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APPLICATION OF DISCRETE-EVENT SIMULATION FOR CAPACITY AND PERFORMANCE ASSESSMENT OF MAINTENANCE OPERATIONS IN A BUS GARAGE

FORTALEZA
2017

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Monografia apresentada ao Curso de Engenharia de Produção Mecânica do Departamento de Engenharia de Produção da Universidade Federal do Ceará, como requisito parcial para obtenção do Título de Engenheiro de Produção Mecânica.

Área de Concentração: Pesquisa Operacional

Orientador: Prof. Dr. Anselmo Ramalho Pitombeira Neto.

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Área de Concentração: Pesquisa Operacional

Aprovada em ___/___/_____.

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To those truly important:

Iara, Laércio, and Iago.

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“The lurking suspicion that something could be simplified is the world’s richest source of rewarding challenges.” (Edsger Wybe Dijkstra)

RESUMO

O presente trabalho apresenta um modelo de simulação computacional que busca reproduzir com fidelidade as operações de manutenção em uma empresa do ramo de transporte rodoviário de passageiros. O comportamento do sistema é estudado através da ótica de diferentes cenários nos quais a quantidade de recursos é alterada de forma que seja possível analisar o impacto das mudanças, facilitando a tomada de decisão em projetos de aumento de eficiência operacional ou de capacidade. O processo de manutenção dos ônibus é modelado a partir da sua chegada na estação de abastecimento, passando pela lavagem externa, lavagem em máquina, inspeção de vala, execução de serviços no setor de manutenção, até os procedimentos finais de limpeza. Cada etapa é simulada com base em observações reais do sistema e analisada estatisticamente através da criação de módulos computacionais lógicos no *software* Arena. Os diferentes cenários testados incluem: incremento de quatro valas mecânicas de manutenção e o impacto sobre a utilização de recursos e sobre o lead-time (tempo total) dos ônibus, as variações no comportamento do sistema para diferentes números de valas mecânicas e, por fim, o remanejamento de recursos visando aumentar a eficiência operacional. Assim, pode-se concluir que tanto a redistribuição quanto o incremento no número de valas podem gerar ganhos significativos com relação ao lead-time e utilização de recursos. O estudo também confirma que os recursos atendem à demanda atual, porém a taxa de utilização, em alguns momentos do dia, é considerada alta.

Palavras-chave: Pesquisa operacional. Simulação de eventos discretos. Gestão da Manutenção.

ABSTRACT

In this study, a computer model based on discrete-event simulation is developed to replicate the maintenance operations of a bus garage. The system behaviour is studied under a different set of conditions aiming at supporting decision-makers on projects that intend to increase operational efficiency to meet demand requirements. The whole maintenance processes are represented. Each procedure is statistically analysed to build the system logic in Arena software. Various alternative scenarios are tested, which include: adding four mechanical pits and testing the impacts over resource utilisation and over the lead-time (total time) of the buses; variations on system performance for different numbers of mechanical pits; reallocating resources to increase operational efficiency. The results show that either redistributing or incrementing the number of mechanical pits can generate significant gains in relation to the lead-time of vehicles as well as benefits concerning to resource utilisation. The resources meet the current demand of the company according to the simulation model. However, the utilisation rates in some moments can be considered high.

Keywords: Operational research. Discrete-event simulation. Maintenance management.

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1. INTRODUCTION

Over the past few years, the extensive mechanisation and automation in industry has dramatically reduced the number of production personnel and has increased the costs with production equipment. As a consequence, capital and manpower employed in the maintenance function has grown. In some industry sectors, the maintenance and operations departments can easily detain up to 30% of the total manpower. Moreover, the amount of resources spent on maintenance tasks can represent the largest fraction of operational budget (DEKKER, 1996). Thus, the main obstacle faced by maintenance managers is to determine whether the capital as well as the manpower are used both effectively and efficiently.

In an ever-changing scenario, service providers and production systems are becoming more complex and facing tougher competition at both national and international levels. In many cases, a number of decisions are made on a regular basis. Most of these decisions are taken based on manager's experience or on simple imprecise assumptions. In some situations, it might be cost effective due to the necessity of fast response and lack of resources. However, as complexity and costs increase, any infrastructure or operational switch may require rigorous analysis in order to avoid expressive losses.

To remain competitive, many manufacturing companies and service providers have to reorganise, improve, and assess the capacity of their maintenance systems (KHEBBACHE-HADJI et al. 2012). All of these tasks are complicated and time demanding since greater asset availability is expected (ALABDULKARIM; BALL; TIWARI, 2013). Therefore, the use of decision support tools such as computer simulation and optimisation is fundamental to precisely predict the behaviour of a real system and also test the effect of alternative scenarios over system performance. From a practical viewpoint, computer simulation allows the design and conception of a numerical model of a real or proposed system to understand it over the influence of a given set of conditions (KELTON; SADOWSKI; SWETS, 2007).

The application of decision support tools such as simulation and optimisation in the bus service sector is still very limited. The maintenance operations in this sector plays a key role in the overall performance of the company and directly affect the customer perception of value. Depending on the total fleet size, maintenance operations can become a complicated task due to the number and variety of mechanical and electrical components of each vehicle. Furthermore, there are different types of maintenance approaches that should be considered: corrective, preventive, and predictive maintenance. Bladikas and Papadimitriou (1986) argued that maintenance costs account for the second highest expense category after vehicle operations.

In a typical transit system, it represents approximately 21% of the total operating costs (PURDY; WIEGMANN, 1987). Providers of bus service are constantly being confronted by pressures to improve service quality, high operational costs, and dwindling sources of support funds (HAGHANI; SHAFAHI, 2002). These facts make maintenance operations one of the most significant and substantial elements of bus transportation services.

In order to approach the issues aforementioned, it is necessary to evaluate, identify, and assess the capacity of the facility to find the appropriate equipment, the best operational policy and so on. In many cases, testing scenarios with distinct characteristics under several circumstances is essential to determine if the capital invested will bring significant performance gains. In this research, a model was developed in Arena simulation software for the maintenance operations in a bus garage located in Fortaleza, Brazil.

Any alteration on physical structures like the number of cleaning machines, inspection pits, and cleaning spaces may require rigorous investigation due to the amount of capital required to implement these changes. As a result, the impact must be evaluated in order to assist manager's decisions. This circumstance presents an opportunity for simulation.

1.1 Objectives

The general objective of this thesis is to analyse how alternative resource allocations in the maintenance department of a bus garage impact its performance measures. The specific objectives of this research are listed as follows:

a) Comprehend and study the complexity of maintenance operations in a large bus garage;
b) Model the main maintenance processes that occur within the bus garage utilising Arena.
c) Determine the capacity of the processes under study;
d) Determine the average lead-time (total time) of a bus within the garage;
e) Test alternative scenarios with increased number of mechanical pits.

1.2 Monograph Structure

The present research is subdivided into 6 chapters: introduction, literature review, model development, results and discussion, and conclusion.

In chapter 1 the study is contextualised with the description of the sector, company under study, approached issues, the thesis objectives, and, finally, the research structure.

