminals.

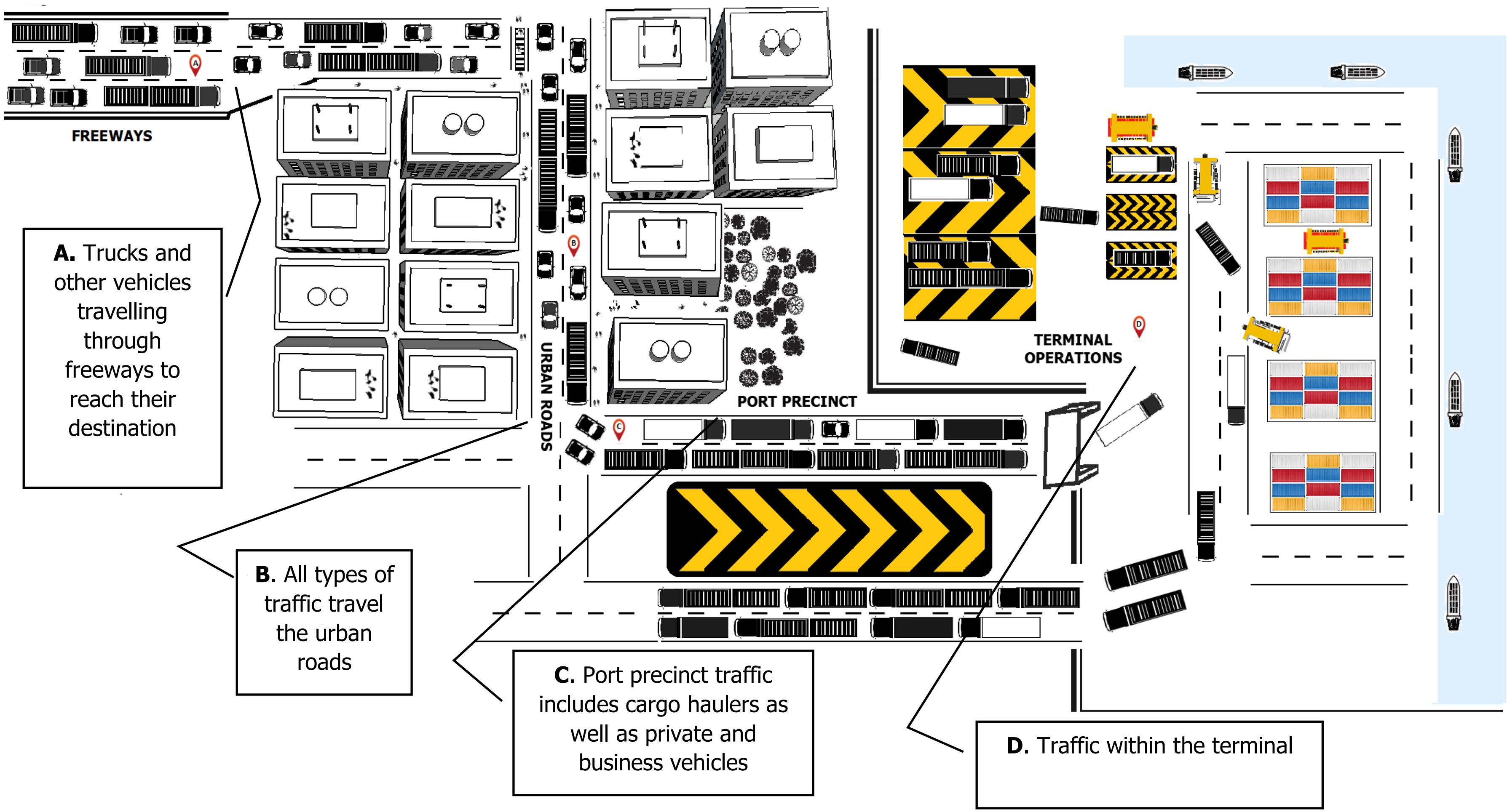

Figure 3.3: Graphical representation of the Travel Route Chain (LR1) depicting Freeways, Urban Roads and Port Precinct in a single view (author's original compilation)

Figure 3.3 shows the different stages of the TRC with potential congestion points denoted at (A), (B), (C) and (D). With studies previously done, and will continue whilst the problem progresses, solutions around Freeway (A) [48, 51, 53, 54], Urban (B) [49, 50, 55] and Port precincts (C) [25, 56, 57] attempt to address traffic challenges in those areas. These solutions in general only address the problem locally to (A), (B) and (C) without appreciating that the root cause to congestion may lie across connected traffic zones. In non-exceptional situations, congestion in (C) is a result of inefficiencies in terminal operations (D) since these two traffic zones are connected and truck appointment solutions only address the symptoms, not the cause. This study demonstrates a novel approach to addressing traffic congestion in (C) through dynamically optimising operations in (D) using heuristic algorithms.

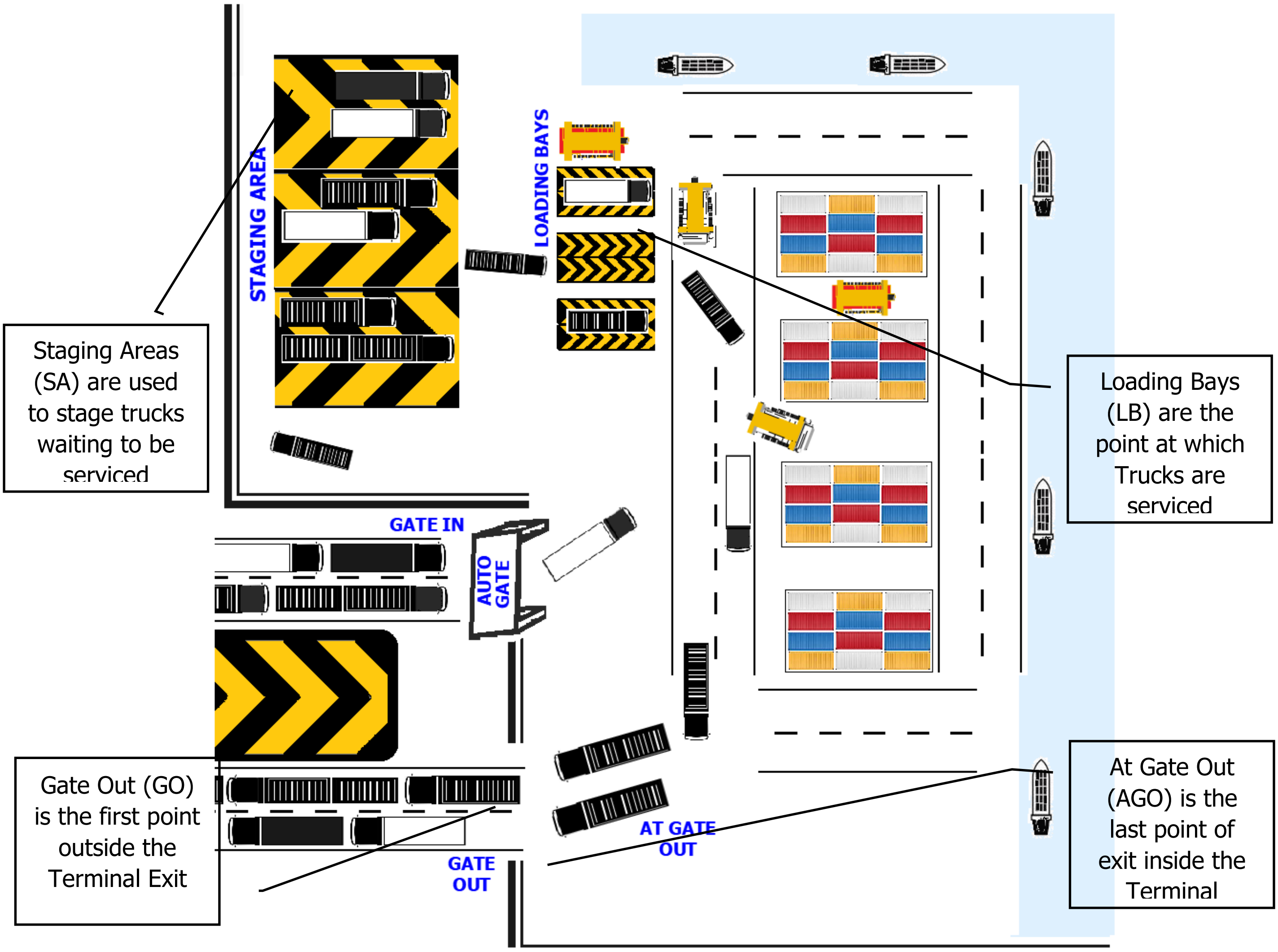

Figure 3.4: Graphical representation of the key areas in the port precinct (author's original compilation)

Focusing our attention on the port precinct, Figure 3.4 depicts key server areas that creates a dependency between the port precinct (C) and terminal operations (D). The service areas at AG (Auto-Gate) and LB (Loading Bays) are efficiency-dependant points, while potential bottleneck areas are at GI (Gate In), SA (Staging Area), AGO (At Gate

Out) and GO (Gate Out). The scenario depicted in Figure 3.4 is representative of Kendall's multi-server queue (Figure 2.2). The Staging Area is considered the queue with multiple servers at the Loading Bays.

Since the Auto-Gate is system driven and those efficiencies depend on the system server speeds, network latency, processor type and memory capacity, these would typically fall into the Technology domain of the ADM (Figure 3.1) and can be addressed in the related SBB of future works. The focus of this studies pertains to the optimisation within the Application Architecture, more specifically the Predictive Traffic Management SBB (*PTM-SBB*).

The solution architecture gives context to the remainder of this dissertation showing key focus areas for optimisation and can be summarised as GI, SA, LB, AGO and GO. While the algorithms related to the preventive objective functions stem from Little's deductions of arrival rates (QTF 1), algorithms of the predictive objective functions employed in monitoring exceptional situations are heuristic. These heuristics are later validated in the simulation use cases.

3.2. Algorithm

In order to address the issue of congestion through optimization, the multi-objective functions make use of heuristic algorithms to achieve this. The preventive objective uses queue limits in conjunction with operational performance limits to avert congestion while the reactive objective uses operational performance limits to address the fluctuation of the supply and demand. The predictive objective employ exceptions algorithm to determine underlying anomalies that may result in congestion.

3.2.1. Queue Limits

Components of the PTM-SBB involves ensuring congestion is avoided in the best case (preventive objective) and managed in the worst (reactive objective) through the use of other SBBs. The preventive objective function of Caudus is employed to avert congestion. This is achieved by setting queue capacity limits and queue threshold limits. In order to avert congestion, monitoring on the truck queue is required such that it does not get to the point of overflow thus creating a traffic jam or congestion in adjoining urban areas.

Figure 3.5 gives a basic representation of a single-server truck queue and based on Kendall [38], deductions using this queue model can also extend to more complex queues.

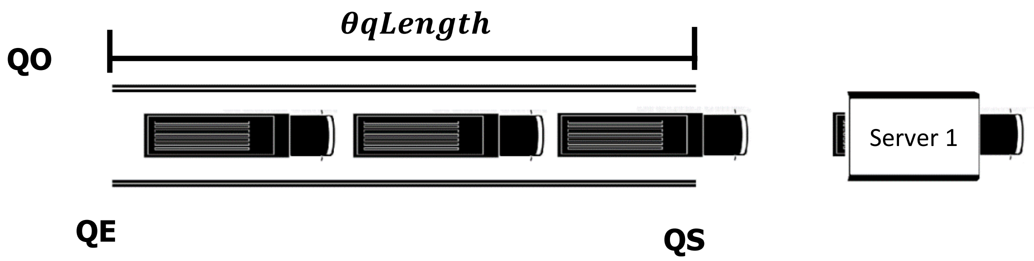

Figure 3.5: Single-Server Truck Queue - θqueue

3.2.1.1. Queue Capacity Limit

Figure 3.5 denotes the start of the queue (QS), end of the queue (QE) and queue road length ($\theta qLength$), which is given by the distance between QS and QE. Therefore, any traffic beyond $\theta qLength$ can be considered as the queue overflow, which is indicative of a congested queue. The queue capacity ($\theta qCap$) of the truck queue ($\theta queue$) is the number of trucks that can fit into $\theta queue$ before it overflows [72]. Using basic arithmetic, $\theta qCap$ is then given by the quotient of the $\theta qLength$ and the average length of the trucks i.e.

$$\theta qCap = \frac{\theta qLength}{Average\ Truck\ Length} \tag{3.1}$$

$\theta qCap$ is better known by Kendall's Notation K as the capacity of the queue system [10] i.e. being the number of trucks that can be accommodated in $\theta queue$. Also, Figure 3.5 depicts the point of overflow (QO). Given the queue capacity is $\theta qCap$, then the queue can be represented in the derived expression:

$$\theta queue \leq \theta qCap \tag{3.2}$$

3.2.1.2. Queue Congestion Limit

Also, since $\theta qCap$ is the queue capacity, then once the queue capacity is reached, any additional entry into the queue i.e. $\theta qCap$ +1, results in congestion ($\theta qCong$) suggesting the following expression:

$$\theta qCong = \theta qCap + 1 \tag{3.3}$$

Using (3.2) and (3.3), the queue can be expressed as:

$$\theta queue \leq \theta qCap$$

$$\Rightarrow \theta queue < \theta qCong$$

The queue $\theta queue$ has a limited amount of truck space that can be accommodated based on the length of the road that leads into the terminals.
When it overflows into junction points and other intersecting areas beyond the queue, traffic congestion occurs. Therefore, the primary objective is to keep $\theta queue$ within $\theta qCap$ (3.2).

3.2.1.3. Queue Threshold Limit

Also, due to the dynamic nature of queues i.e. continuously expanding and shrinking [25], waiting until $\theta queue = QqCap$ maybe too late to implement any preventative measures as this will result in congestion experienced while trying to resolve the problem. To circumvent this risk, the *Truck Queue Threshold limit* (θqtr) is used as a benchmark to pre-empt the potential build-up of a congested situation. θqtr can be any arbitrary value having the property that if the threshold is breached, then there is sufficient time available, based on the limitations of business process capabilities, to employ counter measures before the queue overflows e.g. having the required number of available equipment to increase performance in order to reduce the current queue length and prevent congestion.

θqtr must be set at an amount such that when the number of trucks in the queue is equivalent to θqtr and counter-congestion measures are activated, then there is ample time for the counter-measures to reduce the queue rate. With the truck queue capacity given by $QqCap$, θqtr can then be defined as percentage ρ such that:

$$\theta qtr = \theta qCap \times \rho \tag{3.4}$$

Although there is no exact number for the queue threshold θqtr, an indicative limit may be linked to the amount of time required for additional mitigating actions to be initiated in the event that system counter measures cannot reduce the ensuing congestion. These may be in instances of accidents to contact emergency services, mass-actions or even lack of equipment availability that may require contacting the truck service providers to reduce truck arrivals to the terminals.

To determine a good measure of the θqtr, the time taken from the point the threshold is breached to the point the queue capacity is reached must be calculated. Note, queue congestion and overflow results when the trucks enter the queue at a faster rate than which the trucks leave the queue. Also, since the truck will only leave the queue when there is a spot available at the server [23], leaving the queue becomes dependent on how fast the truck is serviced at the server. Using Little's theorem [14], the truck arrival rate θRq is the rate at which the trucks enter the queue over a period of time, and so heuristically, the service rate θRs at the server is given by the rate at which the truck is serviced over a period of time i.e.

$$\theta Rq = \frac{No\ of\ Trucks\ Entering\ Queue}{time} \tag{3.5}$$

and θRs is the number of trucks serviced i.e. loaded/ offloaded in a specific period of time i.e.

$$\theta Rs = \frac{No\ of\ Trucks\ Serviced}{time} \tag{3.6}$$

Using (3.5) and (3.6), the threshold percentage ρ can be validated for adequacy against the following derived expression:

$$\frac{\theta qCap \times (1-\rho)}{(\theta Rq - \theta Rs)} \geq \tau act \tag{3.7}$$

where τact is the time needed for some action to address the problem. Given the current queue capacity $\theta qCap$, average queue arrival rate θRq and truck service rate θRs, then the threshold percentage ρ must be set such that (3.7) is satisfied. This expression loosely translates to the threshold being set so that the time taken until congestion is reached is longer than the time taken for the required mitigation action to be performed.

3.2.1.4. Queue Safe Limit

One final limit to mention is the Queue Safe Limit. This limit is an indicator that a previously congested queue has subsequently subsided and all counter-measures to alleviate the congestion can be reset. Although there is no ideal value for the queue safe limit, the value should allow a fair amount of time before the threshold is breached again. Therefore, a conservative recommendation for the queue safe limit may be derived as a percentage $\rho 2$ of the threshold amount i.e.

$$\theta qsafe = \theta qtr \times \rho 2 \tag{3.8}$$

3.2.2. Operational Performance Limits

Queue congestion and overflow results when the trucks enter the queue at a faster rate than which the trucks leave the queue. Also, leaving the queue becomes dependent on how fast the truck is serviced at the server. Therefore, by deduction, the rate at which the trucks leave the queue is the same as the rate at which the trucks are serviced at the servers, θRs. Based on this logic, it can be further deduced that congestion results when:

$$\theta Rq > \theta Rs \tag{3.9}$$

and inversely,

$$\theta Rq \leq \theta Rs \tag{3.10}$$

provides the ideal queue conditions. The objective is to keep the operational performance levels within the (3.10) limits.

Similarly, this definition can be generalized to include *n* activity points of the problem area. Suppose there is another service point subsequent to θRs that has operational dependencies, then (3.10) can be used to derive the following relation:

$$\theta Rq \leq \theta Rs \leq \theta Rs{+}1 \qquad (3.11)$$

This definition demonstrates the dependency of one service point to its subsequent service point. Therefore, θRs can be seen as the new queue and its dependency on the following activity can be regarded as the new service point. Hence, where there are inter-dependencies across *n* service activity points, (3.10) can be expressed as:

$$\theta Rqi \leq \theta Rqi{+}1 \qquad \ni i \leq n$$

where *n* represents the number of truck queues.

Trucks are serviced by the allocated equipment. A truck is serviced when the vehicle reaches the Loading Bay (LB) and a container (or any cargo) is offloaded from or loaded onto (or both) the truck. θRs can then be given as the number of trucks either loaded or offloaded (or both) over a period of time. Since one truck can only be serviced by one equipment at a time, *TOn* is the same as the number of times each equipment is performing a service for a truck. Therefore, (3.5) and (3.6) can be re-written using:

$\theta Rs = TOn/\tau$ ∋ TOn - No. Of Trucks Turned Out,

τ - time period (3.12)

$\theta Rq = TQIn/\tau$ ∋ $TQIn$ - No. Of Trucks Queuing In

τ - time period (3.13)

The truck's service start time begins when it enters the terminal gate at GI and the service end time is when it leaves the terminal gate at GO. This is regarded as the Truck Turnaround Time (TTT) per truck [57] and can be simplified as θRs. Given this perspective, θRs is the summation of all service points (inclusive of travel time) within the terminal. With the average travel time being consistent, the focal point for optimisation is in the service times and be expressed in the following derivation:

$$\begin{aligned} \theta Rs &= GI\tau + \lambda m\tau + \lambda s\tau + GO\tau \\ &= [(GIn/Gn\tau) + \lambda m\tau + GO\tau] + \lambda s\tau \\ &= \textstyle\sum_{i=1}^{n} V\tau i + \sum_{j=1}^{k} \lambda s\tau j \end{aligned} \qquad (3.14)$$

where:
$V\tau i$ is the travel time taken for the trucks to travel between activity points such as travel time from the gates ($GI\tau$) to the Staging Areas or to the Loading Bays ($\lambda m\tau$) and back out the gates ($GO\tau$), etc.
$\lambda s\tau j$ is the equipment's service activity time taken to service the trucks at the Loading Bays (LB), j is the number of activities performed by each equipment. Intuitively, with the average travel time ($V\tau i$) across the various activity points being consistent, this study focuses on $\lambda s\tau j$, the varying equipment service time, as the single most impactful area of improvement in addressing θRs. Therefore, (3.14) can be expressed as:

$$\theta Rs = \sum_{j=1}^{k} LBs\tau j + C \tag{3.15}$$

The various service activities performed by the equipment on the trucks at the Loading Bay (LB) includes Loading (LD), Offloading (OFLD), Fetching (*Fch*) and Stacking (*ST*) and can be represented as:

$$\lambda s\tau = OFLD\tau + ST\tau + Fch\tau + LD\tau$$
$$\therefore \theta Rs = \sum_{j=1}^{k} (\lambda s\tau j) + C$$
$$= \Lambda\tau k + C$$

Where:

τ is the time for each activity,
k is the fixed number of activities linked to equipment performance
C is constant

In order to improve the queue service rate θRs, more equipment is required in the service schedule to service the trucks. This in turn increases LB and accommodates additional trucks, thereby reducing the trucks in the queue. Given this change, the algorithm takes the form:

$$\theta Rs = \Lambda\tau k + C$$
$$\therefore \theta Rs + \lambda plus = \Lambda tk + \lambda plus + C$$
$$= \theta Rsnew \tag{3.16}$$

For purposes of demonstrating the impact of equipment performance against θRs, assuming for purposes of simplicity that *C=0*, then in order to prevent congestion:

$$\theta Rq < \theta Rs \leq \theta Rsnew$$
$$\theta Rq < \theta Rsnew$$
$$\theta Rq < \theta Rs + \lambda plus$$
$$\theta Rq - \lambda plus < \theta Rs \tag{3.17}$$

where $\lambda plus$ is the number of loading bays with equipment added to the service schedule. From (3.17), this would suggest that an increase in equipment improves the queue service rate thus preventing congestion. To demonstrate this, a random sample for θRq and θRs was taken to test the effects of adding more equipment to service the trucks. Table 3.1 and Figure 3.6 demonstrate the impact of increasing equipment on the service level performance.

Table 3.1: Truck Queue Rate vs Truck Service Rate vs Truck Service Rate (new)

	Shift	**Max Truck/30min**			
	6am-6pm	20			
Time	**TQIn**	**Time (Minutes)**	θRq **(Trucks/ minute)**	$\theta Rs\ \times$ **3Straddles (Trucks/min)**	$\theta Rsnew \times$ **(3+3) Straddles (Trucks/min)**
6:00	0	30	0.00	0.25	0.41
6:30	6	60	0.10	0.17	0.27
7:00	15	90	0.17	0.19	0.30
7:30	28	120	0.23	0.20	0.32
8:00	35	150	0.23	0.20	0.32
8:30	54	180	0.30	0.18	0.30
9:00	71	210	0.34	0.19	0.31
9:30	72	240	0.30	0.22	0.36
10:00	72	270	0.27	0.17	0.27
10:30	72	300	0.24	0.19	0.30
11:00	80	330	0.24	0.25	0.40
11:30	84	360	0.23	0.20	0.33
12:00	89	390	0.23	0.26	0.42
12:30	94	420	0.22	0.19	0.31
13:00	111	450	0.25	0.20	0.33
13:30	112	480	0.23	0.23	0.38
14:00	119	510	0.23	0.23	0.37
14:30	139	540	0.26	0.18	0.30
15:00	155	570	0.27	0.22	0.36
15:30	175	600	0.29	0.23	0.37
16:00	190	630	0.30	0.22	0.35
16:30	193	660	0.29	0.19	0.31
17:00	199	690	0.29	0.24	0.38
17:30	214	720	0.30	0.20	0.32
18:00	229	750	0.31	0.26	0.42

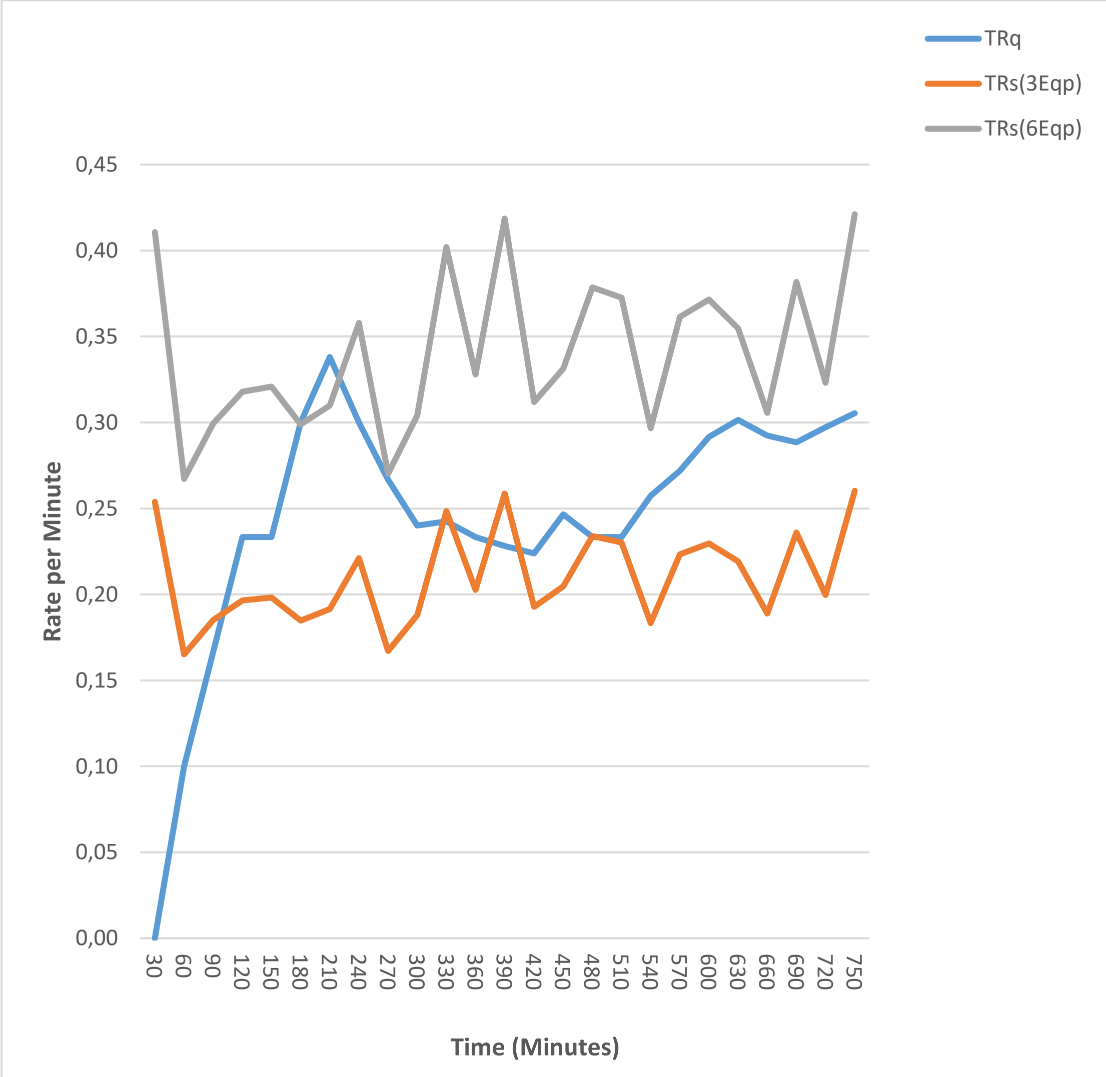

Figure 3.6: Truck Queue Rate (θRq) vs Truck Service Rate(θRs) vs New Truck Service Rate (θRsnew)

Figure 3.6 provides a visual comparison of the performance for the varying combination of equipment servicing the trucks. The graph plots the rate of trucks being serviced over the period of time taken to complete all trucks entering the queue. With the truck rate of entry into the queue (TRq-blue line) on average being higher than the truck service rate using 3 equipment (TRs 3Eqp - orange line), the graph clearly demonstrates that with the use of 6 equipment (TRs 6Eqp - grey line), the number of trucks serviced out-performed the 3 equipment combination thus supporting (3.17) and suggest that adding additional equipment improves the service performance.