Chapter 2 introduce a brief description of operational research (commonly referred to as OR), which is the area that involve the use of various methods in order to identify opportunities for improvements in complex industrial systems. These improvements are essential for companies to reach high levels of competitiveness. Simulation systems are also characterised to give a better understanding of the method utilised to tackle the problems mentioned earlier. This chapter encompass an overview of maintenance techniques as well. Ultimately, a literature review of simulation and optimisation techniques in maintenance systems is proposed.

Chapter 3 presents the methodology of this research, which serves as a basis for the design and implementation of the simulation project. The phases of problem definition, data collection, verification, and validation are described. The study considers the actual policy and procedures executed by the bus garage. The stochastic nature of the problem required the development of a simulation model in Arena. A brief description of the utilised software is also provided.

Chapter 4 concerns to the model development. It describes the processes under study as well as the main limitations of the project. It also shows the results of the statistical analysis and the probability distributions utilised. All the process modules are explained and some examples of the developed logical structure are given to facilitate the overall understanding of the emulated system.

Chapter 5 explains in detail the results of this research. It includes the simulation of different scenarios in order to assess the capacity of the facility under study. As stated earlier, a number of circumstances are taken into consideration in order to determine the average lead-time of the bus, the possible bottlenecks as well as the impact of four additional mechanical pits in the maintenance operations of the company.

Lastly, chapter 6 presents the conclusions and the final considerations. It confirms that the objectives of this research were fully achieved. It also contains some suggestions on how to approach the current problem for future research projects as extensions of this work. The proposed simulation procedure can be applied to any bus depot facility worldwide that relies on inspection pits to perform both corrective and preventive maintenance.

2. LITERATURE REVIEW

In this chapter, it is presented a bibliographical analysis of the research areas related to this study. The chapter is divided into three sections: operational research; maintenance management; simulation and optimisation in related fields. Section 2.1 is subdivided into 6 subsections. First, a background of operational research as well as queuing theory and models are explained. Second, feedback control systems are introduced in order to facilitate the comprehension of the type of system approached. Third, a definition of simulation systems is presented. Fourth, a classification of simulation models is provided. Fifth, the concept of discrete-event simulation is addressed. Sixth, the advantages and disadvantages of simulation methods are presented. Section 2.2 concerns to the challenges and objectives of the maintenance function in an organisation. Finally, section 2.3 presents a literature review of the application of optimisation and simulation methods in related fields.

2.1 Operational research

As the name suggests, operational research concerns to a wide variety of "research on operations". This field involve the application of mathematical methods to solve problems that are related to activities and processes that occur within organisations. The essence of organisations is typically immaterial, which means that OR has been applied in different areas in both public and private sectors such as manufacturing, health care, telecommunications, finance planning, logistics, military, and construction (HILLIER; LIEBERMAN, 2010). It is usually considered as a sub-area of applied mathematics.

The origins of OR can be traced some decades ago when the first organisations attempted to utilise the scientific method in order to obtain solutions for management tasks. According to Hillier and Lieberman (2010), notwithstanding the early use of scientific approaches in organisations, the adoption of the term operational research has commonly been attributed to the British military services in World War II. Due to the critical necessity to provide limited resources to a large number of troops, the military management called upon scientists to bring solutions to strategical and tactical issues.

After the war ended, the scientists engaged with OR developed a variety of mathematical models to handle problems outside the military field. This motivation occurred due to the industrial expansion that followed the war. The organisational problems were becoming more complex which required more sophisticated approaches. Hillier and Lieberman

(2010) state that two factors were essential to the rapid growth of operational research: the rapid improvements of OR techniques, and the extensive use of computers in industry.

In operational research, there is no single general technique to solve the mathematical problems that arise in practice. The type and complexity of the model under study generally define the nature of the solution method (TAHA, 2007). Though any mathematical technique applied to improve a system can be intended as an OR technique, some of them need special consideration. According to Taha (2007), the most prominent methods utilised in operational research are the following: linear programming, integer programming, dynamic programming, network programming, nonlinear programming, and queuing and simulation models.

One common characteristic shared by OR techniques is based on the fact that solutions are not directly obtained in closed formulas. These solutions are determined by algorithms, which contains a series of fixed computational rules that are repetitively applied to a problem in order to find the best possible solution (TAHA, 2007). In many cases, the complexity of the system under study does not allow an optimal solution, then a close to optimal solution must be taken into consideration.

In some situations, finding a single static solution might not be the objective of a scientific study, rather, alternative scenarios and their performance measures may be more attractive. In these cases, it is appropriate to study the queues and stablish performance parameters for the whole system. Then, systems simulation is the most suitable OR tool under these circumstances.

2.1.1 Queuing theory and models

According to Hillier and Lieberman (2010), queuing theory refers to the study of waiting in all of its aspects. Generally, it uses queuing models to represent a variety of queuing systems that arise in practice. In this type of model, formulas are used to demonstrate how the real system should behave, including the average amount of waiting that will occur under a number of different situations.

Queuing models are systems that are capable of estimating the efficiency of waiting lines. These models do not provide an optimal solution or a close to optimal solution like other optimisation OR techniques mentioned in the last section, instead, they define performance measures of the waiting lines such as: the average time in queue, average waiting time for service, a service facility capacity, and the utilisation of these facilities (TAHA, 2007).

2.1.2 Systems simulation

The term simulation usually refers to the emulation of a real-world process or system over time. It is an attempt to mimic the behaviour of real system, commonly on a computer with suitable software. In most situations, it is used as tool to analyse and predict the performance of complex systems. According to Altiok and Melamed (2007), the paradigm of simulation modelling refers to experiment the system through a prescribed guide of objectives such as the improvement of system design, cost-benefit analysis, sensitivity to design parameters, and so on.

In some circumstances, a model can be developed to represent a simple system. In this case, some solutions using mathematical methods such as differential calculus, probability theory, algebraic parameters, or other techniques might bring a feasible solution to the studied problem. Although, in many real-life situations, systems become so complex and complicated that models of these systems are almost impossible to be solved mathematically. In these cases, a computer-based simulation may be appropriate to imitate the behaviour of the system over time. From the simulation, it is possible to gather data as if the real system was being monitored. The data obtained through simulation is then used to establish performance measures.

The use of simulation also presents some drawbacks. The process of developing simulation models is usually very expensive in both time and resources (TAHA, 2007). Furthermore, depending on the size of the proposed model, the execution time may be slow even in a fast computer. Due to these restrictions, it is fundamental to represent only the significant elements of the system under study as well as establish the correct abstractness level. Figure 1 illustrates the levels of abstractness in model development.

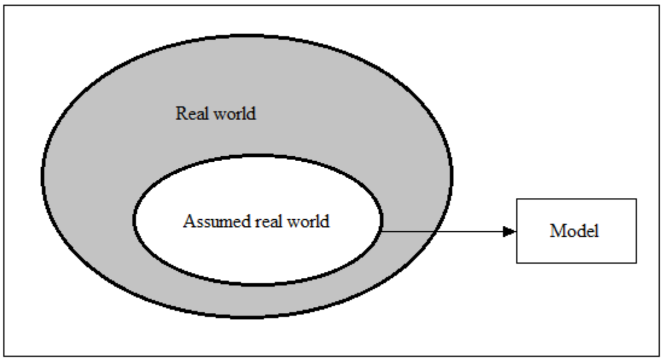
According to Altiok and Melamed (2007), models are frequently used to avoid the unpalatable option of building a real and expensive system. Specially, due to the fact that simulation models are motivated by economic considerations. In order to deal with these restrictions, Altiok and Melamed (2007) proposed the following list of three motivational strands that should be discerned before building a model:

a) *Evaluating system performance under ordinary and unusual scenarios*: The necessity of building a model may rely on the fact that real-life routine operations cannot be disrupted. Testing alternative scenarios might be useful to avoid the severe consequences of stopping the real system.
b) *Predicting the performance of experimental system design*: When the system to be studied does not yet exist it might be an opportunity for simulation.

Constructing and manipulating a real model is often far more expensive and risky than testing the system behaviour in a computer based software.

c) *Ranking multiple designs and analysing their trade-offs*: Allows a deep analysis of multiple investment choices. It often arises when the request of an expensive system is awarded to the bidder with the best cost-benefit performance indicators.

Figure 1 - The levels of abstractness in model development



Source: Adapted from Taha (2007)

2.1.3 Types of simulation

Kelton, Sadowsky and Sweats (2009) argues that there are several different ways to classify simulation models, however, there is a useful way to separate them along the following three dimensions:

a) *Static vs Dynamic*: In static models, time does not play a significant role as it does in dynamic models. Most engineering and management systems are classified as feedback control systems, which are characterised for their dynamic nature (see subsection 2.1.2).

b) *Continuous vs Discrete*: In continuous models, the overall state of the system changes continuously over time. An example of continuous systems is the process of filling a tank. As the liquid flows in or is let out of the reservoir the state of the system changes progressively. In discrete events, instead, the variations over the system state occur only in distinct points in time. An example of discrete system is an assembly line where the parts arrive and leave at specific times. In some situations, it is also possible to identify systems with both discrete and continuous characteristics. These systems are referred to as mixed continuous-discrete models.

c) *Deterministic vs Stochastic*: In deterministic models, there is no presence of random input, rather, they present fixed input times. Examples of such models are strict appointment-book operations. Alternatively, stochastic models operate with at least some inputs being random. The arrival of buses in a terminal usually follows some random characteristics. It is also important to mention that models can have both deterministic and random inputs.

2.1.4 Discrete-event simulation

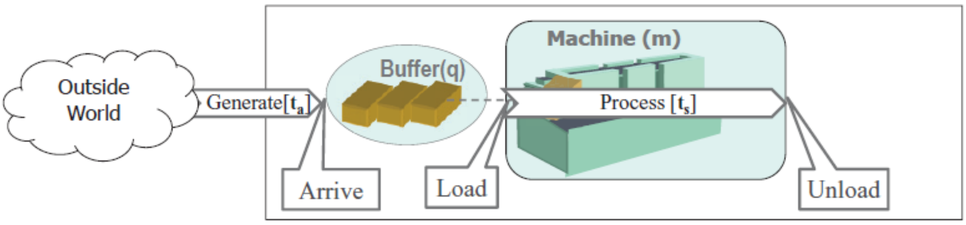
According to Banks et al. (2005), discrete-event simulation refers to systems where the state variable changes only at some discrete points in time. This type of simulation model is generally analysed by numerical methods rather than analytical methods due to the fact that real-world systems present a large amount of data to be manipulated. It is important to mention that analytical methods are based on deductive reasoning of mathematics to obtain a feasible solution to a problem. On the other hand, numerical methods consist of solving mathematical problems through the use of computational tools.

To illustrate a discrete-event simulation, Choi and Kang (2013) give the example of a single service system composed of a machine and a buffer in a factory. The structure of the system is described as follows:

a) An entity arrives at the system with inter-arrival times defined as t_a and the entity is processed on the machine if it is idle; otherwise, the entity waits to be processed in the buffer.
b) The entity is processed with a service time t_s and unloaded;
c) When the entity leaves the system, the next entity is loaded if the buffer is not empty.

The state variables of this system are the number of units in the buffer (q) and the status (m), which can be idle or busy. The events are: arrive, load, and unload. Figure 2 presents a scheme of the single service system:

Figure 2 - Scheme of a single service system



Source: Choi and Kang (2013)

2.1.5 Advantages and disadvantages of simulation

Banks et al. (2005) state that simulation is often attractive to client use because it is able to emulate what happens in a real system or what is expected for a system in design stage. The information generated by the simulation model should directly correspond to the behaviour of a real system. For these reasons, simulation is frequently a choice to solve complex engineering and management problems.

Contrarily to optimisation models, simulation models do not present a single static optimal solution or close to optimal solution. Given a set of circumstances, the behaviour of the system is observed and conclusions are drawn. In addition, it is possible to formulate new scenarios based on different inputs, which makes it ideal for planning changes, implementing new solutions or even testing a non-existent system. Pegden, Shannon, and Sadowsky (1995), list nine advantages of simulation:

a) Analysis of new operating procedures, decision rules, policies, information flows, and schedules.
b) Test alternative hardware design, physical layouts, transportation systems, and logistic chains without relying on the acquisition of physical infrastructure.
c) It is possible to test the occurrence of certain phenomena and assess their feasibility.
d) It is possible to compress and expand time of each simulation run to facilitate the understanding of the system under study.
e) Analysis of the interaction of variables.
f) Define whether a variable is important or not to the overall performance of the system.
g) Identification of bottlenecks and how they impact system performance.

h) A simulation study can help to understand how the system operates instead of how individuals think the system operates.
i) "What if" questions can be answered. It is particularly useful for the design of new systems.

Some disadvantages are these:

a) Model building usually requires special training. If two models are built by different competent individuals, they might share some similarities, but they will hardly be the same.
b) Sometimes, the results of simulation runs can be really hard to interpret, because of the random nature of outputs. Distinguish between system interrelationships and randomness may be difficult;
c) Simulation modelling and analysis can be expensive and time consuming;
d) Simulation is often used when analytical solutions are possible. Analytical methods are usually cheaper and require less time to reach a solution.

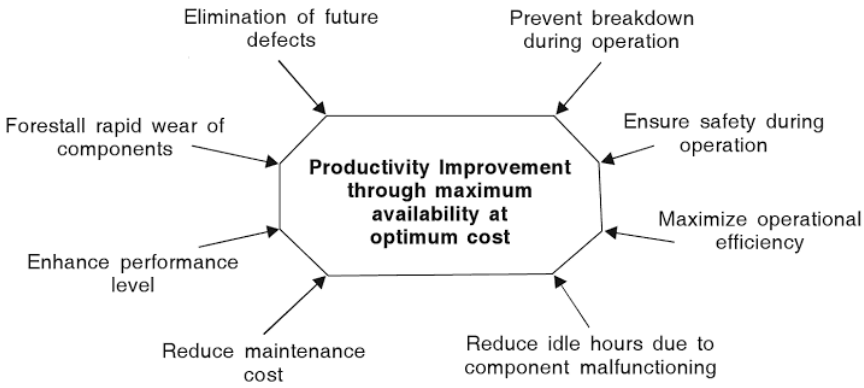
2.2 Maintenance engineering and management

The increasing use of automation in industry has turned maintenance into one of the most indispensable tasks in any organisation. New challenges are being faced by industry and service providers in order to grant the availability of their products. Mishra and Pathak (2012) list some obstacles faced by maintenance departments: the fast growth of technology resulting in current technology becoming quickly obsolete; the necessity of keeping both outdated and modern machines in service; train and upgrade the skill of maintenance personnel; developing maintenance schedules and overhaul the inspections programme.