Table 3.2: TQIn vs TOn vs TOnew

Time	TQIn	Time (Minutes)	Trucks worked (3Straddles)	Trucks worked (6Straddles)
6:00	0	30	7.62	12.32
6:30	6	60	9.91	16.03
7:00	15	90	16.66	26.96
7:30	28	120	23.57	38.14
8:00	35	150	29.74	48.12
8:30	54	180	33.25	53.80
9:00	71	210	40.22	65.08
9:30	72	240	53.08	85.88
10:00	72	270	45.09	72.96
10:30	72	300	56.40	91.25
11:00	80	330	82.00	132.68
11:30	84	360	72.95	118.03
12:00	89	390	100.91	163.27
12:30	94	420	80.96	130.99
13:00	111	450	92.14	149.09
13:30	112	480	112.29	181.68
14:00	119	510	117.43	190.00
14:30	139	540	99.00	160.19
15:00	155	570	127.33	206.03
15:30	175	600	137.73	222.86
16:00	190	630	138.16	223.54
16:30	193	660	124.67	201.71
17:00	199	690	162.82	263.44
17:30	214	720	143.81	232.69
18:00	229	750	195.19	315.83

The specifications and parameters of the Table 3.2 are as follows:

- Shift Times: 6am-6pm i.e. a 12-hour shift
- Max Trucks/ 30minutes - The maximum number of trucks that calls to the queue in a 30minute period
- TQIn - The random selection of the number of trucks entering the queue in the specified time period
- Time (Minutes) - The accumulative minutes from the start of the sample shift
- θRq - The rate of Trucks entering the queue, given by TQIn/ Time. The resulting UoM is Trucks/Minute

- θRs - The rate of Trucks serviced by three equipment given by a random selection of the equipment service time ranging being between 10-20min per equipment to service one truck. The inverse of this rate is the Trucks Serviced per minute
- $\theta Rsnew$ - The rate of service given by θRs with an additional three equipment
- TrucksWorked (3 Worked) - the total number of trucks worked by the three equipment over the specified period
- TrucksWorked (6 Worked) - the total number of trucks worked by the three initial equipment and an additional three equipment over the specified period

Figure 3.6 and 3.7 demonstrate the impact that the increase in service rate has on the truck queue rate. The data for the graphs is documented in Table 3.1 and Table 3.2 with the values derived as follows:

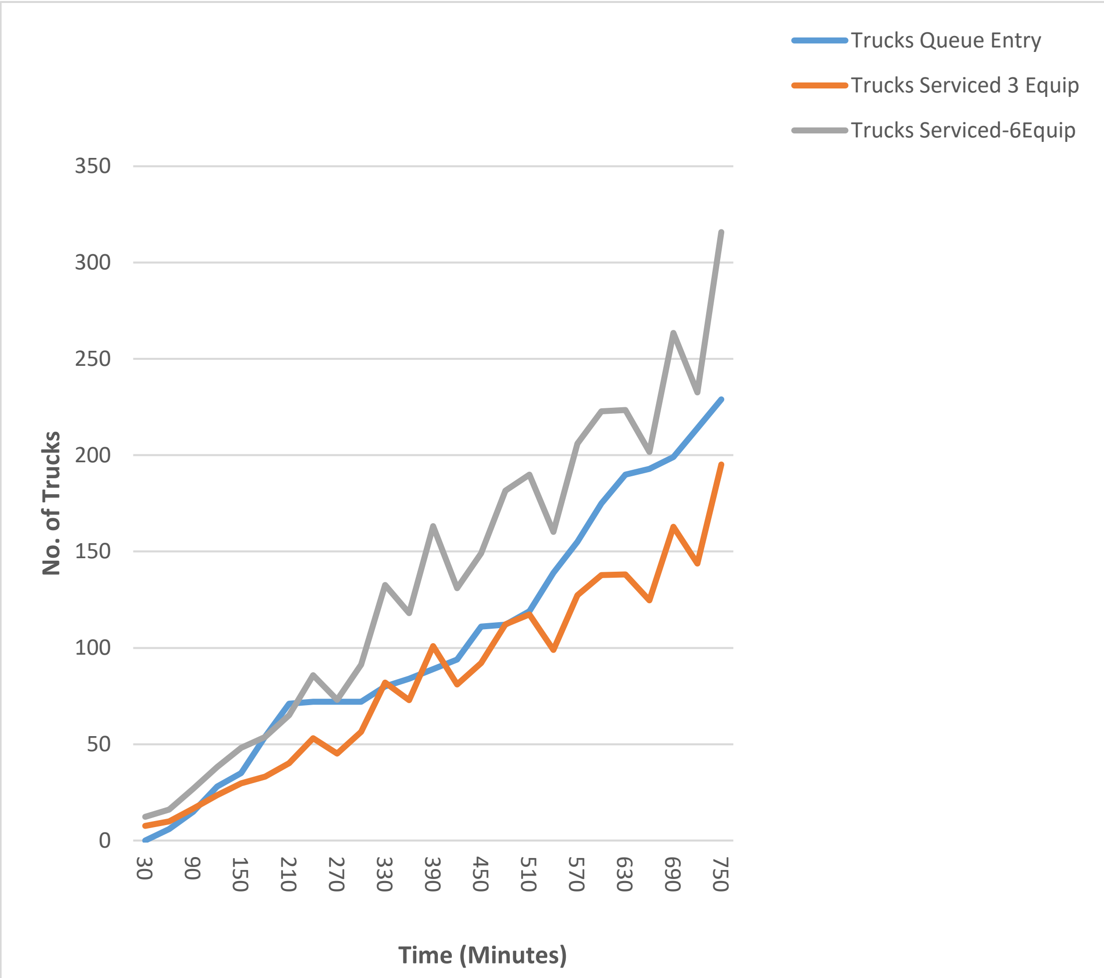

Figure 3.7: No. of Trucks in Queue (TQin) Vs No. of Trucks Worked with 3 Equipment (TOn) Vs No. of Trucks Worked with 6 Equipment (TOn-new)

In the sample above, it is evident that the throughput time of the queue improves when there is an increase in service rate. Although this result is dependent on the random selection of truck queue times and equipment processing times, the assurance that this method will work is that the current processing rate is always lower than the new processing rate. Based on Figure 3.7, this is also given by the following equation [73]:

$$y = \int_0^x \big(g(x) - f(x)\big)dx > 0 \qquad \ni \quad 0 \leq x \leq maxShiftTime$$

where: $f(x) = eqp \times \theta Rs \times x$,
$g(x) = (eqp \times \theta Rs \times x) + (eqpnew \times \theta Rsnew \times x)$

and

eqp is the original number of equipment used,
$eqpnew$ is the additional equipment,
θRs is the rate of service for the original equipment,
$\theta Rsnew$ is the rate of the additional equipment

Function $f(x)$ is the number of trucks serviced using equipment eqp performing at a service rate θRs over the shift period x. Function $g(x)$ is the number of trucks serviced using additional equipment $eqpnew$, performing at a service rate $\theta Rsnew$ over the same shift period x. Based on [73], y gives the difference in the area between the two functions' graph. The positive difference suggests that $g(x)$ using additional equipment outperforms $f(x)$ with lesser equipment. This is also evident in Figure 3.7.

3.3. Exceptions Algorithm

Traffic congestion occurs in normal as well as exceptional situations. In normal situations where congestion is related to performance, predictive monitoring works extremely well. However, there are instances when root causes for congestion cannot be managed by merely ensuring a performance improvement but instead requires exceptional intervention. Some of these root causes may include accidents, breakdowns and, in industrial environments, mass action protests. These root causes cannot always be detected or prevented but there are underlying symptoms that can be used to predict anomalies and mitigated through the use of the Incident Management building block.

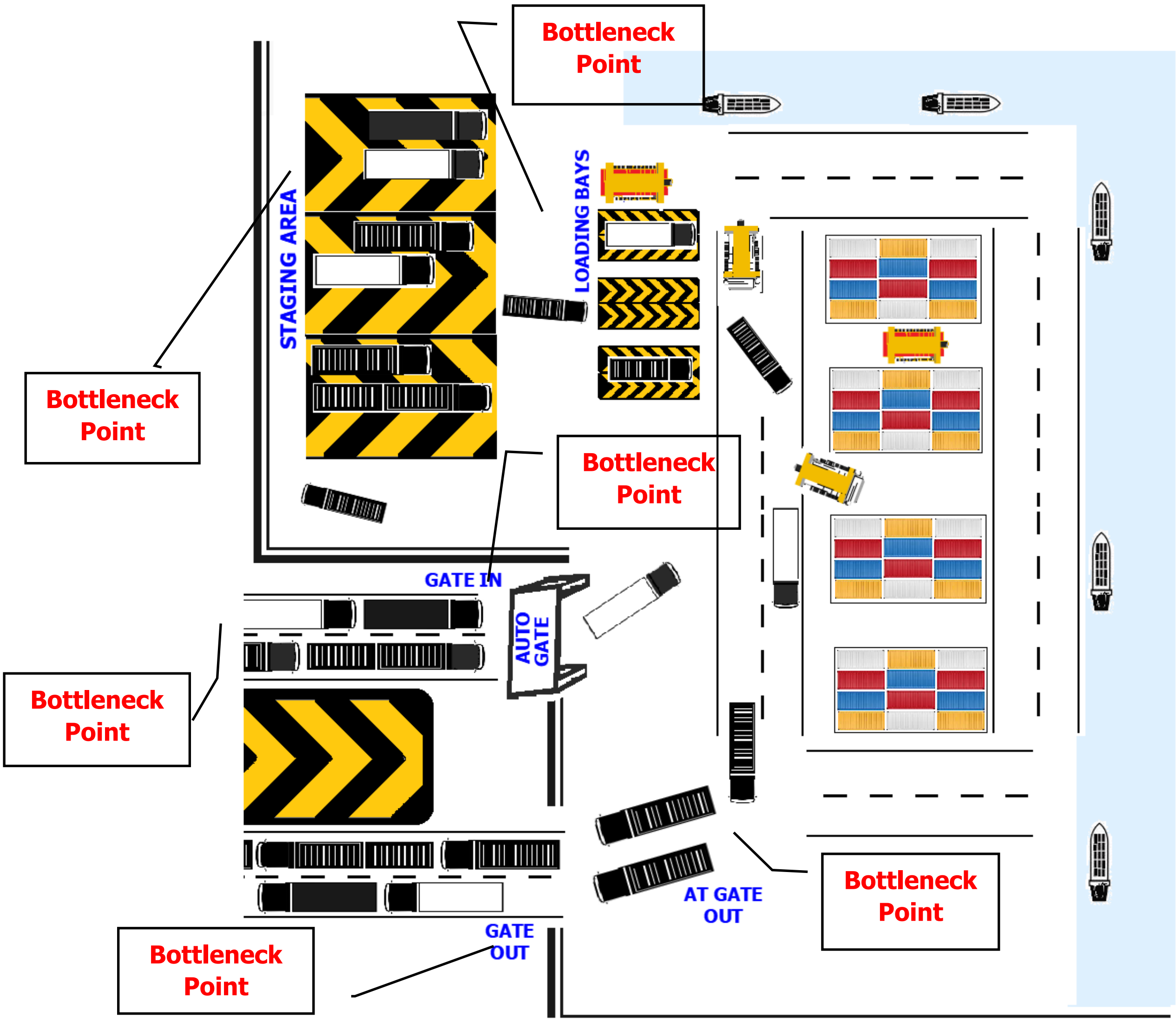

Figure 3.8: Port precinct

In most cases, root causes may vary and are not easily identifiable. However, the outcome is the same and this can be identified. Figure 3.8 shows the different bottleneck points *βpt* in the port precinct. Incidents can occur at the start, between bottleneck points or at the end of the route. In all situations, the outcome is congestion in the area preceding the incident. This is due to the reduced discharge rate of the queue before the bottleneck [74]. Monitoring the extremities of each bottleneck point in order to identify an incident can minimise the impact to subsequent areas. This is achieved by setting a limit at each *βpt* such that:

$$\beta pt_n \leq T_{\beta ptn\_max}$$

where βpt_n is the Bottleneck point *n* with $T_{\beta ptn\_max}$ being the maximum truck capacity set at βpt_n. The βpt_n is necessary to define as it is the varying traffic condition at the specified bottleneck point constrained by the overflow limit $T_{\beta ptn\_max}$.

A breach in the maximum truck capacity at βpt suggests the occurrence of an incident. Assigning a limit to each βpt ensures every incident has the ability to be identified. However, this method provides for a delayed response as the maximum capacity must be breached before it is identified. The more efficient method is to monitor movement across bottleneck points over a period of time using the derived expression:

$$\Delta\tau\left(\beta pt_n - T_{\beta ptn\_max}\right) \rightarrow 0 \;\; as \;\; \Delta\tau(\beta pt_{n+1}) \rightarrow 0 \tag{3.18}$$

i.e. as the capacity at bottleneck point βpt_{n+1} approaches 0, the preceding bottleneck point βpt_n approaches its maximum capacity. This effect demonstrates the impact of an incident on connected areas in the TRC.

Although (3.18) is more efficient in monitoring for congestion than one that is based purely on capacity constraints, there is still a delay involved in identifying incidents across bottlenecks. An alternative may then be to monitor vehicle movement within the same bottleneck points over a period of time using the derived equation:

$$LastMove_{\,\tau} - LastMove_{\,\tau+1} = 0 \quad \forall\, \Delta\tau \geq 0 \tag{3.19}$$

where $LastMove$ is the last movement of trucks between time τ and $\tau + 1$. If there has not been any movement in a specific area for a prolonged period, then this would suggest that an incident has occurred in the monitored area and the Incident Management SBB is employed to resolve the situation before it escalates. Incident Management is a concept that is also used in ITS [65].

3.4. Summary

Although there are several optimisation techniques such as GA, ACO and PSO, Queuing Theory can be considered as the most appropriate for addressing traffic congestion as it has all the attributes of a queue such as the start and end of the queue, queue length and a server for the queue.

The approach taken to address traffic congestion and throughput through optimisation uses tools from the TOGAF [71] framework to identify the various root causes and define solution building blocks (SBB) that will be developed part of this dissertation as well as those that can be developed in future works. The PTM-SBB is the primary building block of this study. Other SBB that Caudus leverages off include the CC-BPN SBB for Incident Management activities in instances where the congestion cannot be managed purely by operational efficiency. ITS and DITS resides in the CC-BPN SBB and is key in providing a macro-solution across the TRC.

The derived algorithms have been included in this section as it is directly related to the PTM-SBB, which aims to resolve traffic congestion caused through operational inefficiencies as well as breakdowns and accidents. This is achieved by defining various queue limits, which are used to address Caudus' three main objective functions viz. Preventive, Reactive and Predictive. The defined queue limits are Queue Capacity ($\theta qCap$), Queue Congestion ($\theta qCap\ +1$), Queue Threshold ((θqtr)), Queue Safe Limit ($\theta qsafe$), and the derived Operational Performance Limits.

The Preventive objective function of Caudus aims to avert congestion altogether. This function uses the queue limits to derive the necessary algorithms to prevent congestion primarily through the use of operational performance. However, there are situations when prevention is not sustainable, and the traffic queue does overflow. This prompts the Reactive objective function to invoke the assistance of the CC-BPN SBB by requesting a delay in forwarding vehicles to the port or engaging emergency and recovery services if an accident or breakdown is identified. The Predictive objective function aims to identify exceptions or anomalies in the port precinct. Exceptions are considered as a situation that is causing congestion that operational performance cannot address. The objective uses the exception monitoring algorithm to identify symptoms of a congestion before the queue overflows. This solution also leverages CC-BPN with integration into port control to confirm the exceptions as soon as it is identified.

Chapter 4: Design and Implementation

This chapter discusses the components of the simulation that demonstrates the effectiveness of the derived algorithms used in resolving traffic congestion through optimization. Section 4.1 Caudus gives an introduction to the new Caudus application, an original design and development for this dissertation using the algorithm derived in this study. Section 4.2 Simulation touches on the components that make up the simulation as well as the underlying tools and applications used to develop and demonstrate the POC. Section 4.3. Caudus Simulation Graphical User Interface, Section 4.4. Caudus GUI Background Processes and Section 4.5. Caudus Back-end Processes respectively details the Caudus Simulation GUI, the Caudus background processes that support the GUI and the Caudus back-end objects and processing logic that forms the Caudus execution engine. Section 4.6. The Caudus Algorithm and The Optimisation Module delves deeper into the Caudus functionality, highlighting the derived algorithm usage and individual components of the optimization module.

4.1. Caudus

In principle, the route travelled by all cargo haulers across logistics is similar with the loading and offloading at warehouse districts, followed by the travel route along urban and national roads, before finally reaching the destination. At various points along this route, these transporters experience and contribute to traffic congestion. Caudus is a novel solution, designed and developed in this study to test and validate the derived algorithms for effectiveness in addressing traffic congestion and throughput through optimisation. The Caudus application is modelled on an operational layout having gate entry (GI) and exit points (AGO, GO), staging areas (SA) and service points (LB). Figure 3.4 provides an illustration the operational layout that the system is based on.

The GI point is the location at which all vehicles intending to enter the port will have to go through. Specific to cargo haulers, these vehicles will normally go through a checkpoint to announce their arrivals. The checkpoint maybe a manual one or automated with the slowest time being dependant on human intervention and standard operating procedures while the automated processes provide for a faster, seamless throughput time. The basis of this study uses the Auto Gate automated system, that serves as a building block in addressing the potential bottleneck at the GI point. The Auto Gate system is already used in several ports to improve the operational efficiency at the entry point e.g. the Durban Container Terminal [75] and the Port of Liverpool [76].

Even though the GI point may be automated and not considered a bottleneck point, there are other contributing factors to the root cause of congestion in this area such as accidents and breakdowns at that point or further down the operational process that can impact the GI point. These are considered exceptions and are catered for by monitoring the throughput at GI over a period of time in relation to subsequent bottleneck locations. This is given by (3.18).

The SA point is used to stage trucks when they arrive at the terminals, but the operational equipment is not in a ready state to service them. The waiting period may range from the time of entry into the staging area until the time an equipment and Loading Bay is available to service the truck. Throughput of this area is directly dependent on the operational performance at the LB servicing point.

Once the trucks are at the SA point, there are no other activities except for waiting to be called to be serviced. This area also works on a First In, First Out (FIFO) queuing principle. Here too, except for accidents and breakdowns, the potential for performance improvements through optimization is minimal at the SA point. Exception monitoring addresses potential congestion in these causes.

The LB point is the single point of interest that will benefit directly from optimization to improve throughput and alleviate potential congestion. The LB point denotes the service area where trucks are loaded, offloaded (or both) by specialized equipment. The service performance of this area directly impacts the amount of waiting time trucks will experience at the staging areas. This has a knock-on effect of vehicles entering the terminals and extends to vehicles congesting the port precinct.

There is different equipment that service the trucks at loading bays. Depending on the operational model of the business, some equipment may be Straddle Carriers, Reach Stackers, or Haulers and Forklifts. Since the equipment type varies across industries and does have relevance to the optimization process in this scope, the Straddle Carrier (ST) is used as reference to the equipment in the simulation.

Once a Straddle Carrier and Loading Bay is available to service a truck, the vehicle is called to the LB point. If the truck has cargo to be delivered, then it will be met with Straddle Carrier to offload the cargo and move it to the stacking area. Once the truck is offloaded, it is ready to leave the terminal through the terminal's exit points. Intuitively, the equipment operation time is a summary of the time taken to offload and time to stack the cargo. The timing for this operation can be regarded as $1 \times EqTime$ such that:

$$EqTime = STLoad\_OffLoadTime + STFetch\_StackTime \tag{4.1}$$

Similarly, if a truck is calling to pick up cargo from the terminal, the equipment will fetch the relevant cargo from the stacking area and load the truck, before the truck exits the terminal. The timing for this operation is also $1 \times EqTime$. In more efficient operations, trucks call at the terminals to drop off one set of cargo and fetch another set to optimize on the round trip of the journey. In this process the timing for this operation is $2 \times EqTime$.

The operational process is normally allocated a default number of equipment and loading bays to service the trucks calling at the terminal. This is also dependent on the number of equipment and drivers that are available at the start of a particular shift. Lack of equipment availability may be due to breakdown, maintenance schedules or even human resource capacity, all of which that can be addressed in the Maintenance Management SBB. The default number of equipment allocated can be adjusted based on demand. It is not necessary to throw the full fleet of equipment at servicing the trucks if there is no direct benefit to the business operations. Over-capacity incurs unwarranted additional costs and should be avoided. Based on the objective, in this case preventing congestion, Caudus adjusts the equipment allocation accordingly. This approach prevents unnecessary wear and tear on the equipment, in addition to cost-savings on fuel, labour and other operational costs.

In addition to the service performance levels, breakdowns and accidents are also contributing factors to the congestion at LB point. Caudus addresses this through exception monitoring.

The AGO and GO are exit points from the terminal. These points indirectly impact congestion within the terminal operations, thereby extending to reasons for congestion in the port precinct. Although there are no direct operational processes that impact delays in throughput at these points, the indirect impact would be due to breakdowns and accidents that may cause congestion at exit gates and subsequent points within the terminal and terminal entry points. The simulation uses exception monitoring to identify these instances.

Splitting the exit points into AGO and GO allows for greater flexibility and fault diagnosis of areas of control within the terminal authority and the municipality jurisdiction. The scope of this simulation includes the AGO point since the GO activities fall within the port regulators and municipality's jurisdiction.

4.2. The Simulation

The simulation is an original design and development for this study. It uses a combination of languages to achieve its objective of demonstrating the effectiveness of Caudus. Programming languages that were used to develop the Caudus simulation include HTML5, SQL scripts, JavaScript and a host of batch programs to kick off the multi-thread processes. Multi-thread processing was used to ensure processor independence in the execution of independent activities in order to mimic the real-world operational processes. Figure 4.1 provides a basic Level 0 graphical view of the simulation, which comprises the following components:

- Graphical User Interface (GUI)
- GUI Background Processes
- Database Back-end Processes

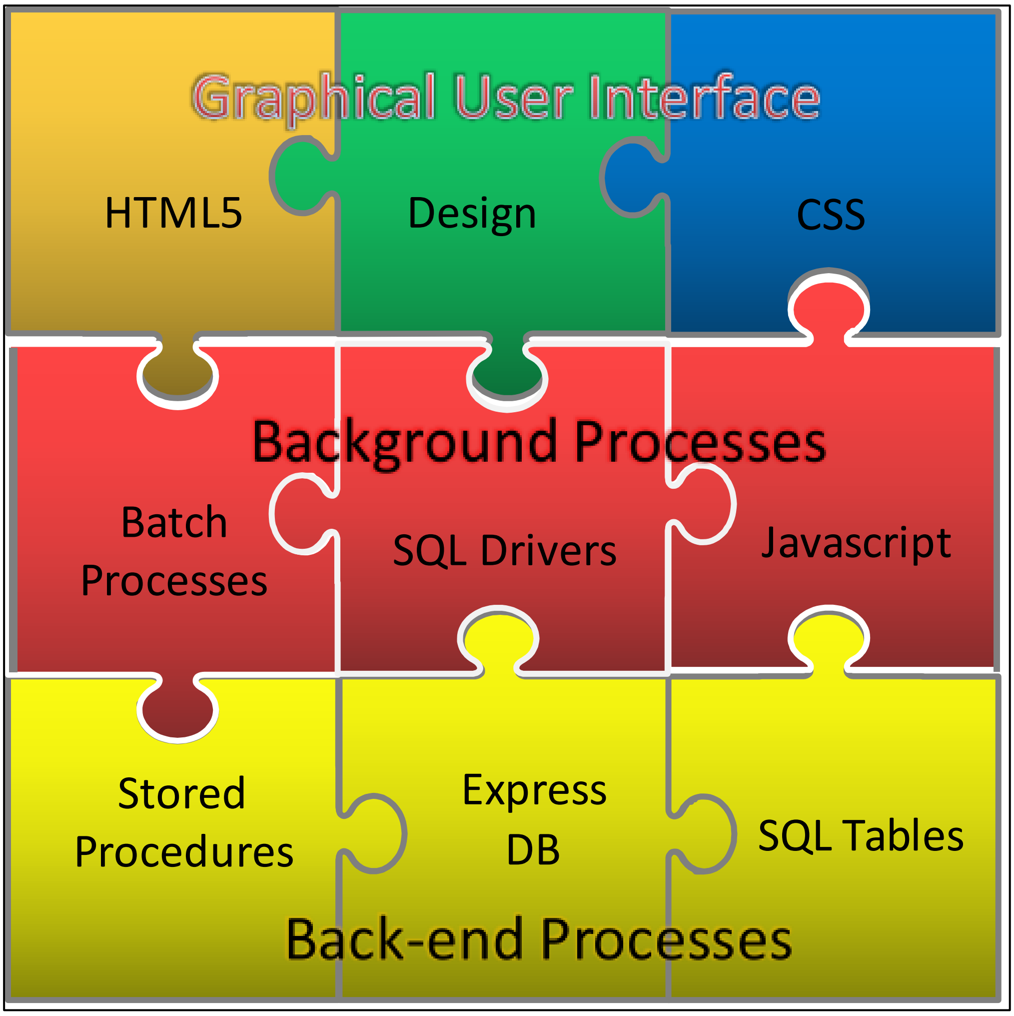

Figure 4.1: Caudus Simulation

The Caudus simulation is developed using a variety of freeware tools. The front-end GUI is developed using Bootstrap Studio, which is a freeware application tool set used for building and designing web applications. The front-end graphics is done using HTML5 and CSS with the programming logic coded using JavaScript.

The back-end is built on a SQL Express database with the data from the simulation stored on SQL database tables. The back-end logic has been developed and implemented using SQL Stored Procedures, which also resides within the SQL Express Database.

The simulation is executed through the use of batch programs to simulate a multi-threaded, parallel processing system. This is to mimic a real-world environment where different equipment and activities work independently of each other. Spawning multiple batch programs independently recreates this real-life simulation, which is represented using Figure 4.3.

In order to avoid the use of web services and APIs in the simulation, Internet Explorer is used to optimize on its native SQL Driver connectivity capability to connect the GUI front end with the back-end SQL database. Compatibility testing for the simulation has been done with Internet Explorer 11.

The Caudus GUI codebase and logic developed using Bootstrap Studio, the underlying back-end database tables, SQL procedures and logic, and the multithread batch programs are all original developments solely for the purpose of this dissertation. Figure A.1 provides a Level 2 architectural view of the Caudus solution.

4.3. Caudus Simulation Graphical User Interface

The Caudus Simulation GUI (Figure 4.2) is the graphical representation of the port precinct and terminal operations. The layout is made up of the Dashboard, Operations Area comprising the "At Port Gates - Before Entry (Gate In), At Staging Area, At Loading Bay, At Port Gates - Before Exit (At Gate Out), Outside Port Gates - After Exit (Gate Out)" sections and the Simulation Configurations. The Stacking Area represents the area where the cargo is stacked at the terminal. The Layout Markers indicate the different sections of the terminal layout and the Current Quantity Markers indicates the current truck quantities in the relevant layout sections.

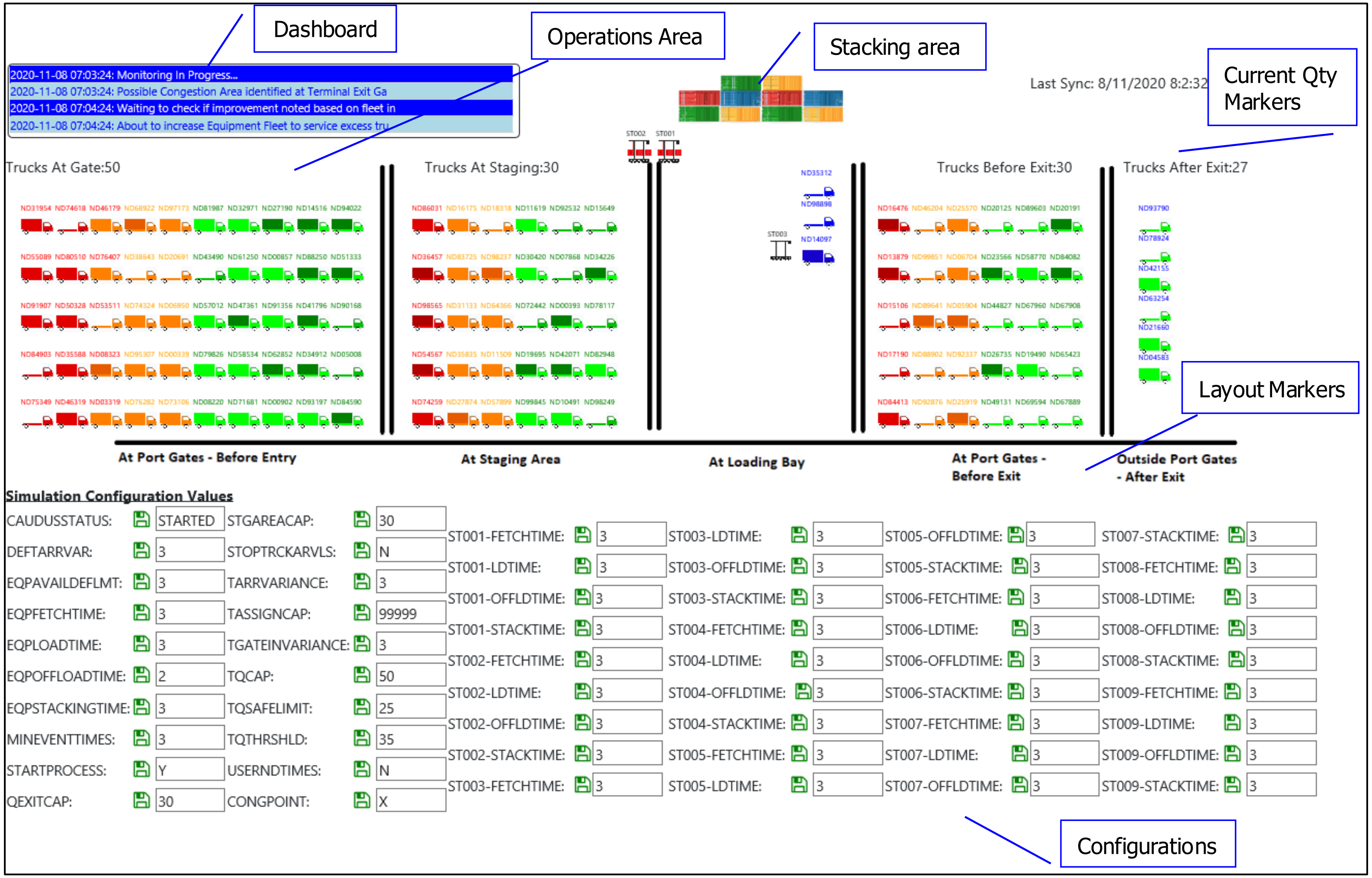

Figure 4.2: Caudus Simulation Graphical User Interface

The Operations Area of the Simulation GUI displays trucks in the relevant areas of the terminal. The "At Port Gates-Before Entry" entry is the GI Point. Trucks are represented in Green, Orange and Red. The Green trucks are representative of the vehicles within the queue Safe Limit, the Orange trucks are representative of vehicles that have exceeded the queue Safe Limit but still within the Queue Threshold Limit, and the Red trucks are representative of vehicles that have exceeded the Queue Threshold Limit. The Green, Orange and Red containers signify cargo on the relevant trucks either being dropped off or picked up from the terminals. A darker shade of the container signifies that the relevant truck is performing a dual activity i.e. dropping off one cargo and picking up another. Dual-moves have been included to simulate all move types of the terminal in order to mimic the near real-life scenarios as far as possible.

The Dashboard is used to display messages based on the back-end processes and activities taking place. The displayed information is composed of the process or activity display time as well as a brief message the process or activity being executed. In a complete, all-encompassing solution addressing all aspects in the TRC to alleviate congestion, the relevant activities reported would integrate into its respective Customer Collaboration and Business Partner Network (CC-BPN) SBBs (Figure 3.2). These activities should be considered as integration points to address the identified problem areas since they cannot be resolved directly through Caudus or other systems and will require business SBBs beyond the scope of this dissertation. The purpose of identifying them in the simulation is to highlight that Caudus has noted the activities part of exception monitoring and the system has the potential to expand the optimization scope by leveraging off ITS or other third-party solution integration. Table 4.1 provides the list of messages.

Table 4.1: Caudus Message Description

Dashboard Messages	Description
'Possible Congestion Area identified at Terminal Exit Gates or Outside Port precinct. Possible reasons include Truck Breakdown or Gate Equipment non-operational. Port Traffic Control and TNPA Notified' OR 'Possible Congestion Area identified At Exit Gate or Outside Gate. Possible reasons include Truck Breakdown'; OR	Warning message when traffic is building up at the specified locations. The CC-BPN SBBs may be used to address this situation when third party notifications are sent. This situation is identified using (3.18)

'Possible Congestion Area identified at Loading Bay area. Possible reasons include Truck Breakdown or Poor Equipment Performance. Traffic Control Notified' OR 'Possible Congestion Area identified at Loading Bay or Before Exit. Possible reasons include Truck Breakdown'; OR 'Possible Congestion Area identified at Staging Area. Possible reasons include Truck Breakdown' OR 'All Equipment standing idle although congestion noted at Gates. Hence, problem exist outside port precinct. Port Traffic Control to be Notified'	
'Monitoring in Progress...'	Informative message indicating Caudus is actively monitoring the process in the background. This also suggests that there are no anomalies in current activities
'Trucks At Gate Exceeds Queue Threshold, At Gate: @trucksAtGate, Queue Threshold: @TruckQueueThreshold'	Warning message indicating the number of trucks in the queue has exceeded the queue threshold limit. This message suggests counteractive measures need to be initiated before the queue capacity is exceeded. This is the queue overflow first warning level

	@trucksAtGate is the number if trucks in the Queue @TruckQueueThreshold is the Queue Threshold limit The threshold is derived from formula (3.4)
'Arrivals Need to be halted, Trucks At Gate Exceeds Queue Capacity, At Gate: @trucksAtGate, Queue Capacity: @TruckQueueCapacity’	Warning message indicating that the trucks in the queue has exceeded the truck queue capacity. This also suggests that increasing the equipment to improve service performance has not reduced the number of trucks entering the port precinct and it is time to involve the trucking companies to prevent the trucks from approaching the terminal. @trucksAtGate is the number if trucks in the Queue @TruckQueueCapacity is the Queue Threshold limit
'Sending notification to customer to halt Truck Arrivals, Trucks At Gate: @trucksAtGate, Queue Capacity: @TruckQueueCapacity’	Informative message indicating that a request is being sent to involve the customers and trucking companies. This action is invoked when the queue capacity has been breached. Notification simulation is demonstrated by inserting a message in the Notifications queue. The CC-BPN SBBs can be used to address this situation.