The main goal of the maintenance engineering function is to grant the maximum availability of equipment or facilities in order to support the achievement of organisational objectives. Another important dimension of maintenance is the establishment of safe conditions both for operating and maintenance personnel. Mishra e Pathak (2012) provide a framework including a vast number of maintenance objectives which is depicted in Figure 3.

In order to deal with the upcoming obstacles and assure that maintenance decisions are carefully taken according to the organisational objectives, it is fundamental to rely on decision support systems. The OR techniques mentioned in the last sections are good examples of these systems. Optimisation and simulation approaches have been used to assist maintenance managers to take decisions in a wide variety of sectors from industry to service providers. The next section encompasses a literature review on the application of OR techniques in the maintenance context.

Figure 3 - The interaction of maintenance objectives



Source: Mishra and Pathak (2012)

2.3 Simulation and optimisation in related fields

The application of optimisation models in maintenance operations is vast. Several algorithms and simulation models were developed to increase the lifecycle of equipment, prevent failure, schedule maintenance operations, and so on. The research conducted by Dekker (1996), showed that maintenance optimisation has flourished as a mathematical discipline within operational research. However, relevant research on simulation of maintenance operations in bus depots is still very limited. Then, it is necessary to refer to research on similar fields.

Haghani and Shafahi (2002) previously addressed optimisation in bus maintenance systems. Their research consisted in the application of mathematical programming to schedule maintenance activities in bus transit operations. A given daily operating schedule for all buses assigned to a depot along with available maintenance resources were considered as input for the model. Close to optimal solutions were obtained with satisfactory computational times. Hamdouni, Soumis, and Desaulniers (2007) studied the parking problem in bus depots considering stochastic arrival times. The problem consisted of assigning buses of different types to parking slots in the best possible way to avoid moving them between their arrival and departures. Leung and Lai (2003) reported the application of the sequential method to define optimal maintenance strategies for a bus service provider in Hong Kong. The aim of the research was to determine when to carry out preventive maintenance actions for an engine and when to replace an engine in use. The research concluded that sequential methods can be used to solve maintenance and replacement problems and its advantages over the non-homogeneous Poisson process model. Constantin and Florian (1995) presented a nonlinear bi-level programming approach to optimise frequencies in real large-scale transit networks. Their algorithm reached good results for short-term planning of transit networks. Savchenko and Milov (2016) developed a decision support tool for an intelligent maintenance-planning system based on a contextual multi-armed bandit algorithm in order to approach two essential problems in maintenance systems: detection of probable dangerous situation, and classification of this situation to prescribe a suitable repair action. A novel algorithm with Bayesian classification was implemented, which generated accurate results.

Simulation of maintenance systems is an extensively addressed theme in literature. Alabdulkarim, Ball, and Tiwari (2013) presented a considerable literature review on the application of maintenance simulation models in industry. Iwata and Mavris (2013) propose a discrete-event simulation modelling environment for aerospace vehicle maintenance and logistic process. Another important contribution was conducted by Fang and Zhaodong (2014), where the authors analyse the influence of part's failure rate and preventive maintenance costs during the lifecycle of aviation equipment. Duffuaa, Ben-Daya, and Andijani (2001) developed a conceptual simulation model for maintenance systems. The conceptual model consists of seven modules: input, maintenance load, planning and scheduling, material and spare parts supply, equipment availability, quality control, and, finally, performance measures. Alabdulkarim, Ball, and Tiwari (2011) attempted to fill the literature gap by specifying, creating, and testing simulation functionality to rapidly model field maintenance systems. In other study, Alabdulkarim, Ball, and Tiwari (2015) assessed asset monitoring levels for maintenance operations in a simulation approach to achieve cost effectiveness. Generic and simulation modules were created to examine how maintenance operation system behave regarding different levels of asset monitoring. Duffuaa and Raouf (1992) developed a simulation model to determine the size of a maintenance crew for a soft drink plant. Gatland, Yang, and Buxton (1997) provided a simulation model to better understand the production capability of an engine maintenance facility by investigating the effects of facility loading on turn time, throughput, and capacity. Their model was capable of testing alternative scenarios of engine mix, repair levels, insourcing levels, types of insourcing, and additional non-engine work.

A hybrid approach of simulation-optimisation is significantly increasing. Oyarbide-Zubillaga, Goti, and Sanchez (2008) combined discrete-event simulation with evolutionary algorithms to determine the optimal preventive maintenance frequencies for multi-equipment systems under cost and profit criteria. The research considered the interaction of production, work in process material, quality and maintenance aspects. Roux et al. (2008) focused on the development of a simulation and optimisation platform to analyse maintenance policies performances for manufacturing systems in which operating characteristics deteriorate with use and whose lifetime and repair duration are random. Alrabghi and Tiwari (2016) proposed a framework that provide adequate level of detail in order to guide both academic and practitioners in optimising maintenance systems. The framework included current issues such as complexity, multi-objective optimisation, and uncertainty. In other study, Alrabghi and Tiwari (2015) reviewed the application of simulation-optimisation techniques in literature concluding that much of the research in the area focus on preventive maintenance.

3. METHODOLOGY

The present study shows a quantitative analysis elaborated together with a case study. The operations of a real bus garage are emulated in a simulation software. This chapter comprises the methods applied to the development of the simulation model. First, a brief description of Arena simulation software is provided. Second, the steps for the simulation design and implementation are approached. The steps consist of problem analysis, data collection, model construction, model verification, model validation, simulation experiments, output analysis, and final suggestions. Third, the problem is defined and explained. Fourth, the process of data collection is mentioned. This generical process is identified the same adopted for modelling the activities that take place in the bus garage. Fifth, the simulation run setup is shown. Finally, the validation procedures are encompassed, which include determining the key performance indicators as well as matching simulation outputs and historical data.