	@trucksAtGate is the number if trucks in the Queue @TruckQueueCapacity is the Queue Threshold limit
'Rate of Trucks arriving at Gate exceeds Equipment Service Rate, Trucks At Gate Rate (per minute): @TrucksPerMinute, Equipment Service Rate (per minute): @ServicePerMinute'	Informative message indicating the rate at which the trucks are entering queue exceeds the rate at which the equipment is servicing them. @TrucksPerMinute is the rate (per minute) at which trucks are entering the queue @ServicePerMinute is the rate (per minute) at which equipment are servicing the trucks This message is derived as a result of (3.12) and (3.13)
'About to increase Equipment Fleet to service excess trucks, if available'	Informative message indicating Caudus is increasing the equipment allocation for the service activities.
'Sending notification to Customers to delay trucks due to congestion'	Informative message indicating a request is sent to the customer to delay sending trucks to the terminals. This action is normally invoked when all available equipment is currently being used to reduce the truck queue rate, but the trucks continue to arrive. Notification simulation is demonstrated by inserting a

	message in the Notifications queue.
'Waiting to check if improvement noted based on fleet increase and delaying arrival...'	Informative message to indicate the service levels have increased and monitoring is in progress to see if the situation gets better. The traffic is not at congestion stage at this time. The waiting period may be a predefined period in order to see if the change in service rate has significantly reduced the additional truck arrival or low performance level.
'New Trucks At Gate Rate (per minute): @NewRateTrucksPerMinute, Initial Trucks At Gate Rate (per minute): @TrucksPerMinute'	Informative message highlighting the change in rate of trucks in the queue
'All equipment in use, little or no improvement noted. New Trucks At Gate Rate (per minute): @NewRateTrucksPerMinute, Previous Trucks At Gate Rate (per minute): @TrucksPerMinute, Trucks At Gate: @trucksAtGate, Queue Threshold: @TruckQueueThreshold'	Warning message highlighting the current situation details and relevant parameter information
'Truck Arrival Rate has not dropped. Customer notification to be sent to delay/halt arrival. Trucks at Gate: @trucksAtGate'	Warning message indicating efforts to reduce the truck arrival rate has not improved the situation and the customers and trucking companies are now being involved. Notification simulation is demonstrated by inserting a message in the Notifications queue. The CC-BPN SBBs can be used to address this situation.
'No. of Trucks At gate has returned below the Safe Limit. Trucks at Gate: @trucksAtGate, Safe	Informative message indicating all efforts taken to reduce the congestion situation has worked

Limit: @TruckQueueSafeLimit. Resetting controls to defaults.' OR 'Congestion subsided. Setting number of Equipment and Bays used back to default. Truck Arrive Rate (per minute): @TrucksPerMinute, Service rate (per minute): @ServicePerMinute'	and equipment levels are being reset to acceptable usage state.
'Setting Truck Arrive Variance to default: @TruckDefaultArrInterval and notifying customers to resume normal arrival.'	Informative message indicating the customers and trucking companies are being contacted to begin sending trucks to the terminals. Notification simulation is demonstrated by inserting a message in the Notifications queue. The CC-BPN SBBs can be used to address this situation.

The Simulation Configuration view provides for an informative view of the current parameter configuration settings for the simulation. Table 4.2 gives a brief description of the purpose of each parameter.

Table 4.2: Configuration Parameters

Parameter	Description
CAUDUSSTATUS	Switch to manage queue congestion for simulation purposes. Values are STARTED/ STOPPED. Simulation default value is STARTED
CONGPOINT	Switch to force congestion at specified points to demonstrate the simulation effectiveness. Values are ● X: No Congestion Point ● BGI: Before Gate In ● AG: At Gate ● SA: At Staging Area ● LB: At Loading Bay

	• AGO: At Gate Out Simulation default value is X
DEFTARRVAR	Default Time Variance (seconds) of Truck Arrivals at Gate for simulation purposes. This value is the ideal arrival time for trucks. Simulation default value is 3 seconds
EQPAVAILDEFLMT	Default No. Of Equipment In Use for simulation purposes. Simulation default value is 3 Straddles
MINEVENTTIMES	Minimum Time (Seconds) Between Events for simulation purposes. This parameter is used to ensure a that every event will have a non-zero time Simulation default value is 3 seconds
QEXITCAP	The Exit Queue Capacity for trucks exiting the terminal gate for simulation purposes Simulation default value is 30 Trucks
ST00*n*-FETCHTIME	Minimum Fetch Time (seconds) for Straddle ST00*n* for simulation purposes. *n* can be 1..9 Simulation default value is 3 seconds
ST00*n*-LDTIME	Minimum Load Time (seconds) for Straddle ST00*n* for simulation purposes. *n* can be 1..9 Simulation default value is 3 seconds
ST00*n*-OFFLDTIME	Minimum Offload Time (seconds) for Straddle ST00*n* for simulation purposes. *n* can be 1..9 Simulation default value is 3 seconds
ST00*n*-STACKTIME	Minimum Stack Time (seconds) for Straddle ST00*n* for simulation purposes. n can be 1..9 Simulation default value is 3 seconds
STARTPROCESS	Indicator to start (Y) and stop simulation Simulation default value is Y
STGAREACAP	Staging Area Capacity is to limit the number of trucks entering the gate for simulation purposes

	Simulation default value is 30
STOPTRCKARVLS	Stop process of arriving trucks at gate for simulation purposes. This indicator prevents additional trucks from calling at the port precinct and simulates the involvement of the customers and trucking companies heeding the Caudus request to halt truck arrivals. This indicator helps demonstrate the CC-BPN SBBs Valid values are Y and N. Simulation default value is N
TARRVARIANCE	Truck Arrival Time (seconds) Variance at Gate for simulation purposes. This value is used to manage arrival times if the queue is too congested and delays trucks from calling at the port precinct, simulating the involvement of the customers and trucking companies heeding the Caudus request to delay truck arrivals. This indicator helps demonstrate the CC-BPN SBBs. The Higher the Number the longer the delay between arrivals. Simulation default value is 3 seconds
TASSIGNCAP	Number of trucks allowed to be assigned a commodity, irrespective of Queue Capacity for simulation purposes Simulation default value is 99999
TGATEINVARIANCE	Variant of Truck Times (seconds) Gated In for simulation purposes. The Higher the Number the more time between truck gate-ins Simulation default value is 3 seconds
TQCAP	Truck Queue Capacity for simulation purposes. Simulation default value is 50 trucks
TQSAFELIMIT	Truck Queue Safe Limit for simulation purposes. This limit suggests the situation is well managed and equipment allocation as well as arrival times can be reset to its default. Simulation default value is 25 trucks.
TQTHRSHLD	Trucks queue threshold limit for simulation purposes. This value is the first threshold that suggest a potential congestion situation is beginning.

	Simulation default value is 35 trucks
USERNDTIMES	Indicator for simulation purposes that controls whether simulation times are generated randomly or using fixed values. Simulation default value is N

The Unit of Measure for the simulation time is *Seconds.* This is to enable the simulation to execute over a shorter period for demonstration purposes.

The Caudus Simulation GUI is an original development solely for the purpose of this dissertation. The layout is a virtual representation of the port precinct and terminal operations.

4.4. Caudus GUI Background Processes

Figure 4.3 gives an overview of the background processes used to simulate the terminal operational activities involved for cargo handling. The processes are spawned off in separate threads using DOS batch commands to recreate the real-life parallel processes involved for the different activities. Table 4.3 give each a brief description of each batch program.

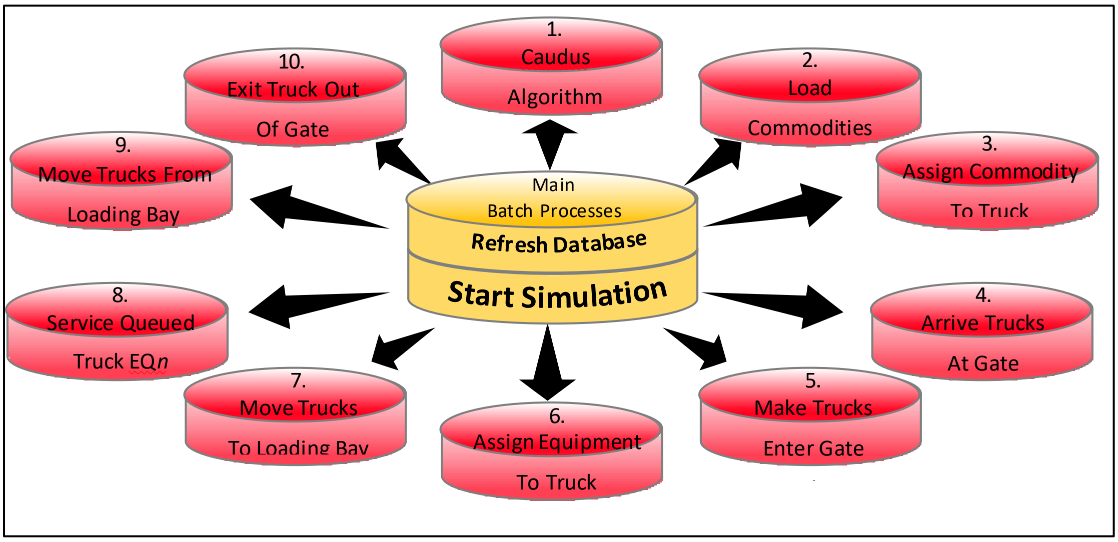

Figure 4.3: Caudus Simulation Multi-thread Processes

There are two main batch programs that are required to start the simulation viz. RefreshDatabase.bat and StartSimulation.Bat. The RefreshDatabase.bat program simply refreshes the simulation database by deleting all simulation data in the relevant underlying database tables and loads the configuration data. The StartSimulation.bat executes the batch programs stipulated in Table 4.3. Since the programs are independent of each other, it is not necessary to execute these programs in any particular order.

Table 4.3: Background Batch Processes

Program	Description
CaudusAlgorithm.bat	Executes the primary database procedure CaudusAlg that contains all the Caudus logic required to manage the traffic situation. Details of the logic is delved into greater detail in Tables 4.5 and 4.6.
LoadCommodities.bat	Executes the database procedure LoadCommodities, which creates sample commodities for the simulation. This is a looped execution for the duration of the simulation
AssignCommodityToTruck.ba t	Executes the database procedure AssignCommodity2Truck, which simulates allocating the sample commodities to trucks. This is a looped execution for the duration of the simulation
ArriveTrucksAtGate.bat	Executes the database procedure ArriveTrucksAtGate, which simulates the trucks arriving at the terminal gate or port precinct. This is a looped execution for the duration of the simulation
AssignEquipmentToTruck.bat	Executes the database procedure AssignEquipment2Truck, which simulates assigning available equipment to service the trucks. This is a looped execution for the duration of the simulation
MakeTrucksEnterGate.bat	Executes the database procedure MakeTruckEnterGate simulating the action of trucks entering the terminal gates.

	This is a looped execution for the duration of the simulation
MoveTruckToLoadingBay.bat	Executes the database procedure MoveTruck2Loadingbay, which simulates the trucks' movement to the Loading Bays. This is a looped execution for the duration of the simulation
ServiceQueuedTruckEQ*n*.bat	Executes the database procedure ServiceQueuedTruckEqp*n*, which simulates the action of the equipment servicing trucks at the Loading Bays. For simulation purposes, the equipment used are Straddle Carriers and *n = 1..9* represents the specific Straddle that is used to service its respective truck. This is a looped execution for the duration of the simulation
MoveTruckFromLoadingBay.bat	Executes the database procedure MoveTruckFromLoadingbay, which simulates the movement of trucks from the Loading Bays towards the exit gates of the terminals. This is a looped execution for the duration of the simulation
ExitTruckOutOfGate.bat	Executes the database procedure MakeTruckLeaveGate simulating the action of the trucks leaving the terminal gates. This is a looped execution for the duration of the simulation

The Caudus Simulation Background processes are all original developments solely for the purpose of this dissertation.

4.5. Caudus Back-End Processes

The Caudus Simulation Back-end processes are related to all objects residing on the SQL Express database. These objects are made up of database tables and stored procedures. Table 4.4 gives a brief description of each object.

Table 4.4: Database Objects

Object Name	Object Type	Description
GeneralConfigs	Table	Stores all configuration parameters and related values required for the simulation program
LoadingBays	Table	Master data table containing the Loading Bays defined for the simulation
CommodityLists	Table	Transactional Data table containing the list of unique commodity identifiers required for the simulation
EquipmentMasters	Table	Master Data table containing the list of equipment identifiers used in the simulation
EquipmentHistory	Table	Transactional Data table containing historic data that can potentially be used for trend and pattern analysis for predictive and prescriptive maintenance in future AI Learning Algorithm SBBs (Figure 3.2)
EquipmentDriverMasters	Table	Master Data table containing the list of equipment drivers used in the simulation
EquipmentDriverHistory	Table	Transactional Data table containing historic data that can potentially be used for driver trend and pattern analysis in future AI Learning Algorithm SBBs (Figure 3.2)
TruckDriverMasters	Table	Master Data table containing the list of truck drivers used in the simulation
TruckMasters	Table	Master Data table containing the list of trucks used in the simulation
Notifications	Table	Transactional Data table containing notifications of congestion related activities. This table is used to demonstrate the CC-BPN SBBs to manage congestion identified in during Exception Monitoring.

CaudusLogs	Table	Transactional Data table containing logs of activities of executed in the simulation
CaudusAlgLogs	Table	Transactional Data table that logs the CaudusAlg activities. Data in this table is displayed in the Simulation GUI (Figure 4.2) to tell the simulation story as its occurring.
ServiceQueues	Table	Transactional Data table containing all activities related to the operational processes of the terminal. This table can be considered as the single source of truth required in the interpretation and algorithmic deduction of its optimisation objectives. All processing logic stems from the data that is generated and stored in this table.
LoadCommodities	Procedure	Creates and inserts a list of unique commodity identifiers into the CommodityLists table used in the simulation
AssignCommodity2Truck	Procedure	Assigns a commodity to a truck
ArriveTrucksAtGate	Procedure	Simulates the action of a truck arriving at the port precinct but has not yet entered the terminal. This essentially enters the truck into the truck queue. In order for the truck to be in the queue, it will have a commodity linked to it
MakeTruckEnterGate	Procedure	Simulates the action of a truck entering the terminal gates. The vehicle must be in the port precinct and have a commodity assigned to it in order to enter the gate
AssignEquipment2Truck	Procedure	Assigns an available equipment to a truck that is already gated in and waiting to be serviced in the Staging Area. The truck must have a commodity linked to it in order to be assigned an equipment

MoveTruck2Loadingbay	Procedure	Simulates the action of a truck moving from the Staging Area to the Loading Bay in order to be serviced. The truck must be in the terminal and have a commodity linked to it
ServiceQueuedTruckEqp*n*	Procedure	Services the truck that it is assigned to. The truck must be located at an active Loading Bay. Individual procedures have been duplicated for equipment *n=1..9*, where *n* is the equipment number. The procedures have been done in this manner to mimic the real-life independent processing capability of each Straddle and avoid sequential processing of the straddle activity during the simulation
getEventTimeEqp*n*	Procedure	Returns the time for each event of the relevant equipment. Individual procedures have been written for equipment *n=1..9*, where *n* is the equipment number to avoid sequential processing during the simulation
MoveTruckFromLoadingbay	Procedure	Simulates the movement of a truck from the Loading Bay towards the exit gate. The truck must have a commodity linked to it, is currently located at the Loading Bay and already been serviced by an equipment
MakeTruckLeaveGate	Procedure	Simulates the truck leaving the terminal through the exit gates. The truck must have a commodity linked to it, have already left the Loading Bay but currently inside the terminal
ChangeEqpDriverShift	Procedure	Used to assign equipment drivers across different shifts. This procedure can be useful in simulation of data for driver trend and pattern analysis in future AI Learning Algorithm SBBs

RetConfigValue	Procedure	Procedure to return configuration values used in the simulation
SendNotification	Procedure	Simulates notifications to ITS providers demonstrating the CC-BPN SBBs to manage congestion identified in during Exception Monitoring.
truckAvailable	Procedure	Returns the next available truck in the simulation
TruckMovementRates	Procedure	Returns the truck movement rate given by (3.13)
trucksQueued	Procedure	Returns the number of trucks queued
logActivity	Procedure	Procedure to insert logs into the CaudusLog table
CongestionAreaNotif	Procedure	This procedure is primarily used for Exception Monitoring across the different bottleneck points given by the (3.18)
CaudusAlg	Procedure	This procedure encompasses all logic pertaining to Caudus. It comprises the algorithms used to monitor and predict potential congestion situation while managing the activities to address the problems. Seen as the “brain” of Caudus, it contains all PTM SBBs and has the capability extend additional learning logic SBBs as a plug-in or enhancement to this procedure.

The Caudus Back-end Processes are all original developments solely for the purpose of this dissertation.

4.6. The Caudus Algorithm and the Optimisation Module

4.6.1. The Caudus Algorithm

Caudus is the encompassment of the derived algorithms used in its objective to address traffic congestion and the supporting programming logic that enable the execution of the algorithms to achieve those objectives.

The following program pseudocode gives an overview of the Caudus logic contextualising the derived algorithms used in the simulation to demonstrate Caudus' effectiveness in managing congestion. Appendix B provides the actual code of the Caudus Algorithm module compiled in SQL.

The Caudus Algorithm

Set Limits:

Set Queue Threshold θqtr using (3.7);

Set Queue Capacity $\theta qCap$ using (3.1);

Set Queue Safe Limit $\theta qsafe$ using (3.8);

Do While Queue Monitoring is Active**:**

Test Current Queue Size $\theta queue$ against Threshold θqtr(Preventive Objective)

If the Threshold is breached ($\theta queue > \theta qtr$)

Increase the service rate $\theta Rsnew$ using (3.16)

Test Current Queue Size against Queue Capacity using (1) (Reactive Objective)

If the Capacity is breached ($\theta queue > \theta qCap$)

Invoke the BPN SBB to halt trucks reduce queue size

Test Current Queue Size $\theta queue$ against Safe Limit $\theta qsafe$ (3.8)

If Safe Limit Returned ($\theta queue < \theta qsafe$)

Reset counter-measures

Test environment for exceptions and anomalies (Predictive Objective)

Test activities across bottleneck points against (3.18)

If bottleneck identified

Invoke Incident Management SBB

Test activities across bottleneck points against (3.19)

Invoke Incident Management SBB

End Do;

Once the Queue limits are defined part of the configuration, the system remains in a continuous monitoring mode until deactivated. The Preventive, Reactive and Predictive objectives are repeatedly tested against the derived algorithms in order to determine the need for counter-measures to avert or alleviate any congestion. The Caudus Algorithm pseudocode emphasises the connection between the derived algorithm and the programming logic used to enforce them.

4.6.2. The Optimisation Module

Figure 4.4 is the graphical representation of the CaudusAlg procedure logic, which is the core optimisation module. The logic is represented in 23 different processes with the 23rd process being a virtual one to highlight the juncture point for additional SBBs and plugins as the needs of the optimisation module evolves in future works. Table 4.5 gives an elaborate description of each process step of the Caudus logic that is depicted in the flow.

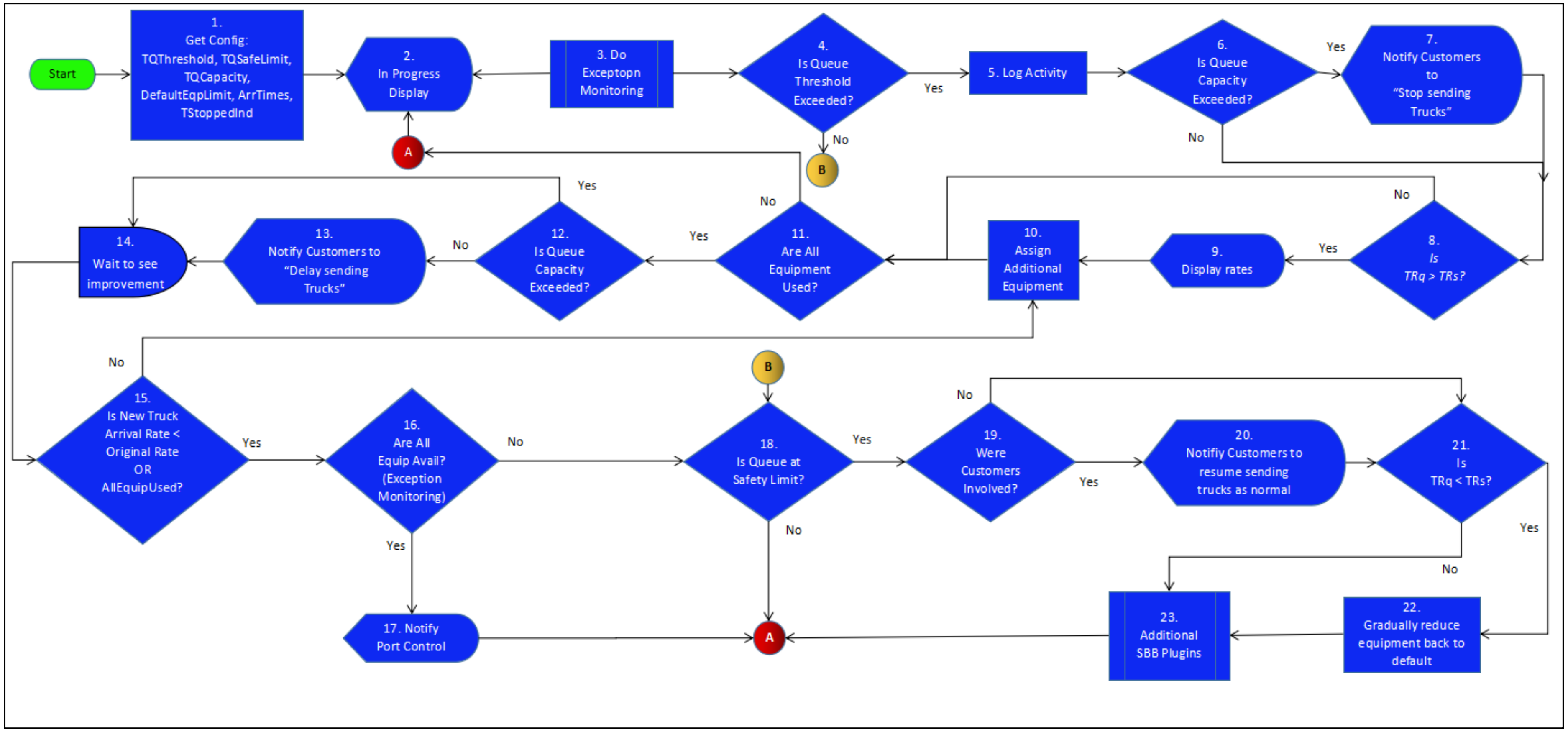

Figure 4.4: Caudus Algorithm - The Optimisation Module

Table 4.5: Caudus Process

Process	Details
1	Retrieves the Simulation Configuration values, which includes: TQThreshold - represents the TQTHRSHLD simulation parameter and is the first threshold that suggest a potential congestion situation is beginning. This parameter is used in Process 4 as the first check point of any potential congestion starting up. TQSafeLimit - represents the TQSAFELIMIT simulation parameter. This parameter is used as a checkpoint in Process 18 to indicate that the situation is back to normal and the customers can resume sending the trucks as normal, as well as all equipment can be set to the default limits. TQCapacity - represents the TQCAP simulation parameter and is used to determine whether the truck queue is congested. Located in Process 6, this is used as the ultimate checkpoint to diagnose a congested situation. This is the point of initiation for all countermeasures to manage the congestion. DefaultEqpLimit - represents the EQPAVAILDEFLMT simulation parameter. Process 22 utilises this parameter to set the number of equipment used in the operations environment back to the default to prevent over-capacity to prevent congestion. ArrTimes - represents the TARRVARIANCE simulation parameter. This parameter is used for simulation purposes to control the rate at which trucks arrive the terminal. Increasing or decreasing this parameter forces Caudus to manage the equipment performance based on the Truck Queue Arrival Rate (θRq). TStoppedInd - represents the STOPTRCKARVLS simulation parameter to indicate that trucks have stopped arriving at the terminals. This indicator is used to simulate Exception Monitoring in Process 3 as well as Process 7 and 20.

2	Display message block used for simulation purposes to depict the progress of the simulation. This block is also the Loop-Back juncture point (represented by Block (A)) for the Caudus monitoring process. Display block messages are shown on the Simulation Dashboard – (Figure 4.2)
A	The Loop-Back connector block
3	“Exception Monitoring” is a sub-routine block that contains logic applied to monitor exceptions in the traffic situation. Table 4.6 gives further detail on this logic
4	Decision block used as a first checkpoint to determine if there is a potential problem that is building up. If the threshold point has not been reached, then this is an indication that traffic is well-managed and there is no need to progress into the algorithm processing logic of Caudus. The process then jumps to Block (B) juncture point.
B	Jump-To connector block
5	Logs the current Caudus process activity for audit and trace purposes
6	Second checkpoint decision block to determine whether the traffic situation is now dire, and a deep dive analysis and rectification is required. (Yes): If the traffic situation is at a boiling point, then resolving the problem is now beyond the optimisation capability and exceptional measures need to be initiated to address it. This is in conjunction with the optimisation measures already employed. This route of the process alludes to the ITS integration and CC-BPN SSBs capability. (No): If the traffic situation is not at a boiling point then there is still some optimisation capability to manage the situation, which is at the point of the queue threshold already being exceeded - Process (4).
7	Display message indicating a notification to customers to Halt the sending of trucks to the terminals. This block represents the CC-BPN SSBs capability in addressing the problem, which is also an existing industry practice using their mobile apps and alert notification platforms [77]. Display block messages are shown on the Simulation Dashboard – Figure 4.2.

8	Decision block to determine if the truck arrival rate into the queue (θRq) exceeds the rate at which the trucks are service by the equipment (θRs) (3.9). (Yes): If the arrival rate is greater than the service rate then additional equipment must be allocated to compensate for the traffic influx. Caudus introduces the equipment gradually since traffic influx is dynamic and allocation to the point of $\theta Rq \leq \theta Rs$ could result in over-compensating with the equipment if the influx drops suddenly. The buffer limit between Queue Threshold and Queue Capacity allows for this gradual increase as well as extends the Caudus capability to introduce bulk equipment allocation if the need arises. (No): No additional allocation is required. This route would suggest that there had been a point at which $\theta Rq > \theta Rs$ but either the traffic has subsided, or additional equipment allocation has improved the service rate
9	Display of Truck Queue Rate (θRq) and Truck Service Rate (θRs) for simulation purposes. Display block messages are shown on the Simulation Dashboard – Figure 4.2.
10	Process used to allocate additional equipment, if available, with the intention of improving the equipment service rate. This is normally the requirement if $\theta Rq > \theta Rs$.
11	Decision Block used to check if there are any more equipment available for allocation (Yes): Proceed to assess the queue situation before allocating further equipment (No): This indicates that all the equipment has been allocated to improve the traffic situation. At this point, all optimisation efforts have been attempted by improving equipment service performance. Recall, Caudus got to this point because the queue threshold was exceeded and possibly the queue capacity as well. Also recall, if the Queue capacity is exceeded then a notification is sent to the trucking company customers to "Stop sending Trucks" -Process (7). This intervention, together with all equipment allocated to improve performance will

	reduce the traffic congestion. Therefore, Caudus need only monitor the progress. Process (11) is the final control point for managing the traffic situation through optimisation efforts. Beyond this process involves either managing the situation through exception monitoring using ITS and CC-BPN SBBs OR returning the optimisation changes made back to normal as optimisation attempts until this juncture point would achieve its objective.
12	Decision block to determine if all efforts made until this point have managed to prevent the queue from exceeding its capacity. (Yes): At this point, all optimisation efforts would have been previously attempted to improve the situation i.e. Exception Monitoring (Process 3), CC-BPN SBBs (Process 7) and allocation of equipment (Process 10). However, the queue is still at an exhausted level and the only alternative in the scope of Caudus at this point is to monitor the situation until the optimisation measures implemented take effect to reduce the traffic congestion (Process 14). (No): Since the Queue Capacity has not yet been exceeded but the Queue Threshold has been exceeded (Process 4) AND the Truck Arrival Rate (θRq) is greater than the Truck Service Rate (θRs) (Process 8) AND all equipment have been allocated (Process 11), the only alternative at this point to alleviate the congestion is by reducing the truck arrivals to the port precinct. This is achieved through the use of CC-BPN SBBs (Process 13).
13	Display message indicating a notification to customers to slow down or Delay the sending of trucks to the terminals. This block represents the CC-BPN SSBs capability in addressing the problem. This approach intends to reduce the truck queue rate thus ensuring $\theta Rq \leq \theta Rs$, which is the ideal queue condition (3.10). Since the queue has not yet been exceeded, a delay in sending the trucks will suffice instead of halting the arrivals altogether. Display block messages are shown on the Simulation Dashboard - Figure 4.2.
14	Delay Process indicating a period of waiting to see whether improvements have been noted

15	Decision Block process to determine whether the customers did respond to delaying the arrival of the trucks to the terminal. This is confirmed by determining whether the new truck queue rate is lower than the previous one. An additional check in this Decision Block Process is the confirm if all the equipment has been allocated. (Yes): If truck queue rate is reduced or all equipment allocated to service the trucks then Caudus need only to monitor whether this improved the situation to the extent of the queue reaching the safety limit (Process 18) or there are exceptions that are hindering the improvement (Process 16). (No): If the truck queue rate has not been reduced and neither has all the equipment been allocated, then more equipment needs to be allocated until the rate has improved (Process 10). This cycle from Process 10 continues as previously discussed until all equipment has been allocated or the truck queue rate reduces.
16	Decision Block process used for exception monitoring. (Yes): The process could have reached only reached this point if the queue was becoming congested (Process 4) or the queue had already overflowed (Process 6). Therefore, in normal situations, all equipment would have been allocated to service the trucks queued at the Staging Area since equipment is only allocated to trucks located at the Staging Area. Since all equipment is available, this would suggest that there are no trucks at the Staging Area, which in turn suggests there is a situation that is preventing trucks reaching the Staging Area. Hence, the CC-BPN SSBs is used to address the problem (Process 17) (No): If there are at least some equipment in use, then Caudus need only to monitor whether this improved the situation to the extent of the queue reaching the safety limit (Process 18)
17	Display message indicating a notification to Port Control to investigate the exceptional situation at Port Gate - Before Entry that is preventing trucks from reaching the Staging Area. This block represents the CC-BPN SSBs capability in addressing the problem.

	Display block messages are shown on the Simulation Dashboard - Figure 4.2.
18	Decision Block process to determine whether the truck queue has reached a safe limit. (Yes): This route suggests that all efforts up to this point has succeeded in reducing the queue to the predefined safe limit (TQSAFELIMIT) and all parameters that were adjusted to achieve this is now at a point to be reset to default values (Process 20 and Process 22). (No): The queue still needs to be reduced and therefore monitoring needs to continue until this is achieved
19	Decision Block process to determine whether customers were previously involved. (Yes): Since the Queue Safe Limit is now reached (Process 18), Notification to customers must be sent advising of a better traffic situation (Process 20) and advising to send trucks as normal. (No): Customers were not involved therefore do not send the notification
20	Display message indicating a notification to customers to resume sending trucks to the terminal. Display block messages are shown on the Simulation Dashboard - Figure 4.2.
21	Decision Block process to check is the truck queue rate is lower than the truck service rate in order to reset the allocation of equipment. The ideal state of the queue is between the safe limit (TQSAFELIMIT) and threshold limit (TQTHRSHLD). (Yes): This would suggest that the equipment is over-allocated to service the queue due to the queue capacity reaching the safe limit (Process 18). Therefore, there is a need to gradually reduce the equipment usage to default settings so not to cause a congested

	situation again ($\theta Rq > \theta Rs$) while limiting the equipment to prevent excessive usage, which increases unwarranted fuel consumption and wear 'n tear maintenance costs. This preventative measure introduces Caudus' Maintenance Management SBBs capability for future works. (No): Equipment allocation remains unchanged due to the situation.
22	Gradually reduce allocated equipment since the congestion situation has subsided
23	Sub-Process Point indicating Caudus' evolving capability to cater for additional SSBs as the need arises in future works

Exception monitoring is the process of predicting traffic congestion that is caused as a result of a situation that is beyond systems control. Some of these causes include accidents, breakdowns, mass actions etc. Process 3 of the CaudusAlg procedure logic (Table 4.5) is a sub-routine process that focuses on exception monitoring in the port precinct. Since the causes of exceptions can be exhaustive, monitoring and identifying of these situations can also grow over time. As a result, it is only fitting to modularise that growing logic into a sub-routine in order to allow it to evolve over time without impacting on the normal processes. Figure 4.5 gives the processes of the exception monitoring module with Table 4.6 giving further detail on the logic used in the module.

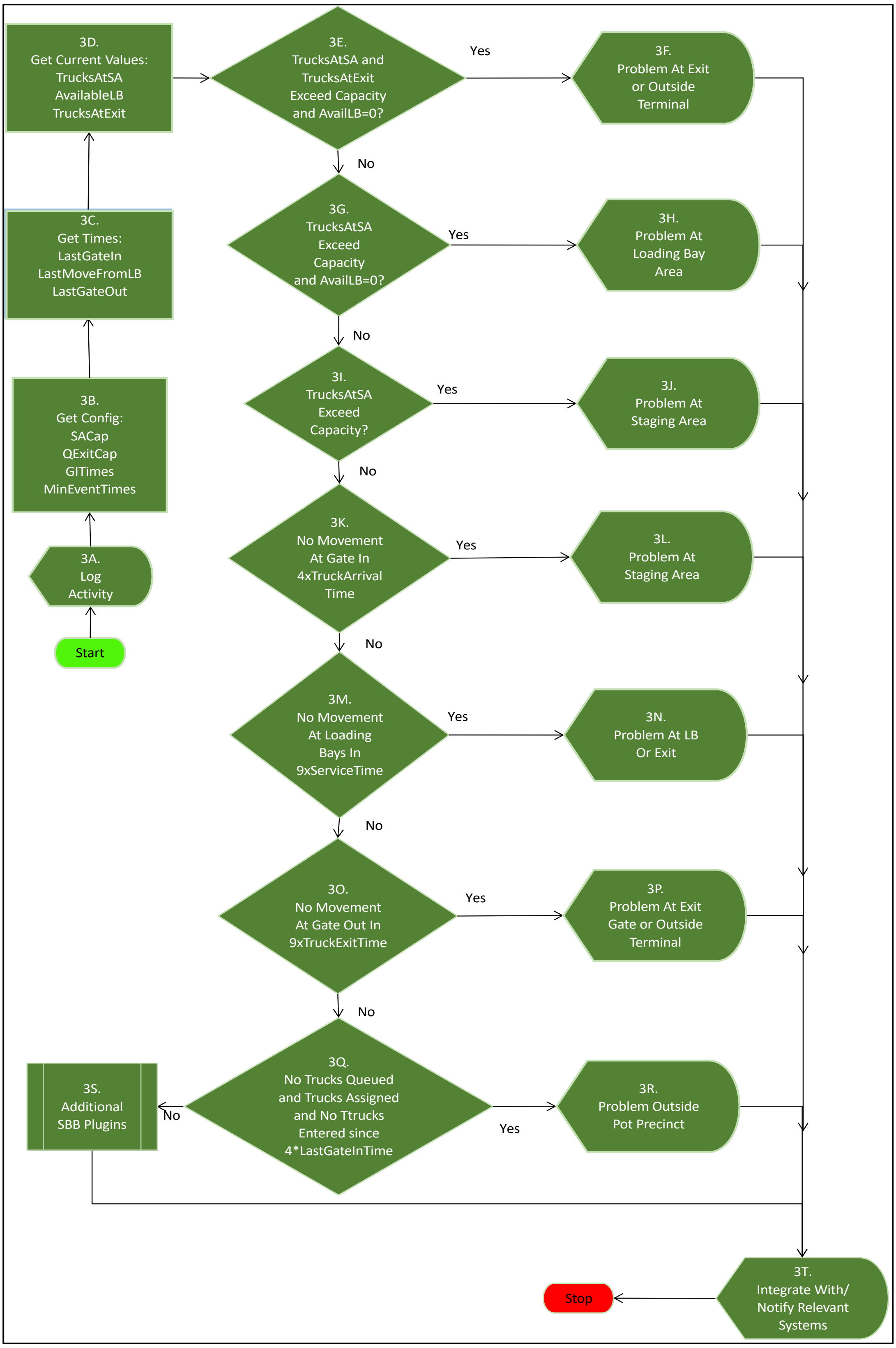

Figure 4.5: Exception Monitoring Sub-Routine

Table 4.6: Exception Monitoring Process

Process 3	Details
A	Logs the current Caudus process activity for audit and trace purposes
B	Retrieves the Simulation Configuration values, which includes: SACap - represents the STGAREACAP simulation parameter and is used to determine when the staging area capacity is reached. QExitCap - represents the QEXITCAP simulation parameter and is used to determine whether the queue at the exit gate has reached its capacity. GITimes - represents the TGATEINVARIANCE simulation parameter used to get the average time across the trucks entering the terminal gates. This parameter is purely for simulation purposes and would normally be calculated using real time data using the average truck times entering the terminal. MinEventTimes - represents the MINEVENTTIMES simulation parameter used to specify a minimum time limit that an event takes to be completed. For purposes of this simulation, the minimum event time is a single period for all events, but this can be varied in a real-life scenario. The parameter ensures no event has a zero period when used in the processing logic
C	Get the following activity times: LastGateIn - the last time that a truck had entered enter through terminal gates. LastMoveFromLB - the last time that a truck had moved from the Staging Area to the Loading Bays LastGateOut - the last time a truck had left the Loading Bays moving towards the terminal exit gates
D	Get the following current values: TrucksAtSA - retrieves the current number of trucks queued at the Staging Area AvailableLB - retrieves the number of available loading bays

	TrucksAtExit - retrieves the number of trucks queued at the terminal exit gates i.e. the number of trucks that have not yet left the terminals.
E	Decision block to determine whether the trucks at the Staging Area has exceeded its capacity while there is no availability at the Loading Bays and the trucks at the exit queue has also been exceeded (3.18). This would suggest that there is a problem at the terminal exit gate area or outside the terminals. (Yes): Problem identified at terminal exit area or outside the terminal and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process F). (No): Check other exception conditions (Process G)
F	Display message indicating there is an incident at the terminal exit gate area or outside the terminal. This process leads to other ITS integration and Incident Management SBB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard Figure 4.2.
G	Decision block to determine whether the trucks at the Staging Area has exceeded its capacity while there is no availability at the Loading Bays - (3.18). This would suggest that there is a problem at the Loading Bays area. (Yes): Problem identified at Loading Bays and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process H). (No): Check other exception conditions (Process I)
H	Display message indicating there is an incident at the Loading Bays. This process leads to other ITS integration and Incident Management SBB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard - Figure 4.2.
I	Decision block to determine whether the trucks at the Staging Area has exceeded its capacity (3.18) suggesting there’s a problem at the Staging Area.

	(Yes): Problem identified at the Staging Areas and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process J). (No): Check other exception conditions (Process K)
J	Display message indicating there is an incident at the Staging Area. This process leads to other ITS integration and Incident Management SSB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard - Figure 4.2.
K	Decision block to determine whether there has been any movement of trucks into the terminal in a specified period (3.19). No movement would suggest an incident has occurred at Gate In or the Staging Area. This method of predicting congestion supersedes Processes E, G and I since time-based predictions are much quicker than constraint comparisons. (Yes): Problem identified at Gate In or at Staging Area and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process L). (No): Check other exception conditions (Process M)
L	Display message indicating there is an incident at Gate In or the Staging Area. This process leads to other ITS integration and Incident Management SSB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard - Figure 4.2.
M	Decision block to determine whether there has been any movement of trucks out of the Loading Bays in a specified period (3.19). No movement would suggest an incident has occurred at the Loading Bays or Exit Gates. This method of predicting congestion supersedes Processes E, G and I since time-based predictions are much quicker than constraint comparisons. (Yes): Problem identified at Loading Bays or Exit Gate and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process N).

	(No): Check other exception conditions (Process O)
N	Display message indicating there is an incident at the Loading Bays or the Exit Gate. This process leads to other ITS integration and Incident Management SSB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard - Figure 4.2.
O	Decision block to determine whether there has been any movement of trucks exiting the terminal (3.19). No movement would suggest an incident has occurred at the Exit Gate or Outside the terminal. This method of predicting congestion supersedes Processes E, G and I since time-based predictions are much quicker than constraint comparisons. (Yes): Problem identified at Exit Gate or Outside the terminal and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process P). (No): Check other exception conditions (Process Q)
P	Display message indicating there is an incident at Exit Gate or Outside the terminal. This process leads to other ITS integration and Incident Management SSB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard - Figure 4.2.
Q	Decision block to determine whether there are no trucks in the truck queue, while there are trucks assigned commodities that need to be moved and there has been no movement of trucks entering the terminal. This would suggest that there is a problem beyond the port precinct that is preventing trucks from reaching the precinct. Although this bottleneck point has a high probability of false-positives due to the area monitored not being in the immediate vicinity, it has been included in the simulation to demonstrate Caudus' monitoring potential of extending beyond the port precinct and as well as to highlight its optimisation capabilities in the resource and equipment planning areas. (Yes): Problem identified beyond Port Precinct and the relevant Incident Management SBB (Figure 3.2) must be invoked (Process R).

	(No): Additional SBB plugins accommodated for future exception monitoring conditions as requirements evolve (Process S)
R	Display message indicating there is an incident beyond the port precinct. This process leads to other ITS integration and Incident Management SSB capabilities in addressing the problem (Figure 3.2) (Process T). Display block messages are shown on the Simulation Dashboard - Figure 4.2.
S	Sub-Process Point indicating the Exception Monitoring capability to accommodate additional SSBs as the need arises in future works
T	This Process block allows for accommodating other ITS integration and Incident Management SSB capabilities to address the problem that is beyond the Caudus scope (Figure 3.2) Display block messages are shown on the Simulation Dashboard - Figure 4.2.

4.7. The Simulation Process

The Caudus Simulation aims to demonstrate the effectiveness of Caudus in any logistics services environment with common activities such as arrival of the truck to the load/ offload destination point, staging of the trucks until ready to be loaded/ offloaded, allocation of the equipment loading/ offloading the trucks and finally the trucks leaving the load/ offload location travelling towards a new load/ offload destination point.

The simulation is initiated by first executing the RefreshDatabase.bat program and then the StartSimulation.bat program. RefreshDatabase.bat logs in to the SQL Express database and deletes all configuration, log, history and transactional data in the underlying database tables pertaining to the simulation. Thereafter, the simulation default values are loaded into the master data and configuration tables. Each time the simulation is started, RefreshDatabase.bat is run so not to distort the results across the use cases.

Master data loaded for the simulation includes the Configuration data (generalConfigs table), Loading Bays (loadingBays table), Driver Master Data (EquipmentDriverMasters table), Equipment Master Data (EquipmentMasters table) and Truck Master Data (truckMasters table). The Configuration data is listed and explained in Table 4.2. The Loading Bays data pertains to the loading bays where trucks will call to load or offload (or both) cargo. There are up to nine Loading Bays created for the simulation with three bays being active and six remaining inactive but available for additional capacity.

When the need arises, Caudus activates the additional bays based on demand by setting the ActiveInd column to "Y", then resets the number of bays back to the default when the demand drops. The order of bay activation/ deactivation does not have any bearing on the simulation results and uses the order of the loading bay id as guide for activation/ deactivation. The Loading Bays data is a discrete dataset chosen for the simulation.

The Driver master data is specific to the equipment drivers. Although not directly impacting on the results of the simulation, the driver master has been included to cater for driver trends and pattern analysis for potential future works in AI Learning Algorithm SBBs (Figure 3.2). Ten general driver profiles have been created for this simulation. The Driver master data is a discrete dataset chosen for the simulation.

The Equipment master data relates the equipment that is used to service the trucks that move the cargo. The equipment is not specific to any environment but relates to demonstrating the capability of servicing a truck. For purposes of this simulation, nine Straddle Carrier equipment are created with three being active by default and six inactive but available to service the demand when truck capacity increases. Caudus controls the allocation/ de-allocation of the equipment based on demand by setting the InUseInd column to "Y". The Equipment master data is a discrete dataset chosen for the simulation.

The Truck master data creates the vehicles that transport the cargo to and from the terminals. A truck is the general logistical mode of transporting goods across different locations and therefore is not specific the ports scenario. This simulation creates a random sample of 300 trucks for every simulation run with the simulation reaching a point of completion only once the 300 trucks have been serviced. The number of trucks is a constant in the Truck master data script and can be changed manually to any preferred amount for the test simulation.

Included in the truck master data is the Violations and the Certified indicators, and truck Permit number to cater for Incident and Accident Patterns for potential future works in AI Learning Algorithm SBBs (Figure 3.2). For purposes of the simulation, the Indicators Violations defaults to "N" and Certified defaults to "Y". The Permit number defaults using the "PERM" prefix together with the truck's five-digit registration number. The truck registration number is generated using the "ND" prefix concatenated with five digits, each digit generated randomly using the RAND () SQL function.

The StartSimulation.bat program initiates the simulation processes listed in Table 4.3 with each process used to perform a specific activity required. The first process initiated is CaudusAlgorithm.bat, which is the control program for the Caudus Algorithm Optimisation module explained in detail in Tables 4.5 and 4.6. Caudus will continue to monitor the environment during the simulation while the CAUDUSSTATUS configuration parameter is set to STARTED. This parameter is used to give a comparison of the situation when Caudus is not monitoring the environment (STOPPED) and when it is activated. The ServiceQueues table is the primary table for the simulation since all activities in the simulation process revolves around the ServiceQueues table.

LoadCommodities.bat is responsible for creating the commodities for the simulation. A commodity represents any cargo that needs to be transported and therefore is not restricted to commodities entering and leaving the port terminals. With this approach to the simulation, the optimisation solution extends to any cargo logistics environment. A random sample of 500 commodities is created for this simulation with a movement type assigned to each commodity. The movement type can be "INTO" for commodities assigned to trucks that are simply dropping off the cargo, "OUT-OF" representing cargo that is being picked up, and in instances where trucks are performing a dual purpose of dropping off one cargo while picking up another, the "DUAL" movement type is used. For cargo linked to dual movements, there is an associated "DUAL00" commodity id linked to the primary commodity id to identify its dual purpose. When a dual commodity is assigned to a truck, the simulation reflects this in a different colour on the GUI and the event times are doubled, one event time for each leg of the move.
The commodity id does not have any bearing on the simulation results and is generated using the "COMM00" prefix concatenated with eight digits, each digit generated randomly using the RAND () SQL function. The dual commodity id uses the primary commodity id's eight digits prefixed with "DUAL00" to denote a dual move commodity. The number of commodities created is a constant and can be changed manually to any preferred amount for the test simulation. Commodities are stored in the CommodityLists table.

The AssignCommodityToTruck.bat activity links the cargo to be moved to a truck that will move it. The commodity linked to a truck signals the truck arrival at the terminal. Only a commodity that has a "READY2MOVE" status can be assigned to a truck and the truck's Avail_Ind status must be set to "Y". Commodities are sequentially selected for assignment with the order of assignment having no bearing on the results of the simulation. Once the commodity has been assigned to the truck, the commodity status changes from "READY2MOVE" to "ASSIGNED" and the truck status changes to indicate it's no longer available to be assigned a commodity. The commodity is assigned to the truck by inserting a record in the ServiceQueues table with the CommodityId column set to the selected commodity and the RegNo column set to the registration number of the selected truck. This record progresses from a QUEUED state to a COMPLETED state where the latter signifies the truck leaving the terminal.

Once the truck is assigned a commodity, it is ready to arrive at the terminal gates, which represents the port precinct. This process is accomplished using ArriveTrucksAtGate.bat and is for simulation purposes only since the arrival times to the point of destination in reality will be given by the vehicle's physical arrival time.
In order for the simulation process to make a truck arrive at the terminal gate, it must be assigned a commodity and the truck cannot be completed with its objective. Trucks are sequentially selected for arrival with the order of truck arrival having no bearing

on the results of the simulation. Updating the datetime column TruckArriveAtGate of the ServiceQueues table with the arrival time for the relevant truck signifies its arrival at the terminal.

The arrival time is given by the sum of MINEVENTTIMES and TARRVARIANCE configuration values with "seconds" being the unit of measure. TVARIANCE is an arbitrary value and can be configured to test different scenarios. Based on this value, the simulation waits for MINEVENTTIMES + TARRVARIANCE seconds before allocating a time to the truck's arrival to the terminal. This approach of waiting the indicated seconds before assigning a time is used to reproduce the simulation as close to the actual process times as possible.

The USERNDTIMES configuration parameter indicates whether the simulation randomly generates the MINEVENTTIMES in seconds or the stipulated values are used as is. If USERNDTIMES is set to "Y" then a random number of seconds from 0 to 9 is generated using the RAND () SQL function and added to TARRVARIANCE. Here too, the point of destination is generic as the simulation precinct is merely marked with an "Arrive At Gate" process, where the gate can be representative of any environment where the simulation is applied to.

Once a truck is at the port precinct i.e. the TruckArriveAtGate time is set and has a commodity linked to it, it is ready to enter the gate. This process is achieved using MakeTrucksEnterGate.bat. The process also checks that there is capacity at the staging area to stage the truck before it is allowed to enter. If there's no capacity, then the simulation starts to demonstrate the congestion effects of the continuous truck arrivals into the queue. The trucks are made to enter the gate in the order they arrive at the terminal. The MINEVENTTIMES+TGATEINVARIANCE configuration parameter gives the value in seconds for the simulation to wait before recording the time that the truck enters the terminal gates. If USERNDTIMES is set to "Y" then a random number of seconds from 0 to 9 is generated using the RAND () SQL function and added to TGATEINVARIANCE instead of MINEVENTTIMES. Assigning a time to the TruckGateIn column of the ServiceQueues table for the specified truck signifies the truck entering the gate and moving to the Staging Area.

The AssignEquipmentToTruck.bat process assigns equipment that will load/ offload the truck it is assigned to. In order for a truck to be assigned an equipment, the truck must have a commodity linked to it and already be located at the Staging Area. In addition, there must be an equipment available to service the truck i.e. the equipment that is to be allocated cannot be currently servicing another vehicle since the time taken for an equipment to service a truck is not truly known as factors such as driver performance, breakdowns and accidents could impact on the service time period. Therefore, allocating equipment to a truck that may never be serviced creates a potential bottleneck at the Staging Area. In order to alleviate this risk, it is a more efficient process to allocate equipment that is currently available. The equipment is allocated to the truck in the order of the earliest one made available. This also ensures that all equipment is equally utilised. Updating the EqpId column of the ServiceQueues table with an equipment id for the specified truck signifies the equipment is assigned to service the truck.

Once the truck is at the Staging Area and assigned an equipment, the truck can move to an available loading bay. This activity is performed by the MoveTruckToLoadingBay.bat process. The truck is moved to the Loading Bay in the order of the earliest one arriving at the Staging Area that has an equipment allocated to it. Assigning a time to the TruckAtLoadingBay column of the ServiceQueues table signifies the move to the Loading Bay.

The equipment assigned to the truck will be used to service it once the truck is at the relevant loading bay. The activity of the equipment servicing the truck once it arrives at the loading bay is performed by the ServiceQueuedTruckEQ*n*.bat process, where *n* is the equipment number ranging from 1 to 9. This method of servicing the trucks ensures each Straddle Carrier equipment has its own process thread to mimic the real-world scenario of the equipment operating without other process dependencies.

The simulation has a maximum of nine Straddle Carriers with three being active by default and six remaining inactive but available to accommodate capacity demands. When Caudus predicts a congested situation, additional equipment is activated by setting the EqpAvail indicator on the EquipmentMasters table to "Y" to accommodate the workload in order to alleviate the queue capacity. Once the capacity demand drops to below the TQSAFELIMIT, Caudus gradually resets the active straddles back to its default number. If the increase in equipment does not alleviate the congestion, then the CC-BPN SBB is used to stop the truck arrivals to the terminal until the congestion subsides. This action is simulated by setting the STOPTRCKARVLS indicator value to "Y". Once the queue TQSAFELIMIT is returned, the indicator is reset so traffic can flow as normal.

The activation of multiple equipment also activates additional Loading Bays since only one equipment can service one truck at a time. An equipment can only service the truck it is assigned to and the assignment of the equipment to the truck is accomplished by the AssignEquipmentToTruck.bat process, previously discussed. Also, multiple equipment cannot service the same truck in a single operations leg i.e. if a truck has cargo to be loaded only, offloaded only, or both offloading a single commodity and then loading another commodity onto the same truck, then the equipment that started the service operation will also be the one that concludes the operation.

The service leg for each operation comprises two event times. For the Offload operation, the cargo to be offloaded must also be stacked in the stacking yard. Therefore, there is an Offload Event Time and a Stacking Event Time for the Offload operations leg. Similarly, for the Load operations leg, the cargo must be fetched from the stacking yard before it is loaded onto the truck. Therefore, the Load operations will have a Fetch Event Time and a Load Event Time. Similarly, for dual operations, there are four event times viz. Offload Event Time and Stacking Event Time for the offloaded cargo, and Fetch Event Time and Load Event Time for loading cargo. By default, these event times are all set at 3 seconds for this simulation linked to each Straddle Carrier and may vary if the USERNDTIMES configuration parameter is set to "Y". The event times are given by the Configuration Parameters *ST00n-FETCHTIME, ST00n-LDTIME, ST00n-OFFLDTIME* and *ST00n-STACKTIME* where n is 1..9 and refers to the equipment number that the time is linked to. Increasing or decreasing these times in the simulation can demonstrate the direct impact it has on the truck queue level. Increasing these event times causes the truck service operation to take longer to complete thus causing the performance levels to drop. This in turn drops the Truck Service Rate (θRs) below the Truck Queue Rate (θRq), which is the condition that leads to congestion (3.9).

Updating the columns EqpCommodityFetchTime, EqpLoadTime, EqpOffLoadTime and EqpCommodityStackTime of the ServiceQueues table with the service times for the specified truck signifies the relevant service performed.

As each straddle performs its service operation, the activity is recorded in the equipment's history, EquipmentHistory table. This functionality enables the equipment trends and pattern analysis capability for potential future works in the AI Learning Algorithm SBBs.

Once the truck has completed being serviced by the equipment, it must leave the Loading Bay and make its way towards the terminal exit. This is achieved by the MoveTruckFromLoadingBay.bat process. For simulation purposes only, the time allocated for a truck to move from the Loading Bay towards the exit gates of the terminal is given by a maximum of (MINEVENTTIMES+1) seconds since there is no operational activities to delay this process. The times may vary depending on whether the USERNDTIMES configuration parameter is set to "Y". The truck that is serviced first leaves the loading bays first. Also, the trucks will only leave the Loading Bays provided there is capacity for it to be accommodated at the terminal exit gate. This is to mimic an overflow scenario due to possible congestion at the exit point (3.19). Updating the TruckLeaveLoadingBay column of the ServiceQueues table with the relevant time signifies the truck leaving the loading bay.

The ExitTruckOutOfGate.bat process reproduces the action of the truck leaving through the exit gates as its business is concluded within the terminal. The process sets the status of the truck to COMPLETED on the ServiceQueues table and marks the truck as once again being available for additional service requests if required in the TruckMasters table. For simulation purposes only, the time allocated for the truck to leaving the terminal is given by a maximum of (MINEVENTTIMES+1) seconds since there is no operational activities to delay this process. This time may vary depending on whether the USERNDTIMES configuration parameter is set to "Y". The truck exits the terminal in the same order it leaves the loading bay. Updating the TruckGateOut column of the ServiceQueues table with the relevant time signifies the truck leaving the terminal.

With the master data for the equipment, cargo and transport all being generic, this simulation, and by extension, Caudus lends itself to any cargo movement environment. Merely adjusting the event timings and configuration data relevant to the use case being studied will demonstrate the effectiveness of the solution to that environment.

Chapter 5: Implementation Results

The Caudus Simulation has been exclusively designed and developed for this dissertation in order to demonstrate the effectiveness of Caudus in addressing traffic congestion and throughput using the algorithms derived for this study. This is achieved by the various use cases which mimic the different real-world port traffic scenarios. Section 5.1. Use Case A provides results of the simulation for the control test or benchmark, Section 5.2. Use Case B documents the comparative results of the Caudus disabled vs Caudus enabled simulation in a congestion situation, Section 5.3. Use Case C provides the results for the exception algorithms tested, and Section 5.4. Additional Tests provides details for supplementary tests and insights.

5.1. Use Case A

This use case simulates the ideal situation where there is no congestion, also referred to as the Benchmark. Two tests are run in this example, one without Caudus enabled (A1) and the second with Caudus enabled (A2). A1 and A2 results are then represented on separate graphs to determine the variation across outputs. Since there is no congestion and Caudus' objective is to prevent congestion, Caudus is not expected to intervene and the result across tests is expected to be the same.

5.1.1. The Benchmark (A1)

Scenario: The Ideal Situation - Simulation is run without activating Caudus. This scenario demonstrates the status quo of the environment without any optimisation implemented.

Key Configuration Parameters:
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)

θRq $\approx$ 0.167 trucks/sec i.e. MINEVENTTIMES+TARRVARIANCE per truck
θRs $\approx$ 0.333 trucks/sec (min) for single move types i.e. (MINEVENTTIMES + Fetch + Load) OR (MINEVENTTIMES + Offload + Stack) seconds per three truck (three straddles).
$\approx$ 0.2 trucks/sec (max) for DUAL move types i.e. (MINEVENTTIMES + Fetch + Load) AND (MINEVENTTIMES + Offload + Stack) seconds per three truck (three straddles).

Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: No congestion build-up for the duration since $\theta Rq < \theta Rs$

5.1.1.1. Results (A1)

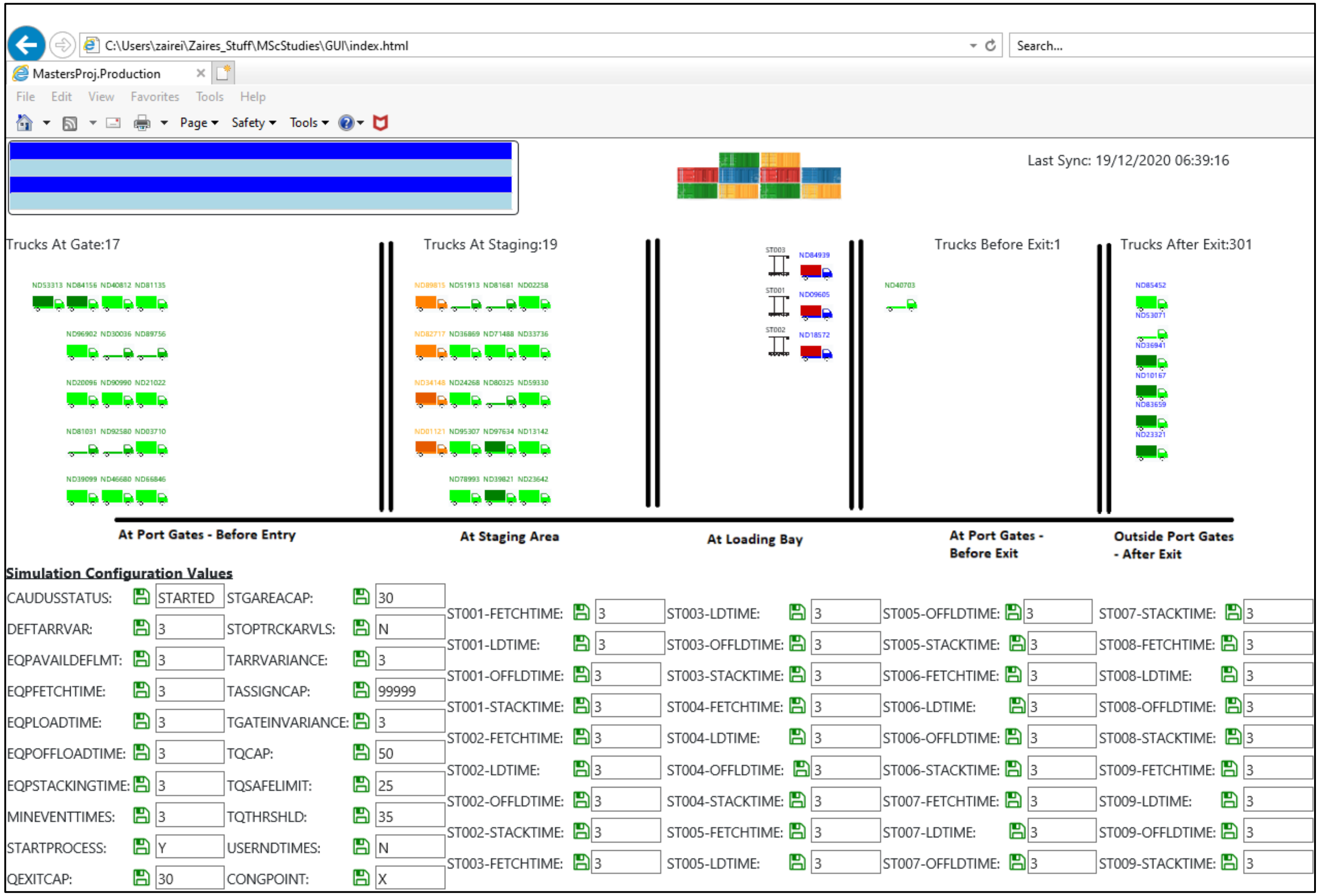

Figure 5.1: A1 Simulation - 30 Minutes into Simulation

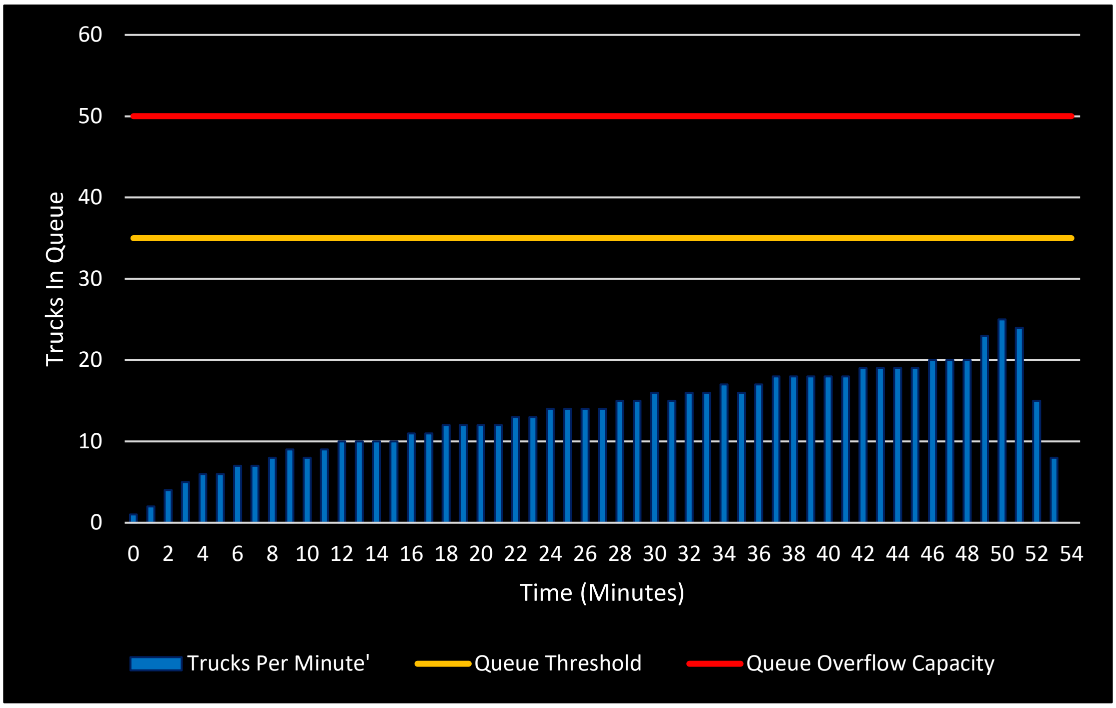

Figure 5.2: A1 Simulation – No. of Trucks in Queue Over Time Without Optimisation

Actual Results: No congestion noted as Trucks per minute into the Queue does not reach Queue Threshold nor Queue Capacity.