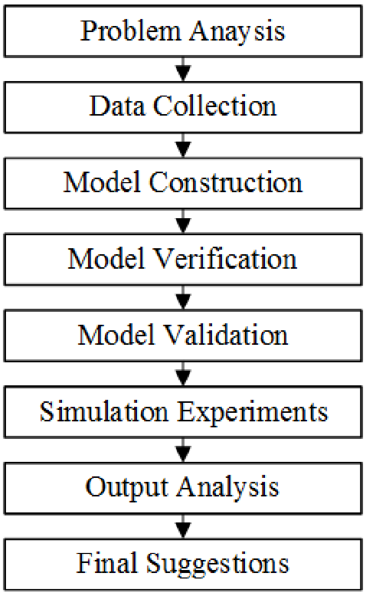
3.1 Arena simulation

The software chosen to emulate the operations of the bus garage was Arena simulation software. It is one of the most popular discrete-event simulation software of the market and allows system modelling using simple flowcharts and modules. The software is developed and distributed by Rockwell Automation®. According to Kelton, Sadowsky, and Sweats (2007), Arena combines the ease of use found in high-level simulators with the flexible aspects of simulation languages as well as general-propose procedural languages, such as Microsoft® Visual Basic® programming system or C/C++. It does this by providing different and interchangeable templates of graphical simulation modelling and analysis modules that can be combined to build a wide variety of simulation models. At any time, it is possible to pull in low-level modules from the Blocks and Elements panel and gain access to simulation-language flexibility. For more specific situations, like complex decision algorithms or accessing data from an external application, it is also possible to write pieces of the model in the procedural languages previously mentioned. All of these characteristics are present in the same consistent graphical user interface regardless of the high or low hierarchy level.

3.2 Steps for simulation design and implementation

The steps that comprehend the design and implementation of a simulation project from the conception to the final results are diversely defined according to each author, although, there are several similarities among them. This study was conducted according to the steps proposed by Altiok and Melamed (2007). The model suggested by theses authors matches with the goals of this research. The steps adopted are depicted in Figure 4.

Figure 4 - Model building iterative scheme



Source: Adapted from Altiok and Melamed (2007)

The 8 major steps of simulation modelling presented by Altiok and Melamed (2007) and represented on Figure 5 are described in detail as follows:

a) *Problem analysis*: The first of steps include the analysis of the problem itself. In this stage, relevant information about the problem is gathered, which encompasses: the identification of input parameters, performance and capacity measures of interest, the flow and rules that occur within the operations, system components, establishment of the relationship among parameters and variables, etc. After obtaining relevant information about the behaviour of the system, a convenient representation is chosen, which includes logic flow diagrams, hierarchy trees, or any other convenient means of representation. Finally, a solution can be mapped out.

b) *Data collection*: In order to faithfully represent the behaviour of the system, it is fundamental to collect data to estimate model input parameters. Real data can be gathered from historical databases to make assumptions on the distributions of random variables in the model. When there is no available data, it is important to establish parameter ranges by interviewing the personnel responsible for the process under study. This step is crucial to validate the model, which means that system output statistics should be compared to their model counterpart.

c) *Model construction*: After studying the problem, collecting data, and understanding the behaviour of the system, it is essential to build the model based on the data gathered. The computer language may be a general-purpose language (e.g. Visual Basic, FORTRAN, C++, SIMAN), or a special-purpose software combined with a simulation language environment (e.g. ARENA, FLEXSIM, PROMODEL, ANYLOGIC, GPSS). As mentioned earlier, this study utilises ARENA.

d) *Model verification*: Consists on the inspection of the constructed model. It is fundamental to compare model code to model specifications. In other words, the verification stage allows the analyst to make sure that the model is running according its specifications and is working as it was supposed to work. If any divergences are found, then it is necessary to adjust the model by modifying either the code or the specification.

e) *Model validation*: In the validation stage, the outputs of the model are finally compared to the behaviour of the real system. Every model must undertake a validation process. The validation process consists in observing how the model matches the empirical data (measurements of the real-life system to be modelled). In case of significant disparities, the proposed model should be revaluated, which means that it calls for modifications. In many cases, it is necessary to go through multiple cycles of construction, verification, and validation in order to achieve a good model fit.

f) *Simulation experiments*: Once the model is validated, the simulation experiments shall be defined. Then, it is possible to draw some estimations in order to facilitate the problem-solving process. Usually, there is a set of alternative scenarios that should be tested in order to obtain into insights of system behaviour under a variety of circumstances. In order to grant statistical reliability of scenario-related performance measures, each scenario should be replicated, and the results averaged in to reduce variability.

g) *Output analysis*: The performance measures are then subject to a statistical and logical analysis. In this stage, it is possible to identify the best design among a number of alternatives.

h) *Final suggestions*: After selecting the best scenario among several competing alternatives, the analyst is capable of formulating final recommendations for the underlying problem. In most cases, a report is presented.

3.3 Problem description

Despite the large size of the company under study, there is a lack of reliable information regarding to the average total time (lead-time) of the buses in the garage as well as the capacity of its resources. No previous study was conducted to attempt to estimate these performance indicators based on mathematical modelling and statistical analysis. The maintenance engineering team is currently working on the implementation of a new information system, which include the update of the maintenance software so that a greater availability of information can help to predict the behaviour of the system. However, it is fundamental to establish whether the average lead-time of the buses is being affected or not due to capacity constraints. The allocation of resources (a detailed representation of the resources utilised by the company is shown in the model development chapter) is another point of interest since the garage coordinator often assign vehicles to the pits that are working with lower capacities in periods of greater demands. In other words, the objective of the simulation model under consideration is to provide a real quantitative analysis, taking into account the stochastic nature of the operations that occur within the garage and emulating them in order to assist the decision-making process by formulating alternative scenarios. These scenarios include testing increased number of resources, their reallocation, and the impact over lead-time and utilisation.

3.4 Data collection

The data required to build the model was extracted from the database of the company's computerised maintenance software. The advantage of using this data is based on the facility of data gathering, because the process is usually automated. Thus, it is possible to quickly obtain a significant amount of information with low cost. Per example, the maintenance reports include information on the date and time the bus arrived at the inspection pit, the time that the bus left, the identification number of each vehicle, the type of maintenance service that was executed, and the employee responsible for the service.

Although, in many cases it was not possible to obtain reliable information in the company's automation system. Sometimes it was difficult to gather precise data regarding to the inter-arrival times of the buses. The company did not control the exact arrival time of the buses at terminal. The system only provided information relative to the arrival time of buses in the regional bus station, however, it could lead to imprecise results. For this reason, manually filled forms had to be analysed in order to get more precise information. Due to the nature of this data, it was not possible to work with large sample spaces, instead, only the necessary observations were utilised. A detailed explanation on the buses inter-arrival times is conducted in the following chapter.

In other cases, neither automated information nor manually filled forms were available to estimate processes time. In this case, the times for each operation were manually taken using a stopwatch. These operations include the lubrification and fuel loading activities, the external washing procedures, and the machine-washing times. The times for all of these procedures were estimated based on sample sizes of over 30 samples in order to grant reliable information.

In some situations, the alternatives aforementioned were not possible to be executed. Some processes times were only estimated by conducting interviews with the responsible employees. For example, the times of maintenance services of electrical, refrigeration, bodywork, and upholstery were evaluated based on the information given by the staff due to the complex nature of these activities. It was impossible to manually take samples of times from various services, because they were extremely time consuming. The company's automation system did not provide any information about these activities.