Total Simulation Time: 53 minutes

5.1.2. The Benchmark with Caudus Active (A2)

Scenario: Simulation mimics Test A1 (Benchmark) parameters but WITH Caudus activated.

Key Configuration Parameters:
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)

θRq ≈ 0.167 trucks/sec i.e. MINEVENTTIMES+TARRVARIANCE per truck
θRs ≈ 0.333 trucks/sec (min) for single move types i.e. (MINEVENTTIMES + Fetch + Load) OR (MINEVENTTIMES + Offload + Stack) seconds per three truck (three straddles).
≈ 0.2 trucks/sec (max) for DUAL move types i.e. (MINEVENTTIMES + Fetch + Load) AND (MINEVENTTIMES + Offload + Stack) seconds per three truck (three straddles).

Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: No congestion build-up for the duration since $\theta Rq < \theta Rs$. Caudus "Monitoring in Progress" to be noted on the Dashboard.

5.1.2.1. Results – A2

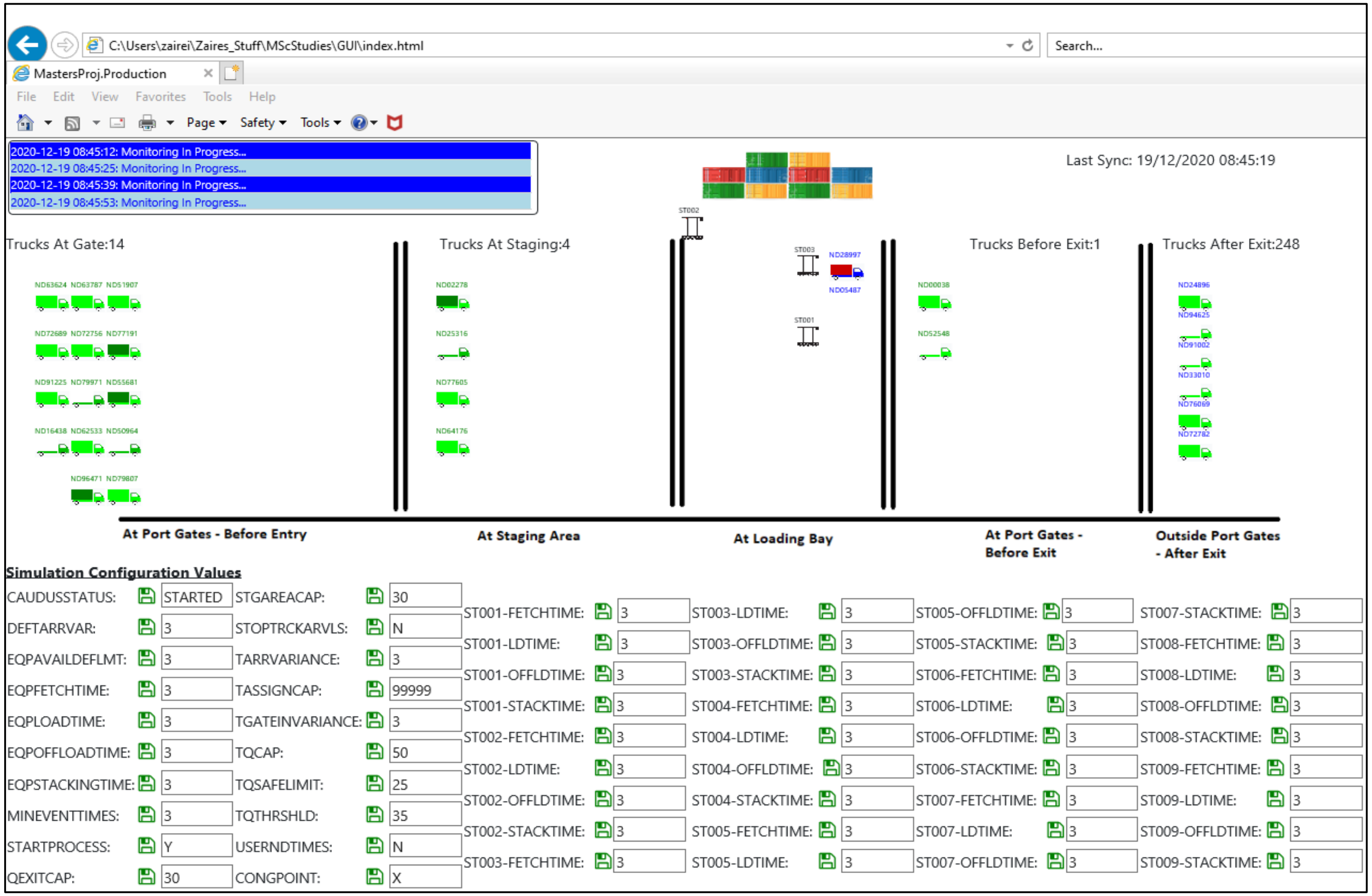

Figure 5.3: A2 Simulation - 30 Minutes into Simulation

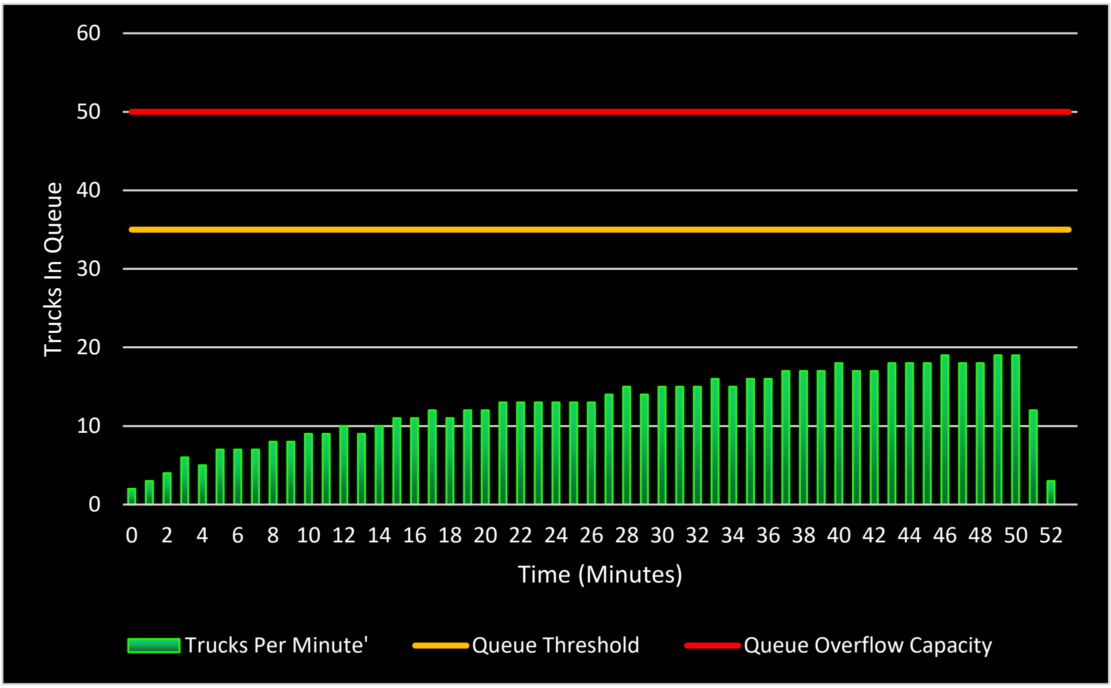

Figure 5.4: A2 Simulation – No. of Trucks in Queue Over Time With Caudus Activated

Actual Results: No congestion noted as Trucks per minute into the Queue does not reach Queue Threshold nor Queue Capacity. As a result, no optimisation necessary and Caudus remains in "Monitoring in Progress" state.

Although there is no congestion experienced in Simulations A1 and A2, it must be noted that capacity at the Staging Area is significantly better managed with Caudus activated (A2).

Total Time: 53 Minutes

5.1.3. Discussion

Use Case A demonstrated the ideal situation with and without Caudus active. Test A1 was the benchmark for an ideal situation where the operational efficiency of the truck service rate accommodated the truck queue rate such that,

$$\theta Rq < \theta Rs$$

Test A2 used the same parameters as A1, except with Caudus active. The results of A1 and A2 were represented on Figures 5.2 and 5.4 respectively. Note, both graphs were exactly the same, which was the expected outcome. Since Test A2 did not experience any congestion and Caudus' objective is to prevent congestion, there was no intervention required and the resulting outcomes were exactly the same. This use case also validated Caudus' credibility. The outcome of Use Case A was as expected.

5.2. Use Case B

This use case simulates an exacerbated situation where congestion is at an exorbitant level. Test B1 will demonstrate the performance without any optimisation while Test B2 will use the same parameters as B1, except with Caudus active. B1 and B2 results are then represented on separate graphs, Figures 5.7 and 5.12 to indicate the variants across outputs. Due to congestion, Caudus is expected to intervene in B2 thereby reducing the duration of the congestion as well as improving the throughput. Results of both tests are further consolidated on Figure 5.13 to demonstrate the effectiveness of Caudus.

5.2.1. Exaggerated Situation (B1)

Scenario: Exaggerated Situation - Simulation is run without activating Caudus. This scenario demonstrates the impact on traffic congestion without any optimisation implemented.

Key Configuration Parameters:
MINEVENTTIMES = 3
TARRVARIANCE = 1
TGATEINVARIANCE = 1
No of Equipment In Use= 2
No of Commodities = 500
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)

θRq ≈ 0.25 trucks/sec i.e. MINEVENTTIMES+TARRVARIANCE per truck
θRs ≈ 0.222 trucks/sec (min) for single move types i.e. (MINEVENTTIMES + Fetch + Load) OR (MINEVENTTIMES + Offload + Stack) seconds per two trucks (two straddles).
≈ 0.133 trucks/sec (max) for DUAL move types i.e. (MINEVENTTIMES + Fetch + Load) AND (MINEVENTTIMES + Offload + Stack) seconds per two trucks (two straddles).

Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: Congestion expected for the duration since $\theta Rq > \theta Rs$

5.2.1.1. Results – B1

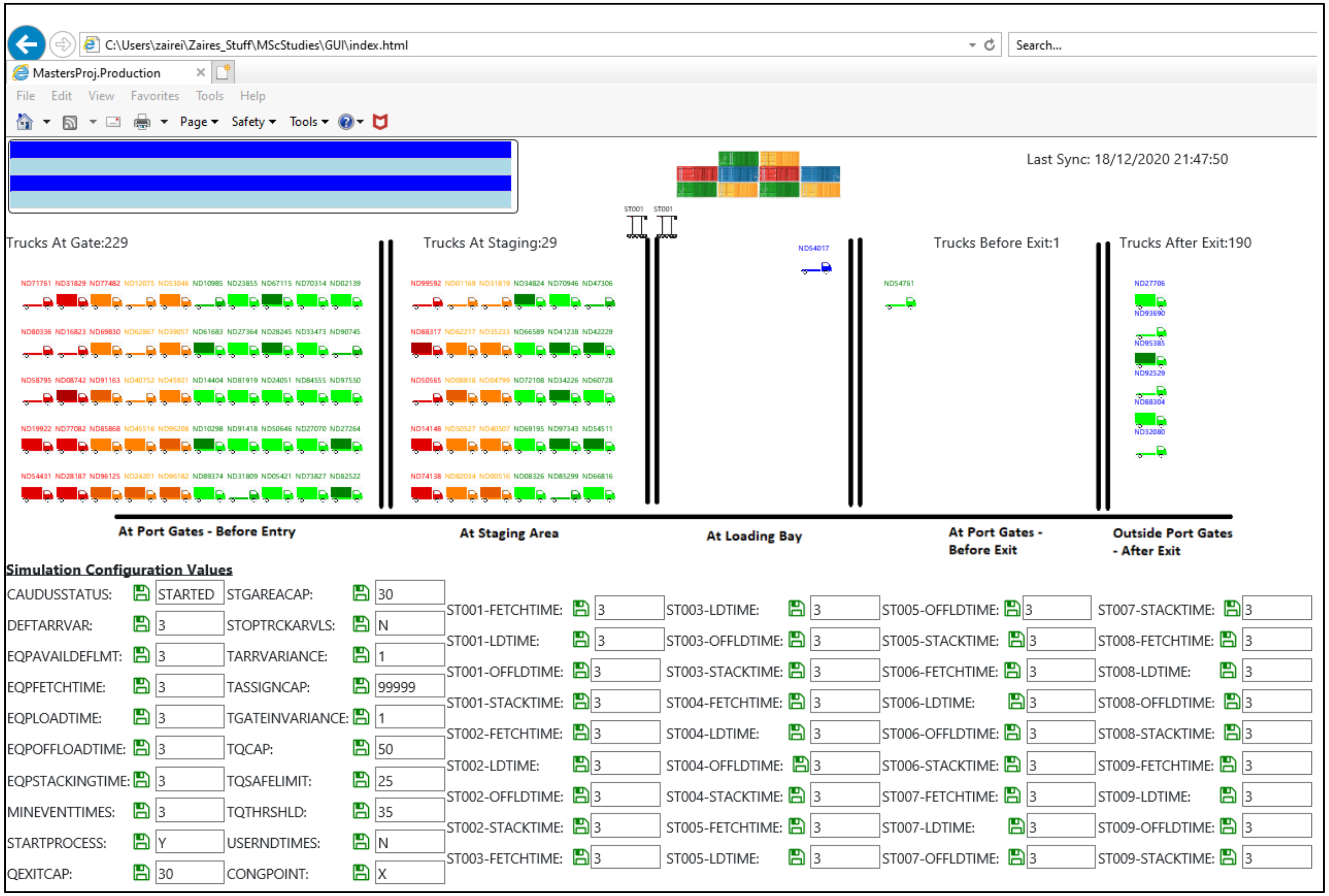

Figure 5.5: B1 Simulation 1 - 30 Minutes into Simulation

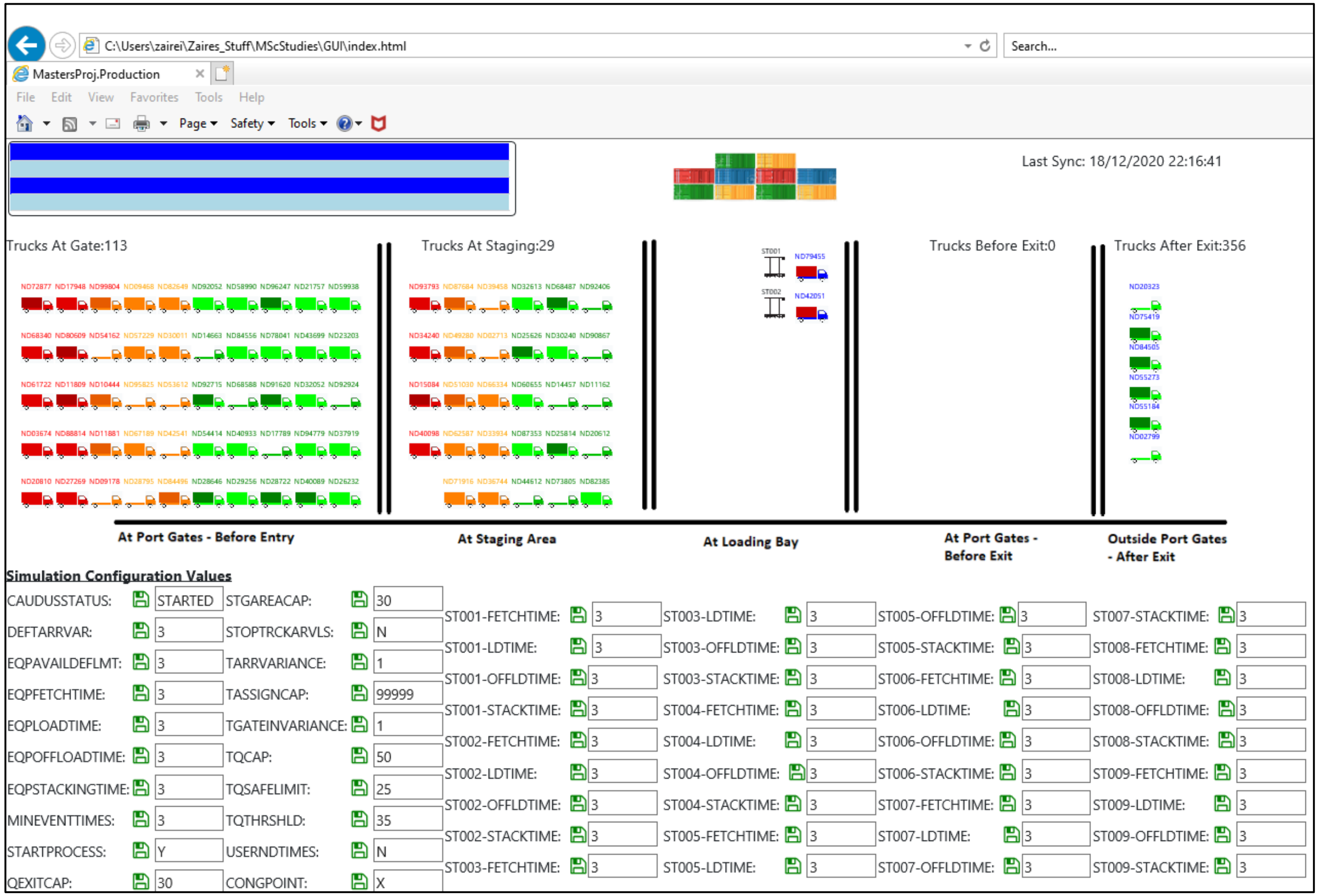

Figure 5.6: B1 Simulation 2 - 60 Minutes into Simulation

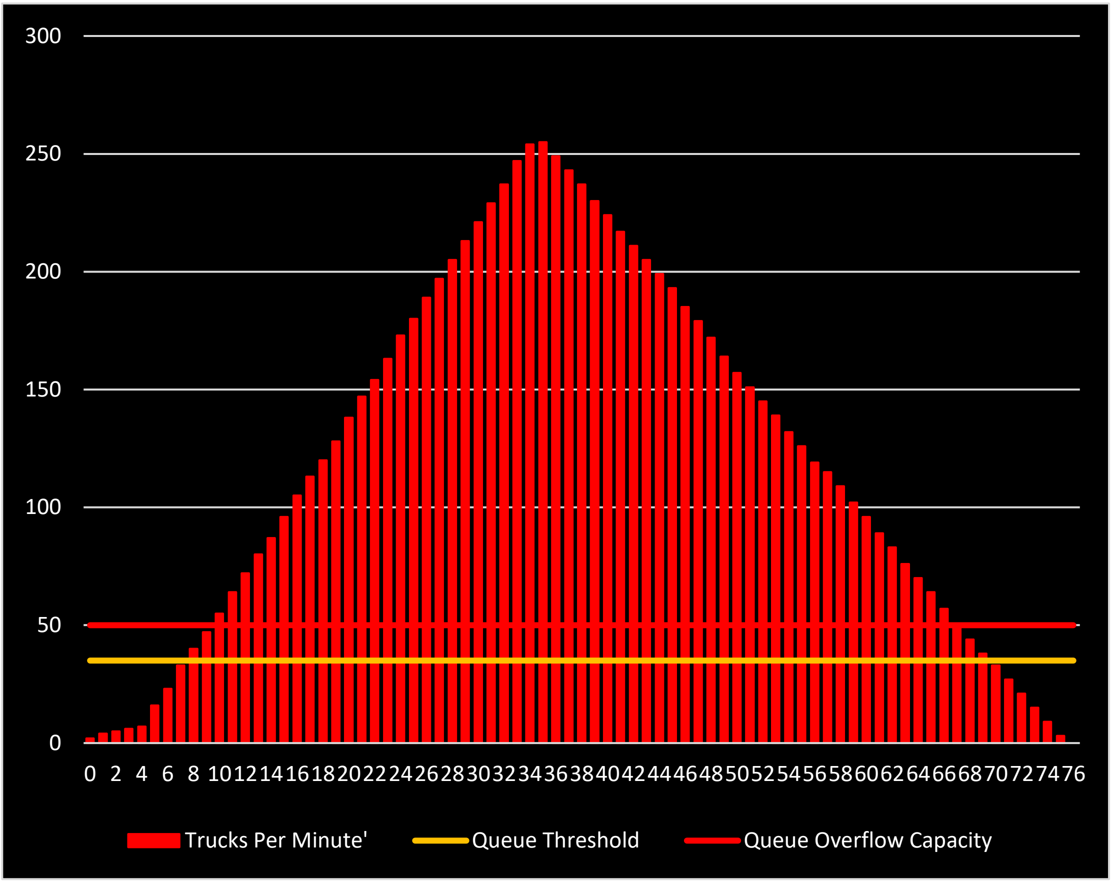

Figure 5.7: B1 Simulation – No. of Trucks in Queue Over Time Without Optimisation

Actual Results: Congestion noted after 10 minutes and lasts for 56 minutes before beginning to normalise.

Total Simulation Time: 76 Minutes

5.2.2. Exaggerated Situation with Caudus Active (B2)

Scenario: Exaggerated Situation with Caudus - The simulation is run with Caudus activated. This scenario demonstrates outcome of traffic congestion and throughput with optimisation implemented.

Key Configuration Parameters:

MINEVENTTIMES = 3
TARRVARIANCE = 1
TGATEINVARIANCE =1
No of Equipment In Use= 2
No of Commodities = 500
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)

θRq $\approx$ 0.25 trucks/sec i.e. MINEVENTTIMES+TARRVARIANCE per truck
θRs (Initial) $\approx$ 0.222 trucks/sec (min) for single move types i.e. (MINEVENTTIMES + Fetch + Load) OR (MINEVENTTIMES + Offload + Stack) seconds per two truck (two straddles).
$\approx$ 0.133 trucks/sec (max) for DUAL move types i.e. (MINEVENTTIMES + Fetch + Load) AND (MINEVENTTIMES + Offload + Stack) seconds per two truck (two straddles).

Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: Congestion expected since θRq > θRs. Caudus thereafter optimises the operation to normalise traffic.

5.2.2.1. Results – B2

At Simulation Start: At 9:37am, TARRVARIANCE is set to 1 second to exacerbate the situation ensuring congestion is imminent. Also, there are only two equipment that is active to force the congestion. Equipment operation time remains at 3 second average.

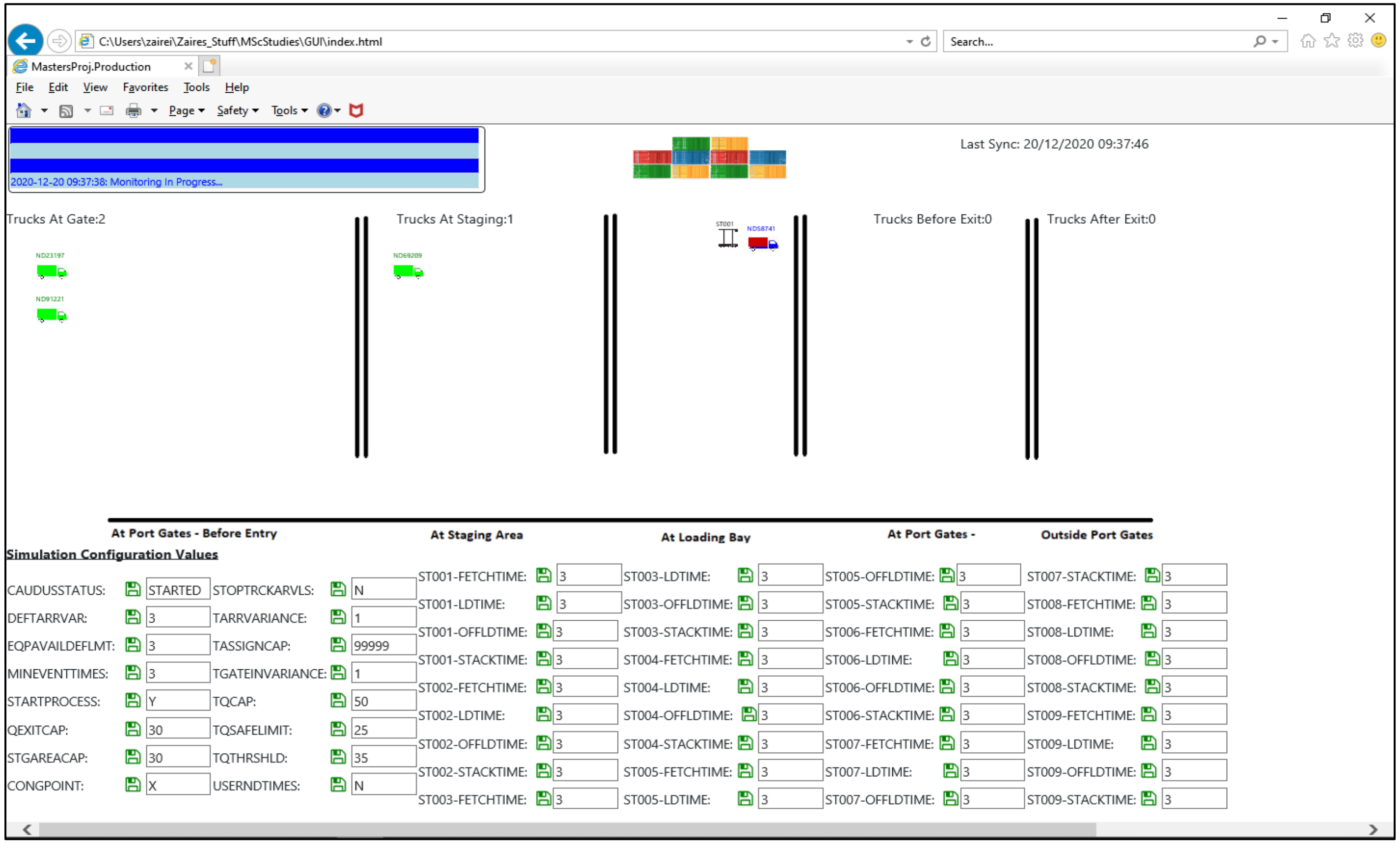

Figure 5.8: B2 Simulation 1 - At Simulation Start

At 9:46am, queue threshold has been breached but queue overflow capacity is still intact. As a result, Caudus initiate counter measures by gradually increasing equipment to manage the congestion. Once equipment has been added, Caudus monitors for a minute to determine whether the new θRq is better than the old θRq. Note the additional equipment servicing the trucks as well as the Dashboard message.

Figure 5.9: B2 Simulation 2

At 9:52am, Caudus continues to add available equipment to the operations until all equipment is utilised in order to alleviate the congestion. This may take time to display an improvement since traffic is dynamic and improvements is a lagging indicator. If Queue Overflow Capacity is breached, Caudus requests a "STOP" from the truck companies (CC-BPN SBB) to halt sending trucks to the terminal. This is denoted by the STOPTRCKARVLS indicator below.

Figure 5.10: B2 Simulation 3

At 10:02am, the traffic situation has normalised and therefore the equipment defaults can be reset so not to over-utilise the equipment. Also, truck-companies and customers are requested to start sending trucks to the terminal, denoted by the STOPTRCKARVLS indicator set to "N". If traffic builds up again, then Caudus will re-introduce equipment to manage the inflow.