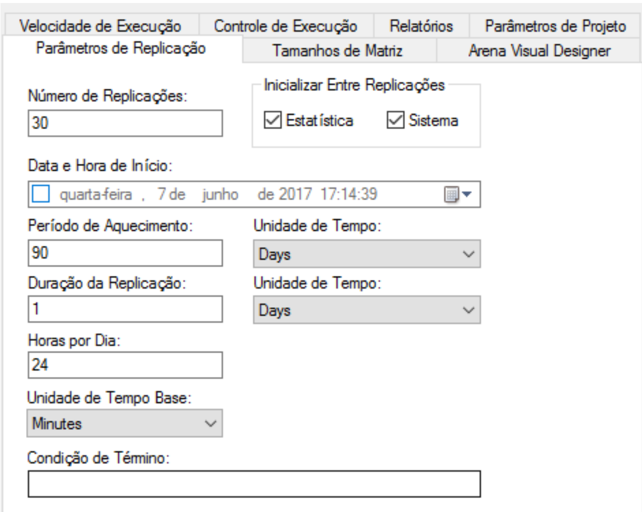
After collecting the data, the information was processed using R statistical software. In case of outlying values, the samples were plotted in a boxplot chart and the outliers were removed. This process was replicated to all activities considered in the simulation model. Then, the processed data were represented using probability distributions. These distributions were chosen based on Arena's *Input Analyser* fit all test. The distributions with the minimum square error value were chosen. They were rejected only if the result for the Kolmogorov Smirnov (K-S) test was under the acceptable value of 0.05. Further information on the process of distribution fitting is given in the next chapter.

3.5 Simulation run setup

The objective of the simulation experiment is to determine the performance of the system by estimating performance measures under a variety of circumstances that configure alternative scenarios. Once the model is composed of diverse probabilistic events, the observed results are sensitive to variability. In other words, the sequence of random numbers (inputs) present in the model will produce different results.

In this study, the performance indicators were measured based on the average of the values produced by each simulation run. The total number of replications was set to 30 and their duration was established as a one-day period. The terminal works 24 hours a day, seven days a week. As a consequence, the operations do not stop from one day to another, instead, they behave as in a continuous system. For this reason, it was necessary to establish a 90-day warm-up period. Figure 5 illustrates the simulation run setup.

Figure 5 - Simulation run setup



Source: Elaborated by the author

3.6 Model verification and validation

As mentioned earlier, the outputs of the model are compared to the behaviour of the real system in order to determine whether the simulation model is valid or not in the validation stage. The developers and users, commonly the decision makers using information gathered from the results of these models, and the individuals affected by the decisions are concerned with the results' accuracy. This concern is also addressed through model validation.

According to Sargent (2005), if the purpose of a model is to answer a variety of questions, the validity of the model needs to be determined with respect to each question. He also argues that numerous sets of experimental conditions are frequently needed to determine the domain of a model's proposed applicability. Therefore, a model may be valid for one set of experimental conditions and invalid in another. A model is considered valid for a set of experimental conditions if the performance indicators or output variables of interest are within its acceptable range. In other words, the acceptable range can be intended as the amount of accuracy required for the model's purpose. It is also important to mention that the amount of accuracy required should be defined prior to starting the development of the model or very early in the model development process.

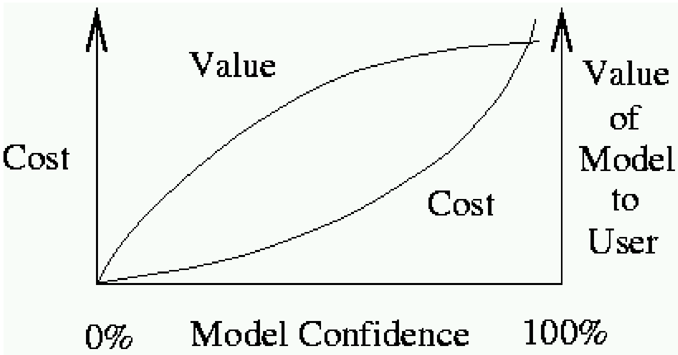
Despite the importance of validation procedures, it is often too costly and time demanding to determine whether a model is absolutely valid over the complete domain of its applicability (SARGENT, 2005). Rather, tests and evaluations must be conducted until a sufficient confidence level is achieved for its intended application. However, defining that a model has enough accuracy for a set of experimental conditions does not guarantee that a model is valid everywhere in its applicable domain. Figure 6 illustrates the relationships between model confidence, cost of performing model validation, and the value of the model to a user.

Sargent (2005) states that there are four basic types of approaches for model validation. These as approaches are discussed as follows:

a) A regularly used approach is for the model development team itself to make the decisions as to whether a simulation model is valid or not. A subjective decision is taken depending on the results of the numerous tests and evaluations conducted as part of the model development process.
b) In the second approach, if the size of the simulation team is not large, it is necessary to have the users of the model heavily involved with the model developing team in determining the validity of the simulation model. In this approach, the focus of model validation changes from the developers to a customer oriented perspective.
c) The third approach is usually called "independent verification and validation". It uses a third independent party to judge if the simulation model is valid. The third party must be isolated from both simulation development team and the model user.
d) The last approach uses a scoring model to determine the simulation model validation. Scores are determined subjectively when conducting numerous

aspects of the validation process and then combined to determine category scores and a general score for the simulation model. The model is only considered valid if its overall and category scores are greater than an established limit. However, this approach is rarely used.

Figure 6 - The comparison between confidence, cost, and user value



Source: Sargent (2005)

In this study, the model validation process was based on the second approach. The development team was composed of only one person. As stated by Sargent (2005), if the simulation team is not large, it is necessary to have the users of the model laboriously involved in determining the validity of the model. In this case, it was necessary to establish a performance indicator measure to be validated by the users. This performance indicator should be able to represent the real system according to the acceptable range predefined during the early stages of model development.

3.6.1 Key performance indicators

The most important performance indicator for the company is certainly the lead-time (total time) of the buses. Currently, the company cannot precisely estimate this performance indicator due to the lack of a reliable information system. Therefore, it is fundamental to provide an estimation of this parameter to facilitate the decision-making process, mostly in moments of high season, when the garage operates with a greater demand.

The average waiting time is also fundamental to understand the behaviour of the system. Currently, this performance indicator is not monitored by the company. It is directly associated with the utilisation of the inspection pits and other physical assets. With this performance indicator, it is possible to determine bottlenecks as well. The waiting time has a strong correlation with the lead time of the buses. Other important time measure includes the value-added time, which can be intended as the total sum of the times spent in value-adding activities.

Another important performance indicator is the number of scheduled buses (number out). The number of scheduled buses vary according to random and seasonal factors. Although, it is possible to assess this indicator by performing a historical analysis of a certain time period. For this reason, the number of scheduled buses was chosen as a performance indicator of interest. In this case, it was the only way of matching historical data and simulation outputs. There are other interesting measures such as the number of work-in-process vehicles and the number of buses that arrive at the terminal (number in).

To assess the capacity of the terminal, there are also some performance indicators. It is possible to measure either instantaneous and scheduled utilisation of each resource. In this study, the scheduled utilisation is considered a better performance indicator because it only considers the working hours of each resource. It is important to measure the utilisation of the inspection pits, external washing platforms, fuel station, and cleaning spaces. Information regarding to mechanical pits scheduled utilisation is especially valuable because the company can evaluate the necessity of expanding the number of resources in order to match increases in future demand. The mechanical inspection pits are expected to have a higher utilisation in comparison to the rest of the resources, because two of the most important operations use them. These operations are: the overall inspections and the execution of mechanical services. Table 1 shows the key performance indicators considered in this study.

Table 1 - Key Performance Indicators

Performance Indicator	**Type**	**Measure**
Value-added time	Entity related	Time (minutes)
Wait time	Entity related	Time (minutes)
Total time	Entity related	Time (minutes)
Number in	Entity related	Units
Number out	Entity related	Units
Work-in-progress	Entity related	Units
Scheduled Utilisation	Resource related	Relative time (%)

Source: Elaborated by the author

3.6.2 Matching simulation outputs and historical data

Before exploring new alternative scenarios, it is necessary to verify whether the simulation model is capable of faithfully reproducing the behaviour of the real system. Otherwise, the conclusions obtained after simulating alternative scenarios would differ from the conclusions obtained in the real system in case of implementation. To validate the results of the model, it was set a confidence interval of 95% and the number of scheduled buses performance indicator was compared to the real system based on real observations from the period of 12nd to 26th of September 2016. The average number of buses scheduled for one day under normal circumstances is expected to be 107.67 buses. The simulation outputs show that the average number of scheduled buses is 104.70. The upper and lower bounds for the confidence interval are respectively 109.94 and 99.47. From these observations, it is clear that the emulated system and the real system share a similar behaviour in relation to the number of scheduled vehicles.

In order to validate the model, the results were shown to the users. The maintenance engineering team of the company under study validated the model based on the number of scheduled buses as aforementioned. It is important to state that this study aims at providing some insights of the behaviour of the real system rather than providing absolute answers. As discussed in section 4.1, it would significantly increase the simulation costs both in terms of time and economical aspects. It is also fundamental to consider the obstacles in finding reliable data for some processes due to the lack of a robust information system.

4. MODEL DEVELOPMENT

This chapter presents the main aspects of the simulation project from the design phase to its conception. First, there is a brief discerption of the main processes that occur within the company under study. Then, the scope and limitations of the simulation study are defined. The last section contains a detailed explanation of the model building. The structure for representing the processes is specified and divided as follows: bus arrival, fuel station, external washing, machine wash, inspection pits, maintenance services, cleaning services, and, finally, the resources for each of these processes are determined.

4.1 Process description

The bus garage is the main maintenance hub of the company under study. In this hub, the company plans the routes, establishes vehicle timetables, and houses the company headquarters. As mentioned earlier, there is an increasing necessity for the capacity evaluation of the garage. No statistical research was previously conducted in order to determine its operational capacity. Another frequent problem faced by the company regards to the identification of possible bottlenecks that occur within the maintenance department. This is a common problem of most companies that operate this type of service in Brazil.

The company under study provides interstate and intermunicipal bus transportation service. It operates in 12 Brazilian states and in the Federal District, reaching more than one thousand destinations in the north, northeast, and central regions of Brazil. The company initiated its operations in 1992 aiming at providing premium bus service and prioritising comfort, quality, and safety in its bus lines. It has a modern fleet of approximately 410 vehicles with an average age of only 2 years. Annually, the company updates around 25% of its fleet. The maintenance department executes several periodic inspections on its vehicles in order to detect possible failures and grant bus availability. The company counts with over 2000 employees.

The main hub receives buses from several destinations spread all over Brazil. It also serves as a bus depot capable of storing approximately 400 vehicles. Over 100 buses arrive each day for inspection or to perform any maintenance service that is necessary for safety and comfort standards. The maintenance operations involve the main processes that occur within the garage. The buses undergo cleaning, inspections, corrective and preventive maintenance. In order to model the system, it is necessary to define the process flow that occur within the terminal.

The maintenance operation process was developed in Business Process Modelling Notation (BPMN) language using Bizagi software. Appendix A depicts the maintenance operations process that occur within the garage.

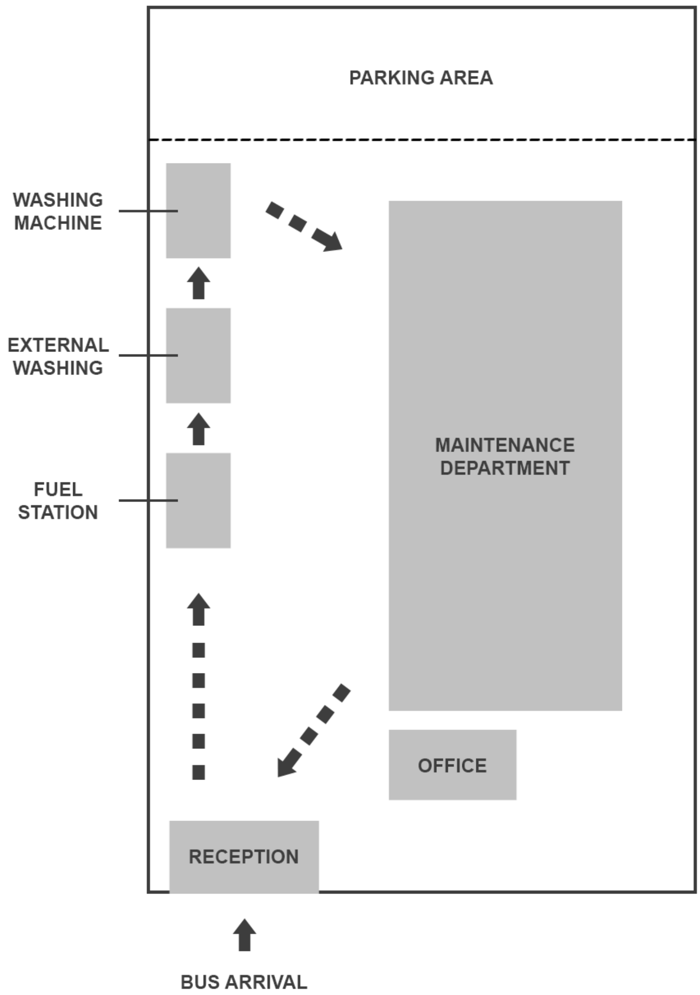
The process starts with a green circle indicating bus arrival. The first procedure is to deliver the travel form to the driver at the reception. This form contains information about the bus and should be filled by the driver. In case of failure or vehicle damage, the driver needs to report what happened in this document in order to facilitate the inspection as well as corrective actions. Then, the travel form is delivered to the staff at the fuel loading station.

The yellow gateway represents multiple tasks occurring in parallel. When the bus moves to the fuel station, several processes occur at the same time. The fuel station personnel prepare the bus for fuel loading and lubricates the mechanical components. Another employee checks the travel form and the filters' expiration. Based on the driver's report (travel form) and on vehicle kilometrage the staff opens a service order, which will be sent to the maintenance department to plan the maintenance procedure for each bus.