Figure 5.11: B2 Simulation 4

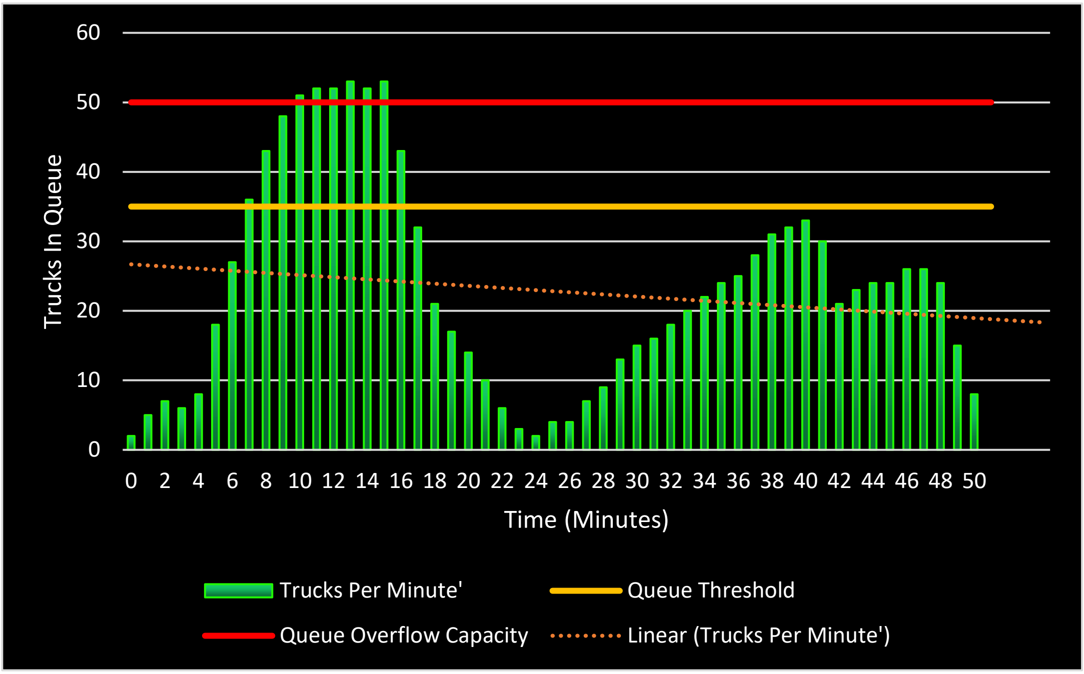

Figure 5.12: B2 Simulation – No. of Trucks in Queue Over Time With Caudus Activated

Actual Results: Congestion noted after 10 minutes and lasts for 5 minutes before beginning to normalise.

Total Simulation Time: 50 Minutes

Note: The parameters were deliberately set to force the Queue overflow in order to demonstrate Caudus' effectiveness is managing congestion through optimisation. B2 also demonstrates that congestion cannot be managed through operational efficiency alone and at times integration into CC-BPN will be required.

5.2.3. Caudus vs No Caudus

With all parameters initially aligned for test cases B1 and B2, Figure 5.13 clearly demonstrates Caudus' optimisation capabilities and confirmation that the underlying algorithms developed is an effective solution to managing congestion and throughput through optimisation.

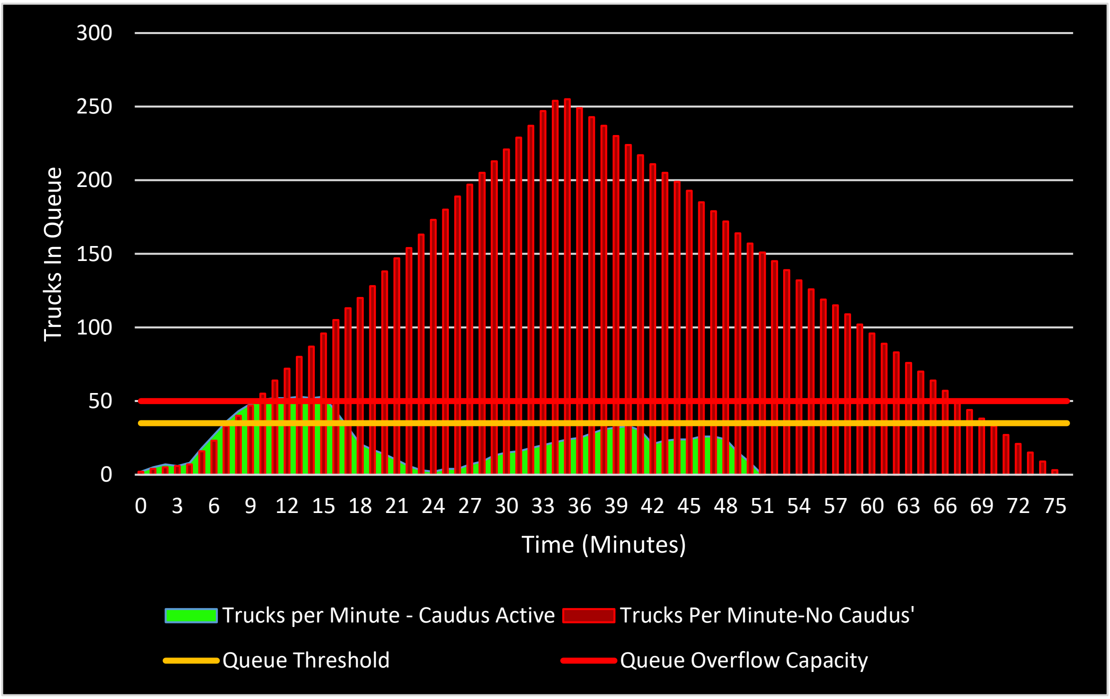

Figure 5.13: No. of Trucks in Queue Over Time With Caudus Disabled Vs Caudus Enabled

5.2.4. Discussion

Use Case B tested an extremely congested situation without and with Caudus active in order to demonstrate the effectiveness of Caudus. Parameters in Test B1 were set to force congestion by ensuring operational performance could not contend with the truck arrival rate such that,

$$\theta Rq > \theta Rs$$

Test B2 used the same parameters as B1, except with Caudus active. The results of B1 and B2 were represented on Figures 5.7 and 5.12 respectively with the consolidated results plotted on Figure 5.13.

In Test B1, where Caudus had not featured, congestion was noted after 10 minutes and lasted for 56 minutes. The total throughput time was 76 minutes. Test B2 had Caudus monitoring the queue. Once the queue threshold was breached after 7 minutes, additional equipment was gradually added to improve the situation. This is evident in Figure 5.9. The gradual introduction of additional equipment mimics the real-world situation where traffic is dynamic, and a brief unknown situation may have occurred during this period. In order to prevent "false-positives" in these situations, it would be recommended to gradually increase performance parameters to determine whether the difference is made.

By the time the situation had escalated to boiling point (50 Trucks in Queue exceeded), the full available fleet was mobilised as well as engagement with third-parties to delay/ stop truck arrivals until the situation is contained. This highlights Caudus' optimisation ability through operational performance management as well as integration with CC-BPN SBB in exceptional situations. Caudus' efforts pay off in the 17^{th} minute where traffic is normalised. Thereafter, the situation is well managed for the duration ensuring the queue does not overflow. This scenario demonstrates the Preventive and Reactive objective functions achieved by Caudus.

The total service duration with Caudus active lasted 50 minutes, which is a 34% improvement to when Caudus was not active during a congested situation.

Figure 5.12 is a typical sine wave pattern with peaks and troughs representative of the real-world. The orange Linear trend line displays the consistent decline in the queue occupancy demonstrating Caudus' effectiveness in managing congestion and throughput through optimisation.

Table 5.1: Caudus Disabled vs Caudus Enabled

Performance Measure	Caudus Disabled (minutes)	Caudus Enabled (minutes)	% Improvement
Congestion Duration	56	5	91
Throughput Duration	76	50	34

Table 5.1 summarizes the results of Use Case B - Caudus Disabled vs Caudus Enabled. The table clearly highlights the benefit of a Caudus-enabled environment for addressing congestion and throughput. The outcome of Use Case B was as expected.

5.3. Use Case C - Exception Monitoring

5.3.1. Test BGI - Before Gate In Bottleneck Point

Scenario: Congestion point at BGI – This scenario tests the performance of Caudus when a bottleneck is simulated at the Before Gate In point.

Key Configuration Parameters:
CONGPOINT: BGI
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3

Expected Results: Caudus identifies a potential problem in BGI area and demonstrates capability to integrate with CC-BPN SBB. This integration capability is represented in the form of a notification displayed in the simulation dashboard confirming that Caudus has identified a problem.

5.3.1.1. Results -BGI Bottleneck Point

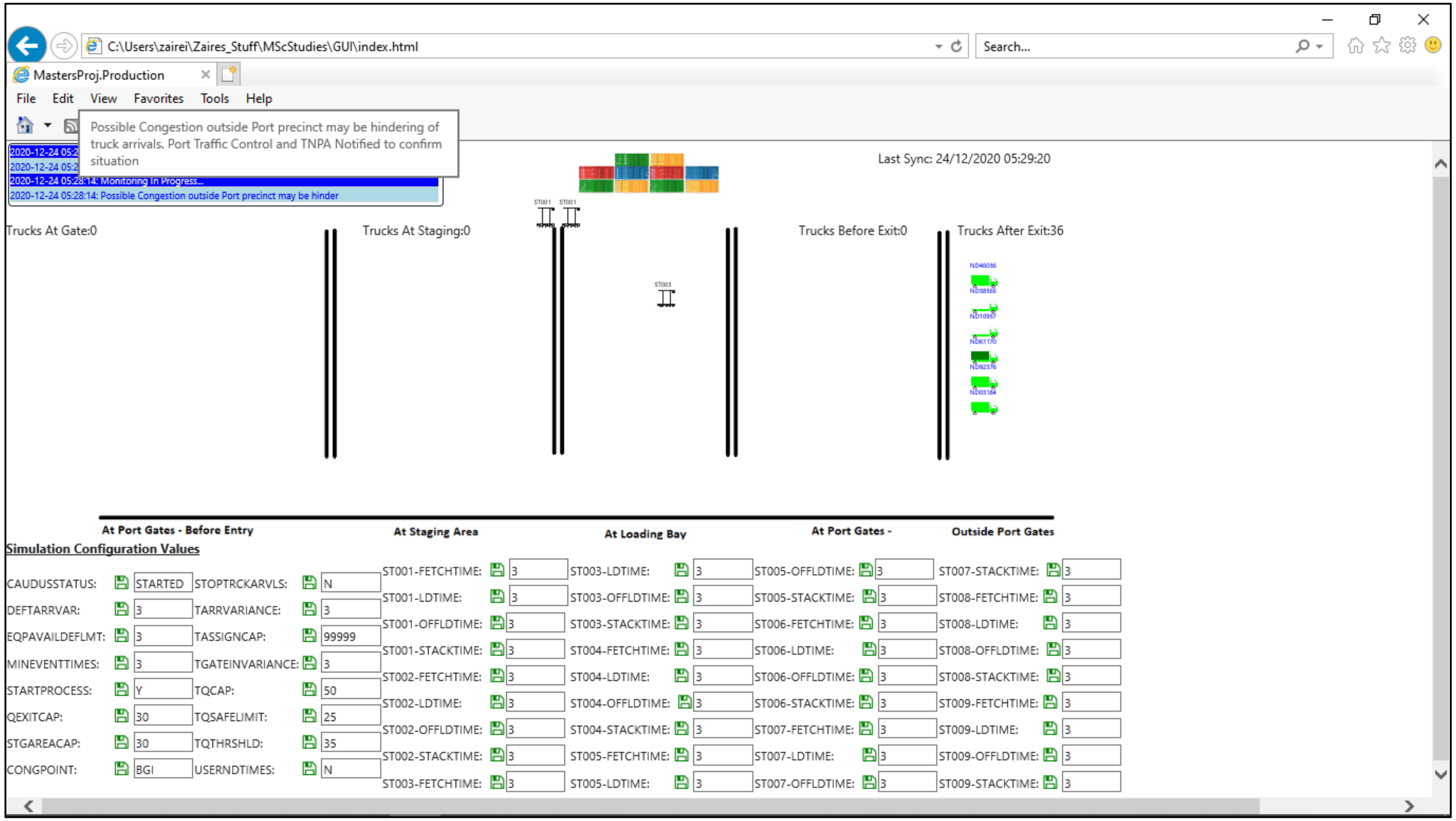

Figure 5.14: BGI Simulation

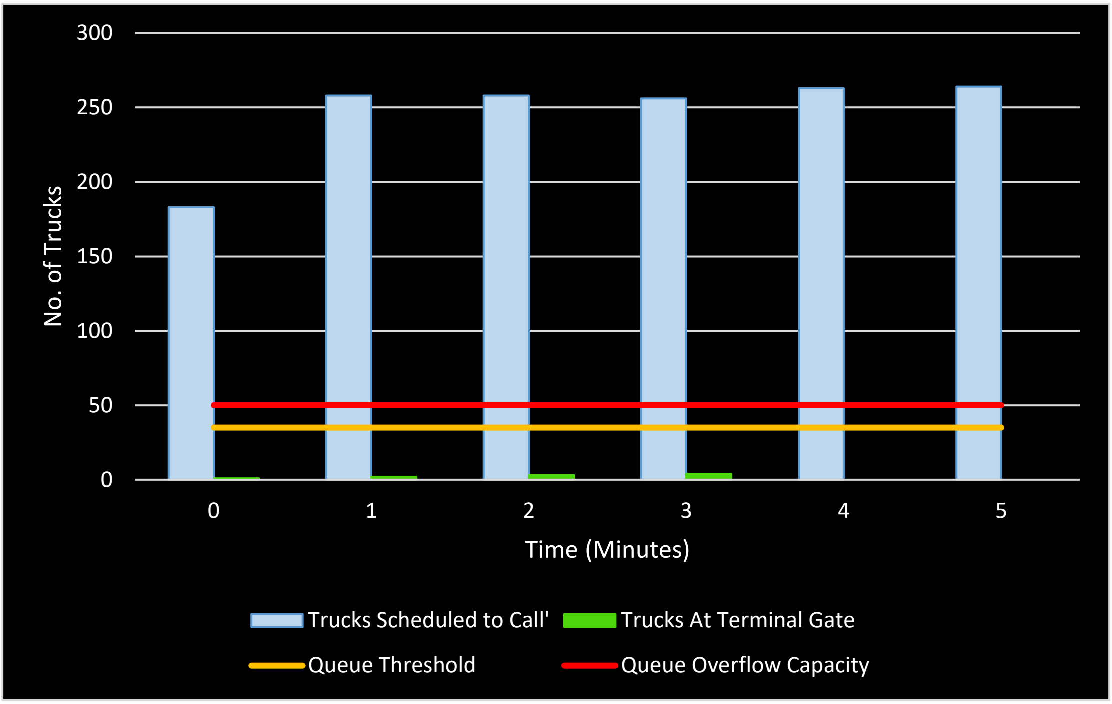

Figure 5.15: BGI BPT Simulation (Exception Monitoring) - No. of Trucks Scheduled to call at Terminal Gates Vs Actual Trucks at Terminal Gates over Time

Actual Results: BGI Congestion Point: The simulation data plots Figure 5.15 thus confirming the algorithm for each bottleneck point:

$$\Delta\tau\left(\Delta\beta pt_n - T_{\beta ptn\_max}\right) \to 0 \;\; as \;\; \Delta\tau(\beta pt_{n+1}) \to 0$$

i.e. as trucks are assigned commodities to call at the terminal increases (Trucks Scheduled to Call), the actual trucks calling at the terminal (Trucks At Terminal Gate) decreases over time (3.18) thus suggesting an incident has occurred outside the port precinct that is hindering the truck arrivals to the terminal. Caudus publishes a notification (Figure 5.14) of the possible problem. The notification is representative of an integration point into CC-BPN to confirm and employ mitigating actions to alleviate the exceptional condition causing the bottleneck such as breakdowns and accidents.

5.3.2. Test AG - At Gate Bottleneck Point

Scenario: Congestion point at AG – This scenario tests the performance of Caudus when a bottleneck is simulated At Gate point.

Key Configuration Parameters:
CONGPOINT: AG
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3

Expected Results: Caudus identifies a potential problem in AG area and demonstrates capability to integrate with CC-BPN SBB. This integration capability is represented in the form of a notification displayed in the simulation dashboard confirming that Caudus has identified a problem.

5.3.2.1. Results -AG Bottleneck Point

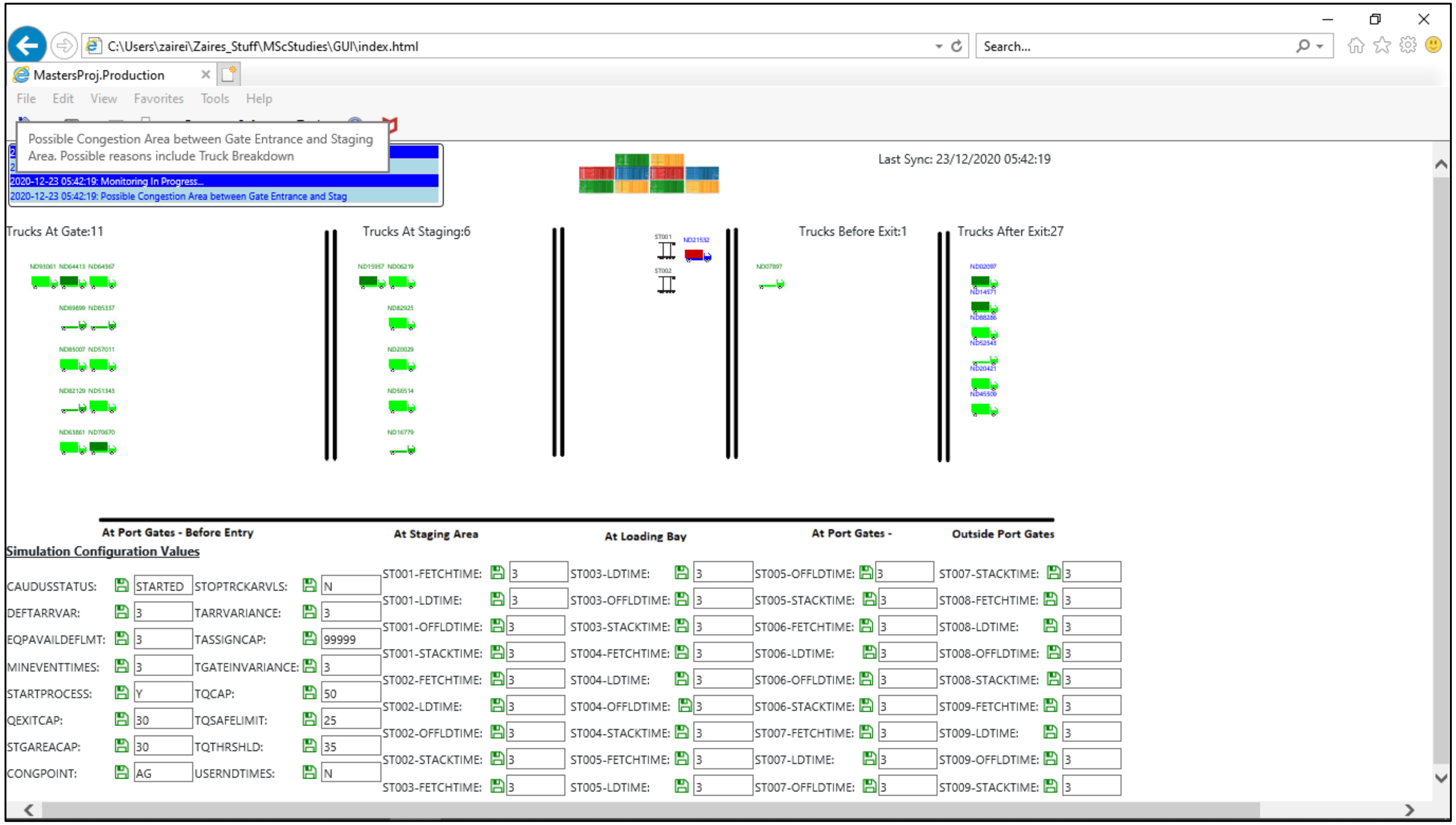

Figure 5.16: AG Simulation

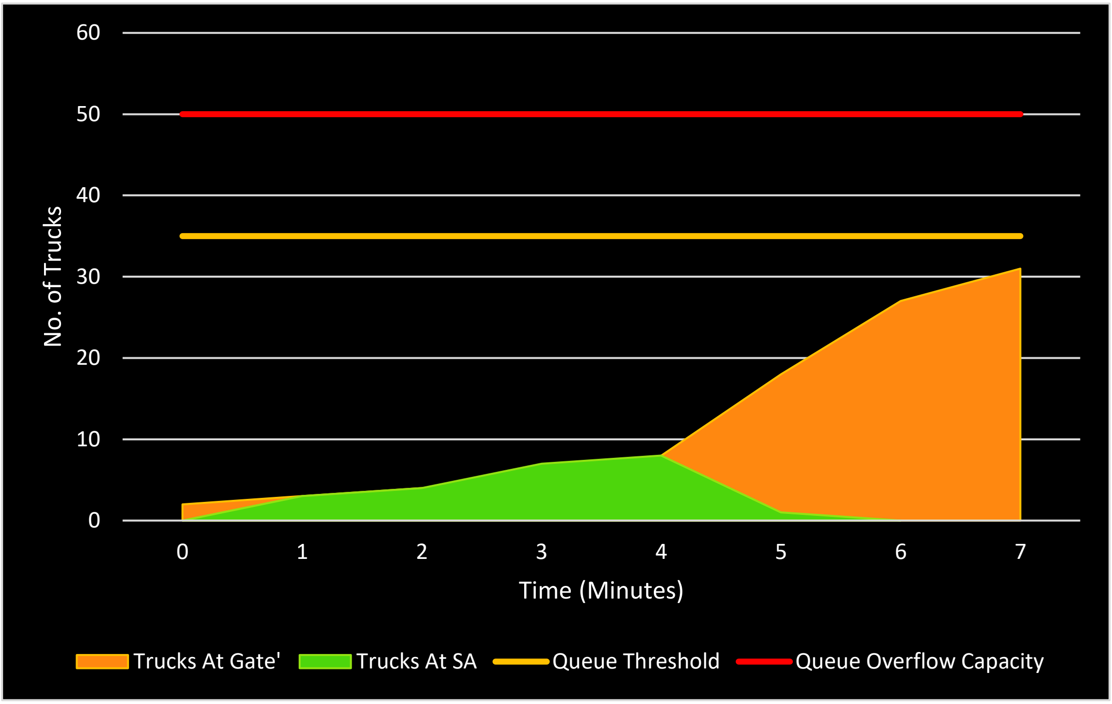

Figure 5.17: AG BPT Simulation (Exception Monitoring) - No. of Trucks At Gate Vs No. of Trucks at Staging Area over Time

Actual Results: AG Congestion Point: The simulation data plots the Figure 5.17 thus confirming the algorithm for each bottleneck point:

$$\Delta\tau\left(\beta pt_n - T_{\beta ptn\_max}\right) \to 0 \;\; as \;\; \Delta\tau(\beta pt_{n+1}) \to 0$$

i.e. as trucks calling at the terminal increases (Trucks At Gate), the trucks being gated into the terminal (Trucks At SA) decreases over time (3.18) thus suggesting an incident has occurred between the Gate Entrance and Staging Area preventing the trucks from entering the terminal. Caudus publishes a notification (Figure 5.16) of the possible problem. The notification is representative of an integration point into CC-BPN to confirm and employ mitigating actions to alleviate the exceptional condition causing the bottleneck such as breakdowns and accidents.

5.3.3. Test SA – Staging Area Bottleneck Point

Scenario: Congestion point at SA – This scenario tests the performance of Caudus when a bottleneck is simulated at the Staging Area point.

Key Configuration Parameters:
CONGPOINT: SA
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3

Expected Results: Caudus identifies a potential problem in SA area and demonstrates capability to integrate with CC-BPN SBB. This integration capability is represented in the form of a notification displayed in the simulation dashboard confirming that Caudus has identified a problem.

5.3.3.1. Results -SA Bottleneck Point

Figure 5.18: SA Simulation

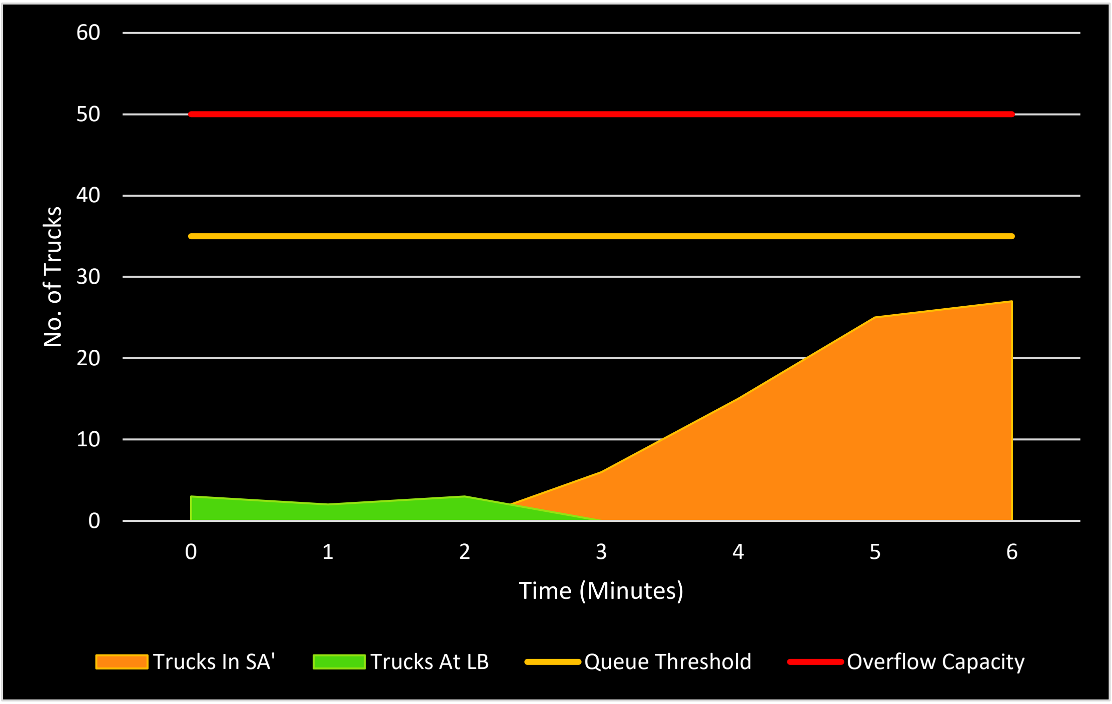

Figure 5.19: SA BPT Simulation (Exception Monitoring) – No. of Trucks at Staging Area Vs No. of Trucks at Loading Bay over Time

Actual Results: SA Congestion Point: The simulation data plots Figure 5.19 thus confirming the algorithm for each bottleneck point:

$$\Delta\tau\left(\beta pt_n - T_{\beta ptn\_max}\right) \to 0 \;\; \textit{as} \;\; \Delta\tau(\beta pt_{n+1}) \to 0$$

i.e. as trucks entering the terminal increases (Trucks in SA), the trucks moving to the Loading Bays (Trucks at LB) decreases over time (3.18) thus suggesting an incident has occurred at the Loading Bays that is preventing the trucks from progressing from the staging area. The notification in the dashboard is representative of an integration point into CC-BPN to confirm and employ mitigating actions to alleviate the exceptional condition causing the bottleneck such as breakdowns and accidents.

5.3.4. Test LB – Loading Bay Bottleneck Point

Scenario: Congestion point at LB – This scenario tests the performance of Caudus when a bottleneck is simulated at the Loading Bay point.

Key Configuration Parameters:
CONGPOINT: LB
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3

Expected Results: Caudus identifies a potential problem in LB area and demonstrates capability to integrate with CC-BPN SBB. This integration capability is represented in the form of a notification displayed in the simulation dashboard confirming that Caudus has identified a problem.

5.3.4.1. Results -LB Bottleneck Point

Figure 5.20: LB Simulation

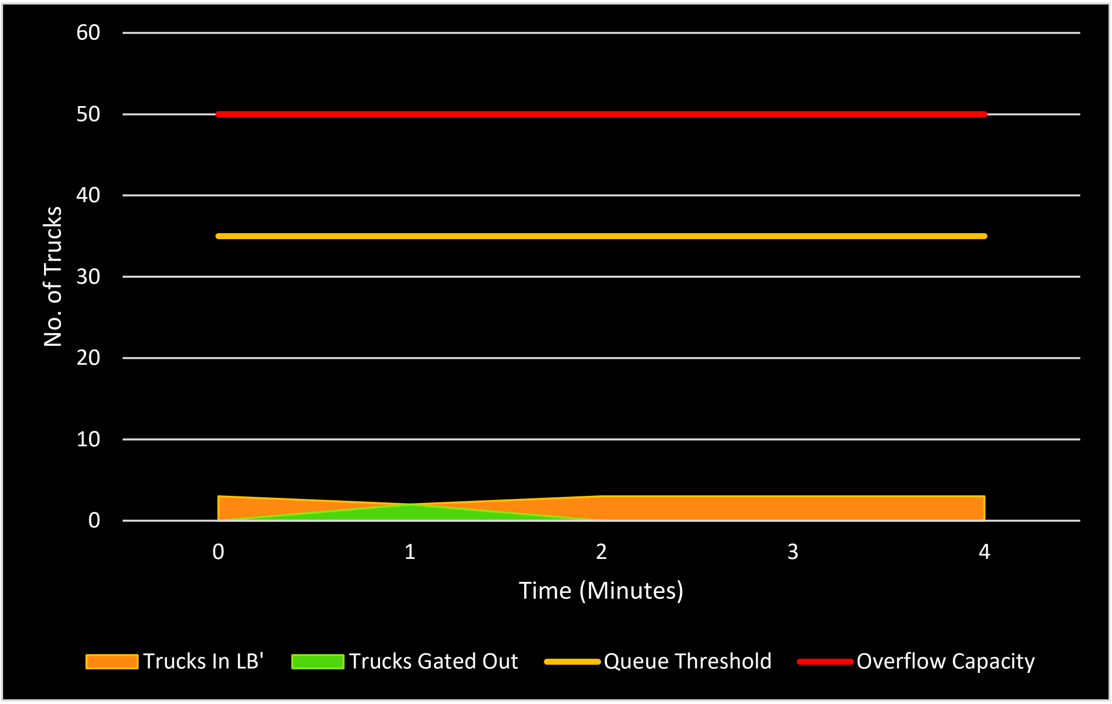

Figure 5.21: LB BPT Simulation (Exception Monitoring) - No. of Trucks at Loading Bay Vs No. of Trucks Gated Out over Time

Actual Results: LB Congestion Point: The simulation data plots Figure 5.21 thus confirming the algorithm for each bottleneck point:

$$\Delta\tau(\beta pt_n - T_{\beta ptn\_max}) \to 0 \ \ as \ \ \Delta\tau(\beta pt_{n+1}) \to 0$$

i.e. as trucks entering the Loading Bays increases (Trucks in LB), the trucks moving to the terminal exit point (Trucks Gated Out) decreases over time (3.18) thus suggesting an incident has occurred between the Loading Bays and terminal exit thus preventing the trucks. The notification in the dashboard is representative of an integration point into CC-BPN to confirm and employ mitigating actions to alleviate the exceptional condition causing the bottleneck such as breakdowns and accidents.

5.3.5. Test AGO - At Gate Out Bottleneck Point

Scenario: Congestion point at AGO – This scenario tests the performance of Caudus when a bottleneck is simulated at the At Gate Out point.

Key Configuration Parameters:
CONGPOINT: AGO
MINEVENTTIMES = 3
TARRVARIANCE = 3
TGATEINVARIANCE = 3
No of Equipment In Use= 3
No of Commodities = 500
Default Average Equipment Service Times = 3

Expected Results: Caudus identifies a potential problem in AGO area and demonstrates capability to integrate with CC-BPN SBB. This integration capability is represented in the form of a notification displayed in the simulation dashboard confirming that Caudus has identified a problem.

5.3.5.1. Results -AGO Bottleneck Point

Figure 5.22: AGO Simulation

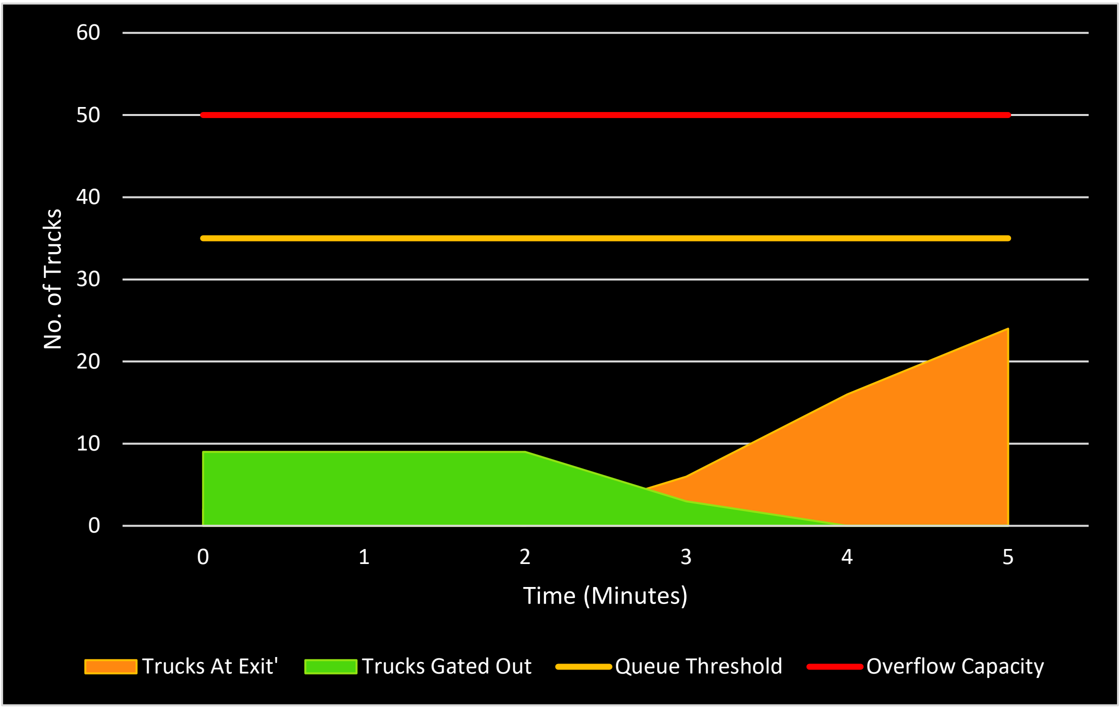

Figure 5.23: AGO BPT Simulation (Exception Monitoring) - No. of Trucks at Exit Vs No. of Trucks Gated Out over Time

Actual Results: AGO Congestion Point: The simulation data plots Figure 5.23 thus confirming the algorithm for each bottleneck point:

$$\Delta\tau\left(\beta pt_n - T_{\beta ptn\_max}\right) \to 0 \;\; as \;\; \Delta\tau(\beta pt_{n+1}) \to 0$$

i.e. as trucks approaching the terminal exit (Trucks At Exit) increases, the actual trucks gated out (Trucks Gated Out) decreases over time (3.18) thus suggesting an incident has occurred at the terminal exit point or outside the terminal gates. This is also depicted in the notification that Caudus publishes (Figure 5.22). The notification is representative of an integration point into CC-BPN to confirm and employ mitigating actions to alleviate the exceptional condition causing the bottleneck such as breakdowns and accidents.

5.3.6. Discussion

Use case C demonstrated Caudus' ability to monitor for exceptional situations that could potentially lead to congestion. Bottlenecks were simulated at strategic points in the port precinct viz. BGI, AG, SA, LB and AGO. Separate simulations were run to test each bottleneck point for the condition,

$$\Delta\tau\left(\beta pt_n - T_{\beta ptn\_max}\right) \to 0 \;\; as \;\; \Delta\tau(\beta pt_{n+1}) \to 0$$

When these conditions were identified in each of the tests, the simulation dashboard reported the findings of an exceptional situation such as a breakdown or accident. This reporting is indicative of Caudus' ability to identify anomalies and potentially invoke the relevant support services through integration into CC-BPN SBB such as Port Authorities, ITS and DITS. These services can be used to confirm the exception and deploy Incident Management procedures. The outcome of Use Case C was as expected.

5.4. Use Case D – Additional Tests

5.4.1. Congestion Optimisation (D1)

Parameters are set to ensure congestion will occur even with Caudus enabled. This is compared to without Caudus enabled to give a like-for-like comparison. The results will demonstrate Caudus' effectiveness to manage the situation through the reactive objective function to ensure the situation is not prolonged and exacerbated for an extended duration as opposed to the situation when Caudus is not enabled.

Key Configuration Parameters:
MINEVENTTIMES (seconds) = 1
TARRVARIANCE (seconds) = 1 (limit exaggerated to increase arrival)
TGATEINVARIANCE (seconds) = 1 (limit exaggerated to increase gate in)
No of Equipment In Use= 3
No of Commodities = 300
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)
$\theta Rq \approx$ 0.5 trucks/sec i.e. MINEVENTTIMES+TARRVARIANCE per truck
$\theta Rs \approx$ 0.43 trucks/sec (min) for single move types i.e. (MINEVENTTIMES + Fetch + Load) OR (MINEVENTTIMES + Offload + Stack) seconds per three truck (three straddles).
$\approx$ 0.2 trucks/sec (max) for DUAL move types i.e. (MINEVENTTIMES + Fetch + Load) AND (MINEVENTTIMES + Offload + Stack) seconds per three truck (three straddles).

Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: Congestion builds up for the duration since $\theta Rq > \theta Rs$. Caudus employs counter-measures demonstrating the reactive objective. No counter-measures exist for a Caudus-disabled situation. Duration of congestion for Caudus-enabled is shorter than Caudus-disabled. Maximum number of trucks at port precinct of Caudus-enabled is lower than Caudus-disabled for the duration of congestion. Workload completion is quicker for Caudus-enabled versus Caudus-disabled.

5.4.1.1. Results - D1

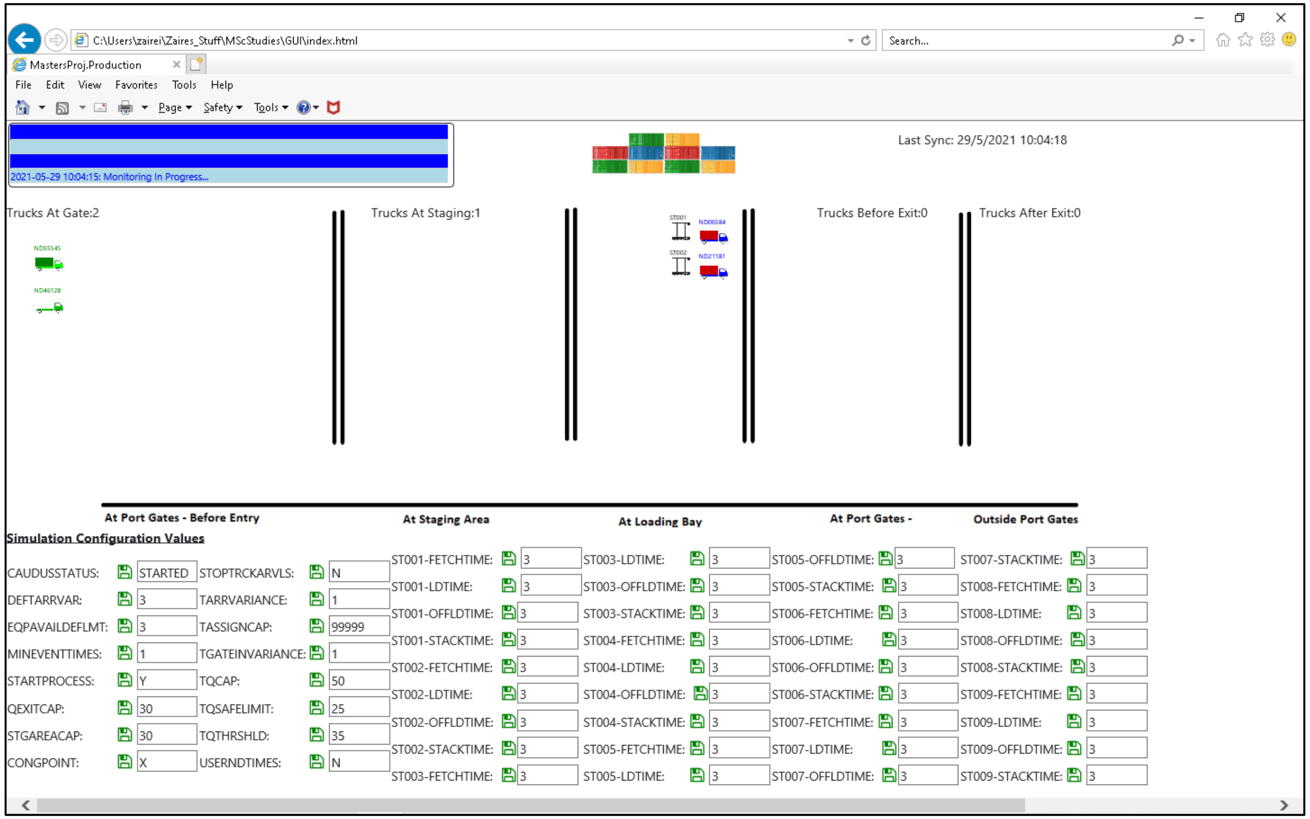

Figure 5.24: Simulation Started (Caudus Enabled): Time: 10:04

Threshold breached after 5minutes. Note Caudus' counter measures activated by increase in equipment to improve performance demonstrating the preventive objective function:

Figure 5.25: Simulation (Caudus Enabled): Time: 10:09

Equipment improvement does not help the situation hence Caudus employs reactive measures by engaging CC-BPN. This is evident in the StopTrckArrvl ='Y' indicator suggesting the customers and business partners have complied with the CC-BPN request and delayed sending trucks to the terminal. This demonstrates Caudus Reactive Objective Function:

Figure 5.26: Simulation (Caudus Enabled): Time: 10:11

Once congestion subsided and queue length is below safe limit, CC-BPN engaged to start sending trucks to the terminal again denoted by StopTrckArrvl ='N'. Take note, excess equipment number is still used to prevent congestion repetition.

Figure 5.27: Simulation (Caudus Enabled): Time: 17:11

Caudus completion time: 10:19am i.e. 15min to completion of queue

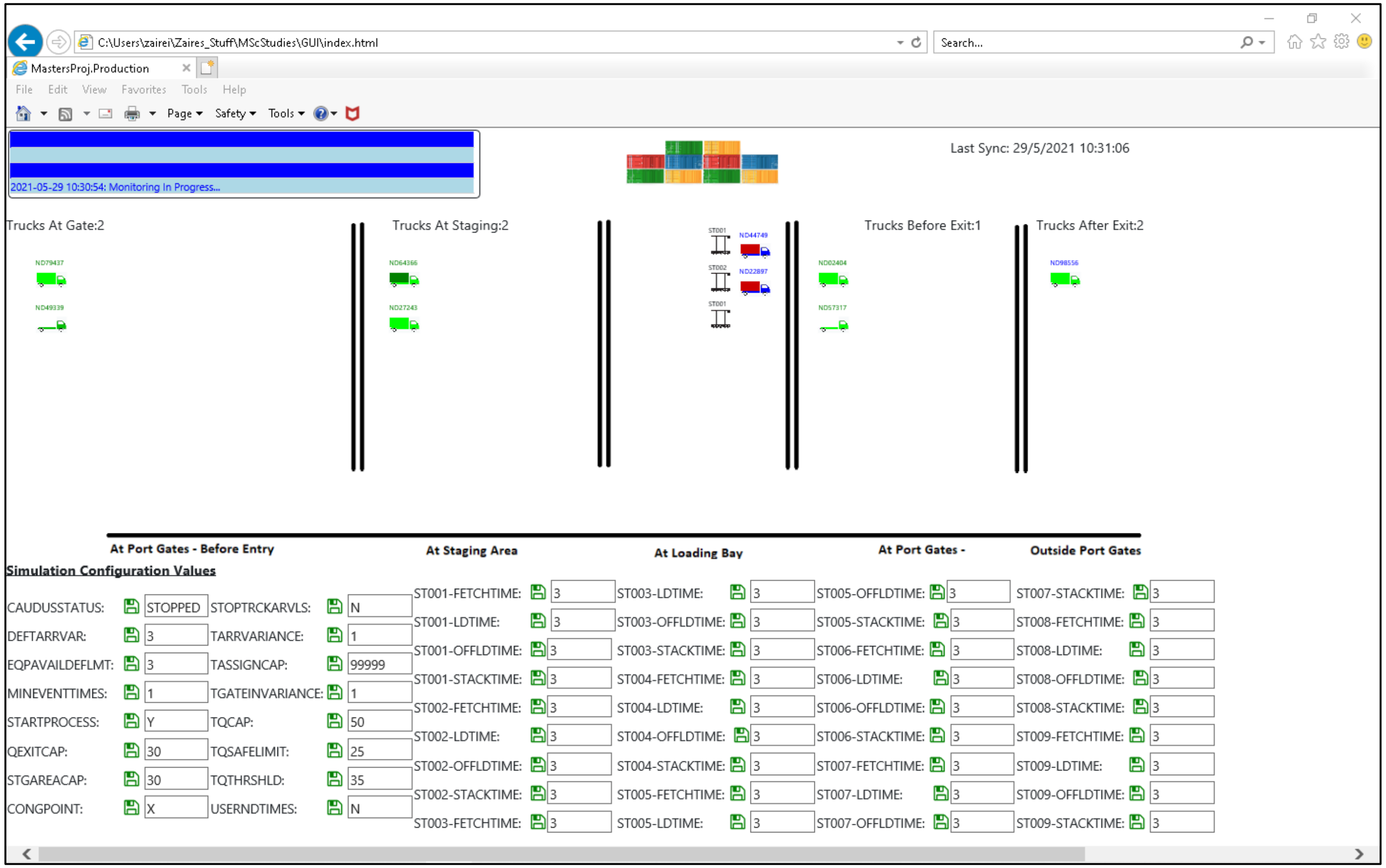

Figure 5.28: Simulation Started (Caudus Disabled): - Start Time: 10:30

Threshold breached after 4minutes. Note Caudus is switched off as a result there are no additional equipment to improve performance:

Figure 5.29: Simulation (Caudus Disabled): - Time: 10:34

Simulation completion time: 10:55am i.e. 25min to completion of queue without Caudus

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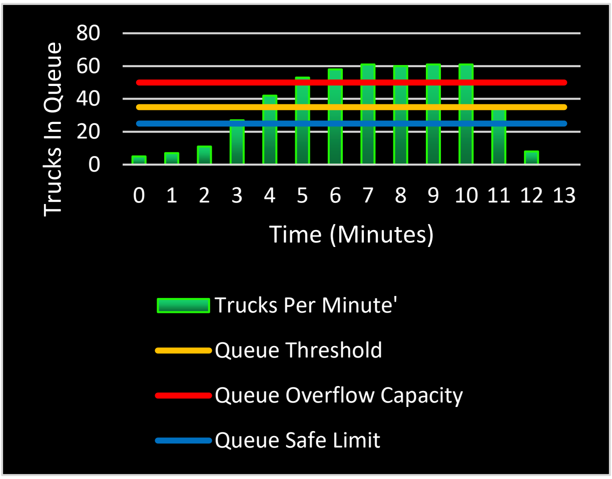
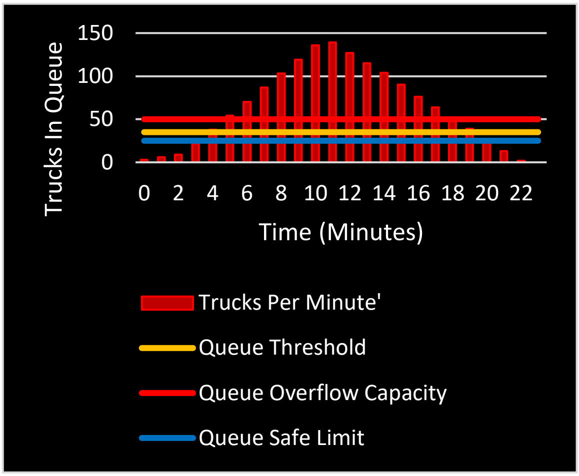


Caudus Enabled – Trucks in Queue over Time



Caudus Disabled – Trucks in Queue over Time

Figure 5.30: Caudus Enabled vs Caudus Disabled

Table 5.2: Comparison of key performance indicators between Caudus Enabled and Caudus Disabled Congestion Management

Measurement	Caudus Enabled	Caudus Disabled
Maximum number of trucks in the Port Precinct	61 Trucks	139 Trucks (127% more than with Caudus)
Congestion duration	5 Minutes	13 Minutes (120% more than with Caudus)
Duration to Clear Queue	13 Minutes	23 Minutes (77% more than with Caudus)

Actual Results: Figure 5.29 and Table 5.2 provides the comparative test results of the between a Caudus-enabled and Caudus-disabled scenarios.

Given the parameters, in the above scenario Caudus experiences congestion as well. However, Table 5.2 demonstrates comparatively that a Caudus-enabled environment manages queue congestion clearance better than a non-Caudus environment. Caudus completed the workload 77% faster than the non-Caudus environment, reducing the number of trucks in the congested port precinct by 127% and a 120% congestion reduction time thus demonstrating Caudus' effectiveness in addressing traffic congestion and throughput through optimisation.

5.4.2. Test Case D2- Throughput Optimisation

The following scenario tests the duration to complete workload cycles of 50, 100, 150, 200, 250, 300 trucks with a Caudus-enabled and Caudus-disabled environment. The results demonstrate Caudus' completion time to be faster than Caudus-disabled, which addresses throughput through optimization.

Key Configuration Parameters:
MINEVENTTIMES (seconds) = 1
TARRVARIANCE (seconds) = 1
TGATEINVARIANCE (seconds) = 1
No of Equipment In Use= 3
No of Commodities = 300
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)
Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: Overall performance of workload completion in a Caudus-enabled environment is better than a Caudus-disabled environment. The results will show that the environment throughput time is better with Caudus enabled.

5.4.2.1. Results – D2

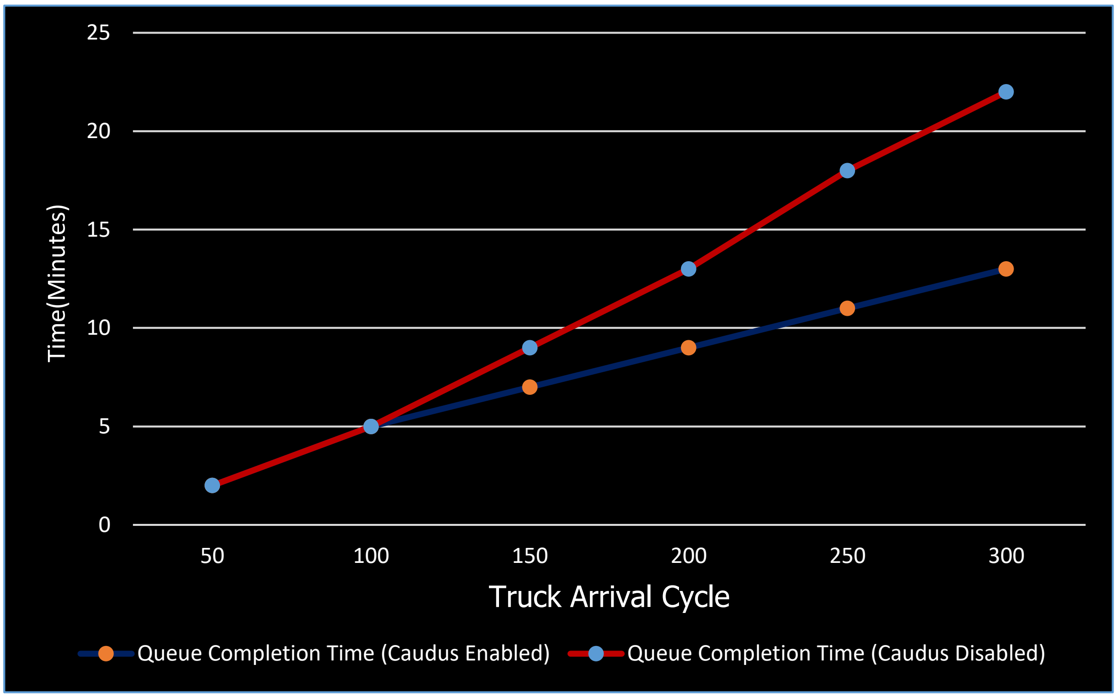


Figure 5.31: Queue Completion Time – Caudus-enabled Vs Caudus-disabled

Figure 5.32: 3, 4, 5, 6 and 9 Equipment vs Time to Completion**Figure 5.31**: Queue Completion Time – Caudus-enabled Vs Caudus-disabled

Actual Results: Comparatively, the simulation results for completed truck arrivals in 50, 100, 150, 200, 250, 300 cycles with Caudus enabled and disabled were plotted on Figure 5.30. The graph shows that throughput completion time using Caudus performed better than without Caudus thus demonstrating the effectiveness of Caudus in addressing throughput through its derived optimisation algorithms.

Note, at 100 queued trucks, there was no difference in performance for both Caudus-enabled and Caudus-disabled environments. This was due to the queue threshold and capacity levels being intact. It is only when there is risk of the queue overflowing that Caudus begins to perform i.e. when the queue levels began to exceed 100 trucks.

5.4.3. Test Case D3 – Equipment Performance

The following scenarios test the duration to complete a maximum number of 300 trucks using a varying number of equipment. The results demonstrate the increase in equipment improves throughput performance thus supporting (3.16).

Key Configuration Parameters:
MINEVENTTIMES (seconds) = 1
TARRVARIANCE (seconds) = 1
TGATEINVARIANCE (seconds) = 1
No of Equipment In Use= Varying
No of Commodities = 300
Default Average Equipment Service Times = 3
USERNDTIMES = N (Randomize=OFF)
Rate of trucks (trucks/second) entering the Staging Area is given by the TGATEINVARIANCE.

Expected Results: Performance improves as the number of equipment increases. This demonstrates Caudus' effectiveness in managing congestion using the derived algorithm (3.16).

5.4.3.1. Results – D3

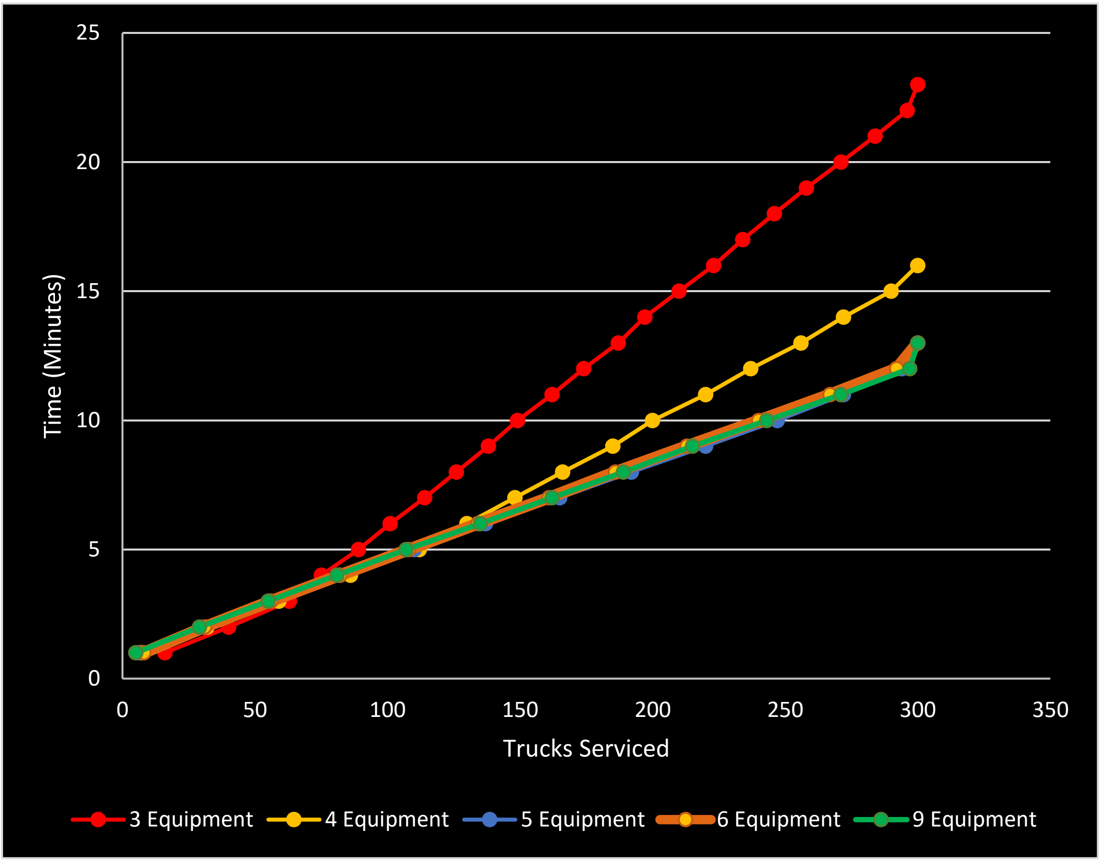


Figure 5.32: 3, 4, 5, 6 and 9 Equipment vs Time to Completion

Actual Results: Figure 5.31 depicts the throughput times of the varying number of equipment to service the same number of trucks. The results comparatively demonstrate that as the number of equipment increases, the throughput time decreases. This effectively demonstrates (3.16) and Caudus' effectiveness to address congestion and throughput through optimisation using the derived algorithms in this study.

5.4.4. Discussion

Use case D tested Caudus' performance against different parameter settings. The simulation tested Caudus' behaviour by varying the number of trucks, number of equipment and number of commodities in different tests. In each situation Caudus performed better than the current status quo.

Some additional insights into this use case, Test D1 also demonstrated that Caudus is not immune to congestion and there was a point at which congestion did occur. However, the time to alleviate the congestion and related throughput time was much faster than without Caudus. Also, Test D2 demonstrated that while Caudus performs better overall, there is a point where the performance between a Caudus enabled and disabled environments are the same. In this scenario, at 100 queued trucks, the Caudus enabled and disabled environments were on par. This was due to the queue threshold and capacity levels not being at risk, which is aligned to Caudus' primary objective of congestion prevention. At this point, there were no congestion to prevent.

Test D3 demonstrated that Caudus' performance is not without bounds. While performance improves with the number of available equipment, it plateaus at some point irrespective of the number of equipment used. In Test D3, this performance peak appeared to be with 5 equipment servicing 300 trucks. Thereafter, additional equipment did not yield as big an advantage.

While performance with additional equipment may exist, the marginal benefits weighed against the cost of equipment utilisation may be considered for future works. In this scenario, Caudus' objective of alleviating congestion and improving throughput was achieved. The outcome of Use Case D was as expected.

Chapter 6: Implementation Discussion

The objectives of this study were to formulate the optimisation algorithms to address truck congestion and to develop a solution that will validate the algorithms. Several use cases were tested to demonstrate the effectiveness of Caudus in applying the derived algorithms to achieve its three objective functions viz. preventive, reactive and predicative. These use cases represented real world scenarios with outcomes displaying attributes of each objective.

The Preventive objective function employs the use of Little's rule [14] to derive the algorithm for preventing congestion. However, congestion is not always avoidable, and the Reactive objective function addresses the problem using Caudus' integration capability with ITS, DITS and CC-BPN, the solution building blocks identified in the solution architecture developed in this study. The Predictive objective function is aimed at ensuring the environment is incident free and provides an early-warning detection of possible exceptions in traffic situations that may lead to congestion. This is achieved using the algorithms derived in this study that identifies bottleneck symptoms in one traffic zone while the root cause can be found in the adjoining traffic area.

This section discusses the results of the simulation that confirm credibility of the system in validating the algorithms and to highlight the relationship between outcomes and objectives of this study. Section 6.1. System Credibility provides the discussion regarding the credibility of the system used to confirm the derived algorithms, Section 6.2. Validating the Preventive and Reactive Objective Functions and Section 6.3. Validating the Predictive Objective Function discusses the relationship between the derived algorithms and the developed system objectives, Section 5.4. Supplementary Tests discussed additional tests performed in the simulation, and the 6.5. provides a brief summary of the entire discussion.

6.1. The System Credibility

Use Case A sets the benchmark for Caudus and also validates the credibility of the system. The tests use two scenarios, the first being with Caudus disabled and the second is with Caudus enabled. The simulation parameters for the disabled test are set so that no congestion is experienced thus satisfying the condition,

$$\theta Rq < \theta Rs$$

This is the "Ideal Situation". The second test uses the same parameters but with Caudus enabled. As expected, the results were exactly the same as depicted in Figures 5.2 and 5.4. This output was attributed to the lack of congestion experienced in both scenarios and therefore no requirement for any intervention. The outcome of this use case validates Caudus' credibility. If the outputs were different then the credibility of Caudus would have been questionable. This test is typically considered as the "control experiment".

6.2. Validating the Preventive and Reactive Objective Functions

Use Case B demonstrated an exacerbated situation where the congestion levels were near un-realistic. Here again, the situation was tested with like parameters for a Caudus disabled and a Caudus enabled scenario. The parameters were set to ensure congestion is inevitable for both scenarios such that condition (QTF 3) is satisfied.

The first test was with Caudus disabled and this merely resulted in an overflowing queue with the congestion lasting up to 74% of the duration. With Caudus enabled, the efforts to prevent queue overflow began when the threshold was breached. Instead of using (QTF 3), Caudus uses the threshold limit as a trigger for the preventive objective in order to allow the queue an opportunity to normalise on its own. This is to prevent false-positives of invoking congestion counter-measures when the problem is temporary.

Once the threshold was breached, Caudus focused on the preventive objective by increasing equipment to improve the service rate. This is evident in Figure 5.9 and 5.10. However, with limitations on equipment resources, once the queue could not be contained solely based on operational performance, Caudus initiated the Reactive objective by engaging with the transporters to delay trucks from approaching the port precinct. This was simulated using the STOPTRCKARVLS indicator, set to "Y" as depicted in Figure 5.10. Once the truck queue began to normalise, Caudus continued with its Preventive objective to ensure the queue does not overflow for the duration. This was depicted in Figure 5.12.

6.3. Validating the Predictive Objective Function

Use Case C tested the effectiveness of Caudus in identifying factors contributing to congestion that are not directly linked to equipment performance. These can be considered as exceptions that Caudus is able to monitor and provide supplementary support by initiating operational activities to address the problems such as informing the relevant authorities or support services through integration with CC-BPN, ITS and DITS.

Caudus identifies exceptions by monitoring bottleneck points in the travel route that impact throughput. By identifying symptoms of congestion at each bottleneck point, Caudus could predict congestion build up and inform the relevant authorities. Five bottleneck points were presented in this use case, four of which were in the immediate vicinity of the terminal and included:

- At the terminal gate entrance denoted as AG (At Gate). This area is within the control of the terminal. An incident at AG will prevent trucks from entering the terminal gates thereby resulting in the reduction of trucks in the staging area and subsequent locations.
- At the staging area denoted as SA (Staging Area). An incident at this point will see traffic build up at the terminal entrance and port precinct while capacity becomes alleviated in subsequent locations.
- At the loading bays denoted as LB (Loading Bay). Traffic build up as a result of LB will be experienced in the staging area, terminal gate entrance and port precinct.
- At the exit point of the terminal marked as At Gate Out (AGO). Similar to AG at the terminal entrance, this area can be impacted by exceptions at the terminal exit point itself, which falls within the terminal control or outside the terminal's exit gate, which is the municipality's responsibility.

The fifth bottleneck point is outside the port precinct but since the impact can be identified within the port vicinity, it was been included in the simulation. This bottleneck occurs before the trucks are gated into the terminal and denoted as BGI (Before Gate In).

The CONGPOINT configuration parameter was used to simulate the congestion at each bottleneck point in the simulation. The BGI bottleneck saw no traffic build up in the port precinct or at the terminal in Figure 5.14, even though trucks are expected to arrive, thereby suggesting the problem is beyond the port precinct. The AG bottleneck displayed a traffic build up at the terminal gate entrance in Figure 5.16 suggesting an incident occurred between the Gate Entrance prior to the Staging Area. The SA bottleneck displayed a traffic build up at the staging area in Figure 5.18 suggesting an incident occurred between the Staging Area and Loading Bays. The LB bottleneck saw a traffic build up at the Loading Bays in Figure 5.20 suggesting an incident occurred between the loading bays and terminal exit. The AGO bottleneck is the last congestion point monitored in the port, which saw a traffic build up at the terminal exit gates in Figure 5.22 suggesting there was a problem at the exit gates or outside the terminals.

In each of the Use Case C simulation tests, Caudus' Predictive Objective function was demonstrated by successfully identifying and reporting the bottleneck points on the simulation dashboard. The dashboard report could potentially be integration into CC-BPN for future works.

6.4. Supplementary Tests

Use Case D provided additional test scenarios to re-affirm Caudus' multi-objective functions. The tests also demonstrated that Caudus is not immune to congestion. However, application of the derived algorithms that Caudus employs provide for a better managed traffic situation than having no alternative. The tests also showed that while Caudus improves throughput performance, the return on investment does reach a peak. This scenario provides for cost-analysis opportunities that can be undertaken in future works.

6.5. Summary

The simulation tested various use cases to validate the derived algorithms of this study as well as to display the effectiveness of Caudus in applying those algorithms. Use Case A confirmed the credibility of Caudus with the "control experiment". This provided a level of confidence in the test results of the following use cases.

The Preventive objective function was successfully demonstrated in Use Case B. This scenario employed counteractive measures to alleviate congestion by increasing the equipment service rate such that,

$$\theta Rq \leq \ \theta Rs$$

Part of the Use Case B example, the simulation parameters were set to force congestion on the system despite the system preventive measures to the extent that,

$$\theta Rq > \ \theta Rs$$

This resulted in the Reactive objective function taking effect. The forced congestion saw Caudus unable to contain the situation through operational performance. The resulting queue overflow ($\theta qCap + 1$) prompted a simulated integration into CC-BPN, using the STOPTRCKARVLS parameter in order to limit the truck arrival to the port precinct.

Caudus also displayed the Predictive objective function in Use Case C where symptoms of congestion where identified using the algorithm,

$$\Delta\tau\left(\Delta\beta pt_n - T_{\beta ptn\_max}\right) \to 0 \ \ \textit{as} \ \ \Delta\tau(\beta pt_{n+1}) \to 0$$

The various scenarios of the use cases displayed the objectives of this study to be successfully achieved.

Chapter 7: Conclusion

7.1. Introduction

While various studies have been done for urban road [49, 50], freeway [48, 51] and vessel traffic optimisation [30, 31], only a few have been found to address port traffic congestion [25, 56]. Here too, these are generally focused on the sea side traffic [30, 31, 58] and only a few attempt to address congestion in the port precinct, with scheduling and appointment systems as the primary remedy [25, 56]. Thus far, none have been found to address the root cause in the inter-connecting port areas.

This study proposed a novel approach to addressing traffic congestion and throughput through optimisation. It involved the original design and development of Caudus, a smart queue process system that utilized the derived algorithms from this study to address traffic congestion. Caudus achieves this by addressing the various root causes to the extended waiting times of trucks in the queue that lead to congestion compared to other studies focus primarily on the symptoms.

The aim of this study sought to address the truck congestion challenges around port precincts. This was achieved through the following objectives:

1. Formulation of the optimisation algorithms to address truck congestion in port precincts;
2. Design and develop the smart queue solution, Caudus, employing the multi-objective function approach viz.:
   2.1. Preventive – To prevent congestion of the truck queues around port precincts
   2.2. Reactive – To alleviate the congested truck queues around port precincts through counter measures
   2.3. Predictive – To predict situations leading to congestion in the surrounding precinct and prescribe rectification measures to avoid congested truck queues
3. Evaluate the proposed Caudus solution through the novel simulation developed for this study using the derived algorithms that support the multi-objectives functions.

7.2. Outcomes

Caudus was designed with the specific purpose of addressing traffic congestion in the port precinct i.e. inside and around the port. In order to achieve this, there were three specific objectives Caudus employed. First and foremost was to prevent congestion and queue overflow. This responsibility lay with the Preventive objective function. The second objective was to restore order should traffic congestion and overflow materialize. This was the responsibility of the Reactive objective function. Finally, the third objective of Caudus was to maintain a healthy traffic environment beyond the port areas. This was achieved with the Predictive objective function.

The effectiveness of Caudus was demonstrated through the use of the Caudus Simulation. The simulation was developed using a number of development tools and tested various use cases (A, B, and C) that represented the different real-world scenarios for congestion experienced at the terminals. Use Case A set the Benchmark for traffic optimisation and also demonstrated the credibility of the system through the control test. This test used two scenarios, first with Caudus disabled and then with Caudus enabled. Both tests yielded the same outcome confirming that if there is no congestion, then Caudus would not intervene.

Tests for the Preventive and Reactive objective functions demonstrated Caudus' effectiveness in managing congestion. These were achieved in Use Case B. This scenario demonstrated Caudus' ability to prevent congestion based on the terminal's equipment resource capability. It validated supply against demand using arrival rates versus service rates based on the derived algorithm (3.11). As demand increased, Caudus began adjusting supply dynamically through the use of (3.16). However, when Caudus identified that the demand could not be satisfied by the available resources using (3.9), the breach in capacity using (3.2) was the trigger to initiate the Reactive objective function. Using a combination of the derived algorithms, Caudus managed to contain the congestion more effectively than without any intervention thus achieving this study's objective of addressing congestion through optimisation. In addition, with the significant improvement in completion time demonstrated in Use Case B, this study's objective of addressing throughput was also achieved.

The Predictive objective function was tested for effectiveness in Use Case C. This scenario monitored for traffic congestion symptoms in inter-connecting areas that impacted subsequent traffic zones. This method of addressing congestion is a novel approach that has not been found in other studies reviewed. The view of the traffic relationship across the TRC was explained using Figure 2.5 and the ensuing literature discussion. In order to achieve the Predictive objective function, Caudus monitored strategic bottleneck points using algorithms (3.18) and (3.19) for congestion symptoms before initiating counter-measures to resolve the situation if they were to be found.

The various use cases covered demonstrated the effectiveness of Caudus in addressing traffic congestion and throughput through the derived optimisation algorithms.

7.3. Contributions

In contrast to previous research topics pertaining to congestion in port precincts where they were limited to addressing congestion through truck appointments and scheduling systems or on the sea side where the challenges of vessel congestion in channels are addressed, this study presented a different view to addressing traffic congestion. Scheduling solutions only address the symptoms while the root cause to congestion may be due to operational inefficiencies [4] or other external factors that affect internal processes [79]. This study focused on a holistic approach to addressing traffic congestion in the port and inter-connecting areas by looking at the relationships of *supply-versus-demand* as well as *cause-and-effect*.

The approach used in this study provided a more dynamic solution by continuously monitoring the situation as it changed and addressing supply against demand. This solution is also more sustainable since the scheduling systems of previous studies are fixed at planning time and cannot evolve as demand increases. Intuitively, throughput time also increases in scheduling and appointment systems whereas this study also improves throughput as demonstrated. In the case of Caudus, as demand increased, so did the supply of available resources to accommodate. Similarly, when demand dwindled, the supply was reduced. This dynamic nature of addressing congestion also reduced wastage of resources, which was not evident in previous studies. Also, the cause-and-effect relationship used in identifying traffic problems by monitoring the effects of traffic across connected areas is a novel approach that Caudus employs to addressing traffic congestion, which has not been found in other studies.

In addition, this study also contributes in areas of 4IR, Big Data and Computing Systems. This is evident in the acceptance of this dissertation for presentation at the International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD 2021) under the title "CAUDUS: An Optimisation Model to Reducing Port Traffic Congestion" [84].

7.4. Limitations

Traffic congestion exist in all traffic zones. However, this study was limited to traffic around the port precincts with the layout in focus being the Durban port (Figure 3.3). Additional limitations pertain to the supply-versus-demand and cause-and-effect attributes of congested areas. In addressing the demand against supply, the equipment in the simulation were limited to a minimum of 3 and maximum of 9 based on the ratio of 1:10 in relation to the Durban port. Also, the remedies for congestion in inter-connecting areas required intervention from CC-BPN, ITS and DITS. Although system integration has been referenced, this study was limited to the derived algorithms and the theoretical intervention of integrated systems.

7.5. Future Works

Traffic congestion is not a problem that can be addressed in isolation. Given the relevant use cases, several building blocks are required to achieve the desired output. The Architecture Reference model derived in this study makes for a host of potential solutions for future works. Some of these include integration with ITS solutions to invoke supplementary support for emergency situations and providing an integrated view of traffic situations in connected traffic zones. Learning algorithms is also contender for future works. With Caudus providing Big Data insights into port traffic patterns and operations statistics, some key performance indicators may include equipment and driver patterns, truck arrival and scheduling patterns, incident and accident patterns and causes. These future works can provide a plethora of sustainable solutions to addressing traffic congestion through optimization globally.

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Appendices

Appendix A – The Caudus Architecture

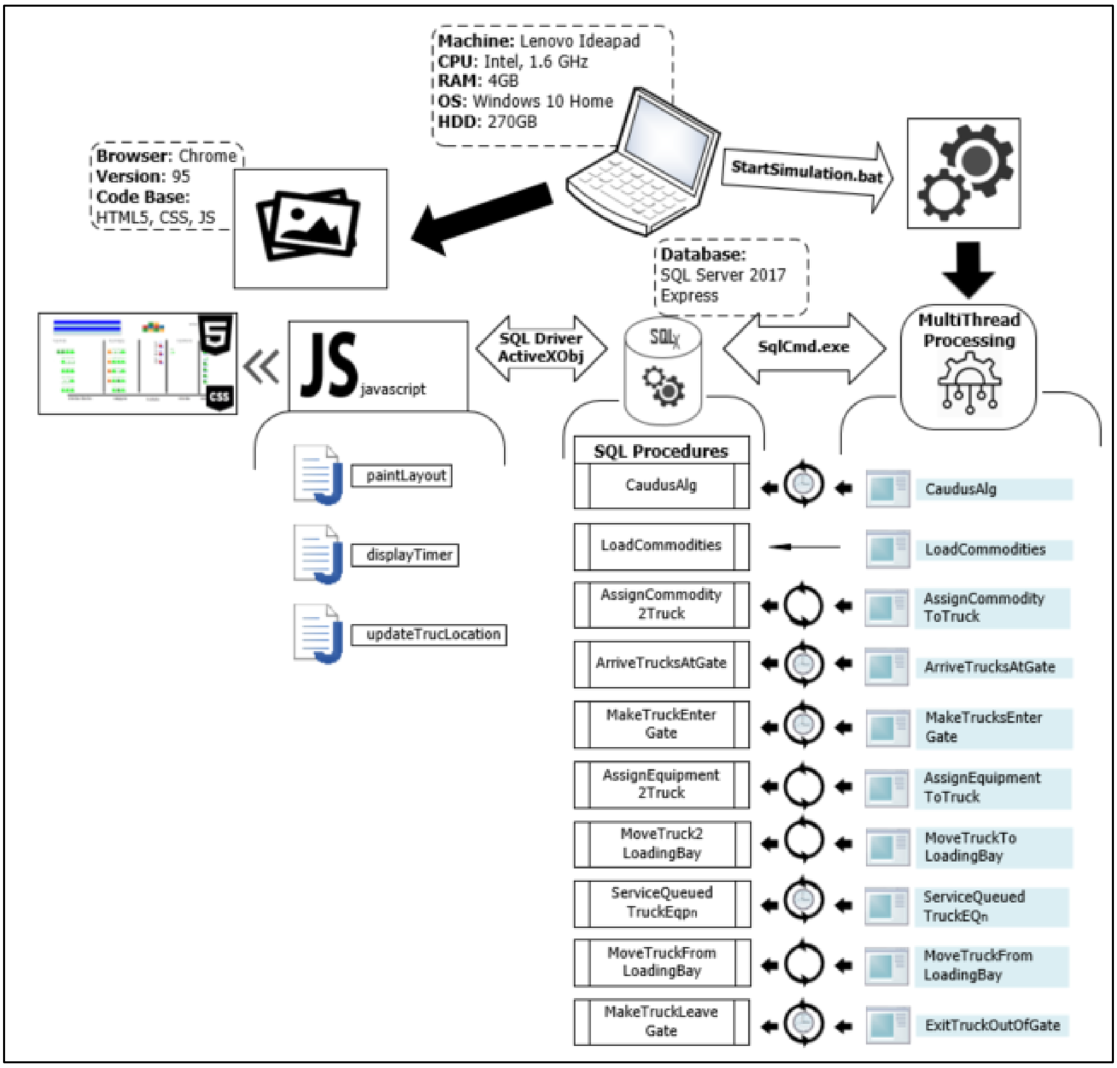

Figure A.1: Level 2 Architecture of the Caudus Simulation

Appendix B – The Caudus Algorithm Module

```
/** Object: Stored Procedure [CaudusAlg]   Script Date: 2021/11/03 5:55:02 PM **/
USE [MastersProj];
go
SET ansi_nulls ON;
go
SET quoted_identifier ON;
go
CREATE PROCEDURE [Caudusalg]
WITH EXECUTE AS caller
AS
    DECLARE @trucksAtGate          INT,
        @CaudusStatus          VARCHAR(15),
          @DriverId              INT,
          @TrucksStoppedArriving   VARCHAR(15),
          @CaudusCycle           INT,
          @CaudusCycleTime       DATETIME,
      @TruckQueueCapacity      INT,
          @TruckQueueSafeLimit     INT,
          @TruckQueueThreshold     INT,
          @ActiveEqp             INT,
          @TruckArriveInterval     INT,
          @TruckDefaultArrInterval INT,
        @DefaultActiveEqp        INT,
          @TrucksPerMinute        FLOAT,
          @NewRateTrucksPerMinute  FLOAT,
          @ServicePerMinute        FLOAT,
          @MinAtGateDate          DATETIME,
          @MaxAtGateDate          DATETIME,
          @MinAtBayDate           DATETIME,
          @MaxLeaveDate           DATETIME,
          @do_loop               VARCHAR(1),
          @AllEqpAvail           VARCHAR(1),
          @AllEqpInUse           VARCHAR(1),
         @keepMonitoring         VARCHAR(1),
          @congestionNoted        VARCHAR(1),
          @tEqpid                VARCHAR(15),
          @tDriverId             INT,
          @DummyCall             INT;

 BEGIN
      EXEC Logactivity
     'CaudusAlg',
       'Start...' -- TQTHRSHLD  -- TQSAFELIMIT -- TQCAP
    EXEC Retconfigvalue
     'TQTHRSHLD',
```

```
  @TruckQueueThreshold output

EXEC Retconfigvalue
  'TQSAFELIMIT',
      @TruckQueueSafeLimit output

EXEC Retconfigvalue
  'TQCAP',
      @TruckQueueCapacity output

EXEC Retconfigvalue
  'EQPAVAILDEFLMT',
      @DefaultActiveEqp output

EXEC Retconfigvalue
  'DEFTARRVAR',
      @TruckDefaultArrInterval output

EXEC Retconfigvalue
  'STOPTRCKARVLS',
      @TrucksStoppedArriving output

SET @AllEqpInUse = 'N';
   SET @keepMonitoring = 'Y';
   SET @congestionNoted = 'N';

-- included to prevent going into check if Caudus stopped at outset - 29052021
EXEC Retconfigvalue
  'CAUDUSSTATUS',
      @CaudusStatus output

IF @CaudusStatus = 'STOPPED'
      SET @keepMonitoring = 'N';

WHILE ( @keepMonitoring = 'Y' )
      BEGIN
            EXEC Retconfigvalue
       'CAUDUSSTATUS',
             @CaudusStatus output

      EXEC Retconfigvalue
       'STOPTRCKARVLS',
             @TrucksStoppedArriving output

      EXEC Geteventtime
       'CAUDUSCCYCLE',
             @CaudusCycleTime output
```

```
        EXEC Retconfigvalue
          'TARRVARIANCE',
                @TruckArriveInterval output

        IF CURRENT_TIMESTAMP > @CaudusCycleTime -- every 60s
          BEGIN
                    -- check if the problem area can be found ***********
             EXEC Congestionareanotif;
                    -
- should check congestion possibility even before thresholds are reached
             INSERT INTO caudusalglogs
                                (alglogname,
                                   alglogdesc)
                    VALUES      ('CAUDUSCYCLE',
                                   'Monitoring In Progress...');

             SELECT @trucksAtGate = Count (1)
                    FROM   servicequeues
                    WHERE  truckarriveatgate IS NOT NULL
                           AND truckgatein IS NULL
                           AND queuestatus <> 'COMPLETED';

             IF @trucksAtGate > @TruckQueueThreshold -- first limit check
               BEGIN
                          SET @congestionNoted = 'Y';

                 INSERT INTO caudusalglogs
                                      (alglogname,
                                       alglogdesc)
                          VALUES      ('THRESHOLDCHECK',
                          'Trucks At Gate Exceeds Queue Threshold,At Gate:'
                          + Cast (@trucksAtGate AS VARCHAR)
                          + ', Queue Threshold:'
                          + Cast (@TruckQueueThreshold AS VARCHAR));

                 IF @trucksAtGate >= @TruckQueueCapacity
                           -- stop arriving trucks if capacity is reached
                   BEGIN
                                INSERT INTO caudusalglogs
                                    (alglogname,
                                           alglogdesc)
                                VALUES      ('QUEUECAPACITYCHECK',
'Arrivals Need to be halted, Trucks At Gate Exceeds Queue Capacity,At Gate:'
+ Cast (@trucksAtGate AS VARCHAR)
+ ', Queue Capacity:'
+ Cast (@TruckQueueCapacity AS VARCHAR));

UPDATE generalconfigs
```

```
SET    configvalue = 'Y'
WHERE  configname = 'STOPTRCKARVLS';

INSERT INTO caudusalglogs
                (alglogname,
                 alglogdesc)
VALUES      ('CUSTNOTIFDELAY',
'Sending notification to customer to halt Truck Arrivals, Trucks At Gate:'
+ Cast (@trucksAtGate AS VARCHAR)
+ ', Queue Capacity:'
+ Cast (@TruckQueueCapacity AS VARCHAR));

INSERT INTO notifications
                (senderid,
                 receiverid,
                 notifheading,
                 notifdetails)
VALUES      ( 'CAUDUS',
                  'CUSTOMERS',
                  'Congestion Alert',
'Congestion unmanageable. Halt Arrivals of trucks until further notice.' );
END;

--*************** preventive measures ****************
SELECT @MinAtGateDate = Min(truckarriveatgate),
          @MaxAtGateDate = Max(truckarriveatgate)
FROM   servicequeues
WHERE  queuestatus = 'QUEUED';

SELECT @MinAtBayDate = Min(truckatloadingbay),
          @MaxLeaveDate = Max(truckleaveloadingbay)
FROM   servicequeues
WHERE  queuestatus <> 'QUEUED'
          AND truckatloadingbay IS NOT NULL
          AND truckleaveloadingbay IS NOT NULL;

EXEC Truckmovementrates
  'ARRIVALRATE',
   @MinAtGateDate,
   @MaxAtGateDate,
   @TrucksPerMinute output

EXEC Truckmovementrates
  'SERVICERATE',
   @MinAtBayDate,
   @MaxLeaveDate,
   @ServicePerMinute output
```

```
IF @TrucksPerMinute > @ServicePerMinute -- trucks arriving too fast
  BEGIN
        INSERT INTO caudusalglogs
                        (alglogname,
                        alglogdesc)
        VALUES      ('RATECHECK',
'Rate of Trucks arriving at Gate exceeds Equipment Service Rate, Trucks At Gate Rat
e(per minute):'
+ Cast (@TrucksPerMinute AS VARCHAR)
+ ', Equipment Service Rate (per minute):'
+ Cast (@ServicePerMinute AS VARCHAR));

SET @do_loop = 'Y';

WHILE @do_loop = 'Y'
BEGIN
-- loop to slowly add straddles
-- Add straddles equipment to move more units
INSERT INTO caudusalglogs
        (alglogname,
         alglogdesc)
VALUES      ('FLEETINC',
'About to increase Equipment Fleet to service excess trucks, if available'
);

UPDATE loadingbays
SET    activeind = 'Y'
WHERE  bayid = (SELECT TOP 1 bayid
FROM   loadingbays
WHERE  activeind = 'N'
ORDER  BY bayid);

SELECT TOP 1 @DriverId = driverid
FROM   equipmentdrivermasters
WHERE  violationsind = 'N'
AND assigned = 'N'
ORDER  BY driverid;

UPDATE equipmentmasters
SET    inuseind = 'Y',
driverid = @DriverId
WHERE  eqpid = (SELECT TOP 1 eqpid
FROM   equipmentmasters
WHERE  inuseind = 'N'
ORDER  BY eqpid);

IF @@rowcount = 0
SET @AllEqpInUse = 'Y';
```

```
ELSE
BEGIN
UPDATE equipmentdrivermasters
SET    assigned = 'Y'
WHERE  driverid = @DriverId;
END;

IF @AllEqpInUse = 'Y'
-
- no more bays/straddles to allocate,so last option is to slow arrivals down and exit lo
op
-- reactive measures using Customer Collaboration and Business Partner Networks
BEGIN
IF @trucksAtGate < @TruckQueueCapacity
-- if queue capacity exceeded then halt message to be sent already
BEGIN
INSERT INTO caudusalglogs
            (alglogname,
             alglogdesc)
VALUES      ('CUSTNOTIFDELAY',
'Sending notification to Customers to delay trucks due to congestion')
;

INSERT INTO notifications
(senderid,
receiverid,
notifheading,
notifdetails)
VALUES      ( 'CAUDUS',
'CUSTOMERS',
'Congestion Alert',
'Delays experienced at terminals. Delay arrival please'
);
END;

-- reduce arrivaltime by notifying customers
UPDATE generalconfigs
SET    configvalue = Cast (( Cast (configvalue AS INT) + 10 ) AS
                     VARCHAR)
WHERE  configname = 'TARRVARIANCE';
END;

INSERT INTO caudusalglogs
(alglogname,
alglogdesc)
VALUES      ('CAUDUSWAIT',
'Waiting to check if improvement noted based on fleet increase and delaying arrival...
'
```

```
);

WAITFOR delay '00:01';

-
- wait for a minute to see if improvement noted. Minute is the benchmark since rate
has been calculated per minute
EXEC Truckmovementrates
'ARRIVALRATE',
@MinAtGateDate,
@MaxAtGateDate,
@NewRateTrucksPerMinute output

IF ( @NewRateTrucksPerMinute < @TrucksPerMinute )
-- i.e. new rate < orig.rate, -- adding eqp worked or   all equip no longer assigned
then no point looping, so exit
OR ( @AllEqpInUse = 'Y' )
BEGIN
IF ( @NewRateTrucksPerMinute < @TrucksPerMinute )
INSERT INTO caudusalglogs
   (alglogname,
    alglogdesc)
VALUES      ('RATECHECK-2a',
    'New Trucks At Gate Rate(per minute):'
    + Cast (@NewRateTrucksPerMinute AS VARCHAR)
    + ', Initial Trucks At Gate Rate (per minute):'
    + Cast (@TrucksPerMinute AS VARCHAR));
ELSE
INSERT INTO caudusalglogs
   (alglogname,
    alglogdesc)
VALUES      ('RATECHECK-2b',
'All equipment in use, little or no improvement noted. New Trucks At Gate Rate(per
minute):'
+ Cast (@NewRateTrucksPerMinute AS VARCHAR)
+ ', Previous Trucks At Gate Rate (per minute):'
+ Cast (@TrucksPerMinute AS VARCHAR)
+ ', Trucks At Gate:'
+ Cast (@trucksAtGate AS VARCHAR)
+ ', Queue Threshold:'
+ Cast (@TruckQueueThreshold AS VARCHAR));

SET @do_loop = 'N';
END;
-- increase in straddles did its job
END; -- while do_loop;
END;
```

```
-- if truck rate too fast
IF @AllEqpInUse = 'Y'
-- this implies rate hasnt dropped but all eqp allocated
BEGIN
SELECT TOP 1 @AllEqpAvail = 'N'
FROM   equipmentmasters
WHERE  ( inuseind = 'N'
      OR eqpavail = 'N' );

IF @@rowcount = 0
SET @AllEqpAvail = 'Y';

IF @AllEqpAvail = 'Y'
-
- if trucks queued at gate but all straddles idle, then no trucks entering gate. Hence
problem at gate entrance – predictive objective
BEGIN
INSERT INTO caudusalglogs
            (alglogname,
             alglogdesc)
VALUES      ('RCACHECK-1',
'All Equipment standing idle although congestion noted at Gates. Hence, problem exi
st outside port precinct.Port Traffic Control to be Notified'
);

INSERT INTO notifications
(senderid,
 receiverid,
 notifheading,
 notifdetails)
VALUES      ( 'CAUDUS',
   'TRAFFICCONTROL',
   'Congestion Alert',
   'Problem at Gate Entrance. Possible truck breakdown' );
-- no need to stop trucks
END;
END; -- end AllEqpInUse
END; -- end if truck at gate > threshold
ELSE IF @trucksAtGate < @TruckQueueSafeLimit
-
- trucks less than queue threshold, check if additional equipment changed or truck ar
rivals delayed and reset until it picks up again
-- ************ Reset Everything to Default *****************
BEGIN
IF @congestionNoted = 'Y'
INSERT INTO caudusalglogs
        (alglogname,
         alglogdesc)
```

```
VALUES      ('SAFELIMITCHECK',
'No. of Trucks At gate has returned below the Safe Limit. Trucks at Gate:'
+ Cast (@trucksAtGate AS VARCHAR)
+ ', Safe Limit:'
+ Cast (@TruckQueueSafeLimit AS VARCHAR)
+ '. Resetting controls to defaults.');

IF ( ( @TruckArriveInterval <> @TruckDefaultArrInterval )
AND ( @congestionNoted = 'Y' ) )
BEGIN
INSERT INTO caudusalglogs
     (alglogname,
      alglogdesc)
VALUES      ('TARRVARIANCE',
      'Setting Truck Arrive Variance to default:'
      + Cast (@TruckDefaultArrInterval AS VARCHAR)
      + ' and notifying customers to resume normal arrival.');

UPDATE generalconfigs -- reset default arrival variance
SET    configvalue = @TruckDefaultArrInterval
WHERE  configname = 'TARRVARIANCE';

INSERT INTO notifications
     (senderid,
      receiverid,
      notifheading,
      notifdetails)
VALUES      ( 'CAUDUS',
       'CUSTOMERS',
       'Congestion Subsided',
'Congestion has subsided. Trucks may be instructed to arrive as normal.' )
;
END;

IF @TrucksStoppedArriving = 'Y' -- reset receiving trucks
BEGIN
UPDATE generalconfigs
SET    configvalue = 'N'
WHERE  configname = 'STOPTRCKARVLS';
END;

SELECT @ActiveEqp = Count(1)
FROM   equipmentmasters
WHERE  inuseind = 'Y';

-- queue back to controlled, so reset to defaults
-- check new rates to determine whether to pull equipment out of field
SELECT @MinAtGateDate = Min(truckarriveatgate),
```

```
@MaxAtGateDate = Max(truckarriveatgate)
FROM   servicequeues
WHERE  queuestatus = 'QUEUED';

SELECT @MinAtBayDate = Min(truckatloadingbay),
@MaxLeaveDate = Max(truckleaveloadingbay)
FROM   servicequeues
WHERE  queuestatus <> 'QUEUED'
AND truckatloadingbay IS NOT NULL
AND truckleaveloadingbay IS NOT NULL;

EXEC Truckmovementrates
'ARRIVALRATE',
@MinAtGateDate,
@MaxAtGateDate,
@TrucksPerMinute output

EXEC Truckmovementrates
'SERVICERATE',
@MinAtBayDate,
@MaxLeaveDate,
@ServicePerMinute output

IF @congestionNoted = 'Y'
INSERT INTO caudusalglogs
(alglogname,
 alglogdesc)
VALUES      ('DEFEQUIPINUSE',
'Congestion subsided. Setting number of Equipment and Bays used back to default. T
ruck Arrive Rate(per minute):'
+ Cast(@TrucksPerMinute AS VARCHAR)
+ ', Service rate (per minute):'
+ Cast (@ServicePerMinute AS VARCHAR));

IF ( @TrucksPerMinute - @ServicePerMinute ) <= 0
-- only reset one at a time if rate dropped. -- leave room for any exceptions
BEGIN
IF @ActiveEqp > @DefaultActiveEqp
BEGIN
SELECT TOP 1 @tEqpid = eqpid,
             @tDriverId = driverid
FROM   equipmentmasters
WHERE  inuseind = 'Y'
ORDER  BY eqpid DESC

UPDATE equipmentmasters
SET    inuseind = 'N',
       driverid = NULL
```

```
WHERE  eqpid = @tEqpid
       AND inuseind = 'Y';

UPDATE equipmentdrivermasters
SET    assigned = 'N'
WHERE  driverid = @tDriverId;

UPDATE loadingbays
SET    activeind = 'N'
WHERE  bayid = (SELECT TOP 1 bayid
                FROM   loadingbays
                WHERE  activeind = 'Y'
                ORDER  BY bayid DESC)
       AND activeind = 'Y';
END; -- @ActiveEqp <  @DefaultActiveEqp
END; -- if truckrate < service rate

-- queue back to controlled so reset to defaults
SET @congestionNoted = 'N';
END; -- @trucksAtGate < @TruckQueueSafeLimit
END; -- end if caudus cycle time

IF @CaudusStatus = 'STOPPED'
SET @keepMonitoring = 'N';
END; -- while keep monitoring

EXEC Logactivity
  'CaudusAlg',
   '...End'
END;

-- main
go
```