After, the bus proceeds to the washing department. An initial external wash is performed to remove any type of gross dirt present o the bus body. It is an activity that depends mostly on labour. Usually, a team of five people is employed to do this task. Subsequently, the vehicle is displaced to a washing machine to perform an additional wash. This second wash is necessary to remove any remaining dirt from the bus body. Next, the staff checks whether the bus is scheduled in order to establish the priority. If there is free space available in the inspection pits, the bus goes directly to perform the maintenance procedures that were defined in the service order. On the other hand, if all inspection pits are busy, the vehicle is moved to the parking area to wait for available space in the maintenance department. A sign is commonly place on the windshield of the buses to identify their status.

As soon as the bus arrives in the maintenance department, an employee is responsible for assigning it to an inspection pit. First, he checks the type of service order requested. Frequently, all the buses need to perform an overall inspection, which means that it has to pass through all kinds of inspections such as: mechanical inspection, electrical inspection, refrigeration inspection, upholstery inspection, and bodywork inspection. Thereafter, if there are any preventive or corrective actions, a new service order must be opened. Then, the bus need to be displaced to the relative inspection pit. In other words, if a bus has to perform any corrective or preventive actions it needs to move from one department to another depending on the service type. To facilitate the visualisation of the physical layout of the garage Figure 7 is provided.

Figure 7 - Garage's layout



Source: Elaborated by the author

When the bus finishes all maintenance procedures, it is ready to go to the final stage. A final cleaning operation is necessary in order to provide the best environment as possible to the customer. First, the cleaning staff goes to the interior of the bus to remove any remaining garbage, left by the last passengers. Another crew is responsible for cleaning the windows as well as the windshield. Finally, there is a final inspection to make sure that there is no client's personal belongings or dirt from the last trip inside the vehicle.

The garage works 24 hours a day, from Monday to Sunday. Usually, the demand for buses suffers variations during the week days due to some factors. Per example, on Friday the terminal is busier because of the larger demand of buses for the weekend. Monday is also a very busy day during the morning because most of the vehicles are arriving from the weekend travels. The weekdays are more regular because the demand is commonly lower. It is important to mention the fact that other seasonal events have a strong correlation with demand increase, such as: public holydays and high season periods (November, December, and January are busier in relation to other months), and special events like concerts and parades.

Even though the garage works 24 hours a day, it is important to mention that the internal procedures, tasks, and processes do not have the same capacity all day long. Per example, some processes do not work during the night shift due to the increased labour costs and diminished demand. Each process has its own schedule. These schedules will be described in detail in the following sections.

4.2 Definition of simulation scope and structure

Simulation modelling is frequently associated with abstraction and simplification. Defining the correct level of abstractness is fundamental due to the fact that simulation is often motivated by economical and time restrictions. If the model is intended to represent the real system with a maximum level of detail, it would probably be inefficient in terms of costs and time. The abstractness level of a model was previously described in subsection 2.1.3.

Among all the processes executed in the garage, this study tries to represent the preparation and maintenance processes of the vehicles. Another several processes occur within the main hub of the company, such as financial support, accountancy, human resource management, inventory management, resource management and sourcing, traffic planning, schedule planning, etc. The maintenance and preparation activities were chosen because they represent the core business of the company. Granting the availability of the buses, comfort, and system safety is fundamental to this type of business due to the impact that these activities have over the client's perception of added-value. Therefore, it is essential to be able to understand the capacity of the terminal in order to support the decision-making process.

One of the main goals of this research is to represent the real system in a way that the processes' times as well as the performance measures obtained with the simulation reach close values in relation to the real observations, thereby making it possible to configure the model in order to observe the system under different circumstances and scenarios. Due to the high complexity of the system under study, there are a number of activities that were not modelled. The reason for this is related to the economic and time cost of the final model that would significantly increase, and would probably make the model inefficient rather than useful. Some premises and simplifications were adopted during the modelling of the system. The assumptions are described as follows:

a) The model does not consider variations in demand influenced by external factors, such as: public holidays, seasonality, bus availability, and other factors. The demand of buses was estimated based on real observations and, then, were segmented into time intervals.
b) It is assumed that increases in bus demand keep the same proportion. Inter-arrival times for each time segment maintain the same proportions and can be modelled using the same probability distributions. By way of explanation, it is only necessary to multiply the inter-arrival times by a constant.
c) The model does not consider sporadic failures on the system including failures on the fuel pump, maintenance of the fuel station, fuel quality inspections, washing machine maintenance interruptions, breakdowns, and other events that rarely occur.
d) It is assumed that the buses follow a First Come First Served (FCFS) allocation police. In other words, the buses are assigned to inspection pits according to their arrival order. The model does not consider the schedule of each bus in order to allocate them on the inspection pits.
e) The transfer times between processes are not consider in this model. The time spent on transfer from reception to fuel station, from fuel station to external washing, from external washing to washing machine, from washing machine to inspection pits, and from an inspection pit to another were no considered. These times are neglectable since they do not effectively affect the operations. They are also susceptible to variations, thereby being hard to measure.

4.3 Model building

In this section, it is discussed how the model was developed. The following subsections details the important components of the models as well as the procedures adopted to simulate the operations at the facility. First, the process of bus arrival is addressed. Demand variations, probability distributions, and data gathering processes are described in detail. Second, the fuel loading operations are discussed. Third, it is encompassed the characteristics and model structure for external washing operations. Fourth, it is presented the machine-washing process and how it was approached. Finally, the processes within the maintenance department are described. It includes the mechanical, electrical, refrigeration, upholstery, and bodywork inspections as well as the services performed by each one of these sectors. Figures, charts, diagrams, and tables are provided in order to facilitate the understanding of the model conception.

4.3.1 Bus arrival

In order to simulate the bus arrival event, it was necessary to obtain information of bus arrival times in the past few months. However, the company did not store the arrival times of buses in its database. Then, it was utilised a document called “fuel loading bulletin” that was filled by the employees responsible for lubrification and fuel loading tasks at the fuel station. This document contains information about the time that each bus arrives at the fuel station. Therefore, the model was calibrated to simulate bus arrivals at the fuel station rather than arrivals at the reception. This abstraction was necessary, because the travel distance between the main entrance (reception) and the fuel station (first process) is relatively short and, thus, can be ignored.

A sample of 15 days was taken from the fuel loading bulletins. These data were retrieved from the company’s archive. All the information contained in the documents was filled by hand. Then, it was necessary to transfer the information to a computer spreadsheet in order to utilise them in the model. A total number of 1615 arrival times were extracted and transferred. Next, the information was processed to gain some insight about the behaviour of the system. In order to easily comprehend the bus arrival events, the day was divided into 8 time intervals of approximately 3 hours each. The time intervals are the following: interval 1 (from 00:00 to 02:59); interval 2 (from 03:00 to 05:59); interval 3 (from 06:00 to 08:59); interval 4 (from 09:00 to 11:59); interval 5 (from 12:00 to 14:59); interval 6 (from 15:00 to 17:59); interval 7 (from 18:00 to 20:59); and interval 8 (from 21:00 to 23:59). It is also important to mention that the data was extracted from a relatively regular month. The fifteen-day period selected encompasses the time period ranging from 12nd to 26th of September 2016. This time period was chosen due to the fact that there were no public holidays and special events occurring, so that a regular behaviour is expected. Table 2 shows the total number of arrivals for each day.

Table 2 - Total number of arrivals

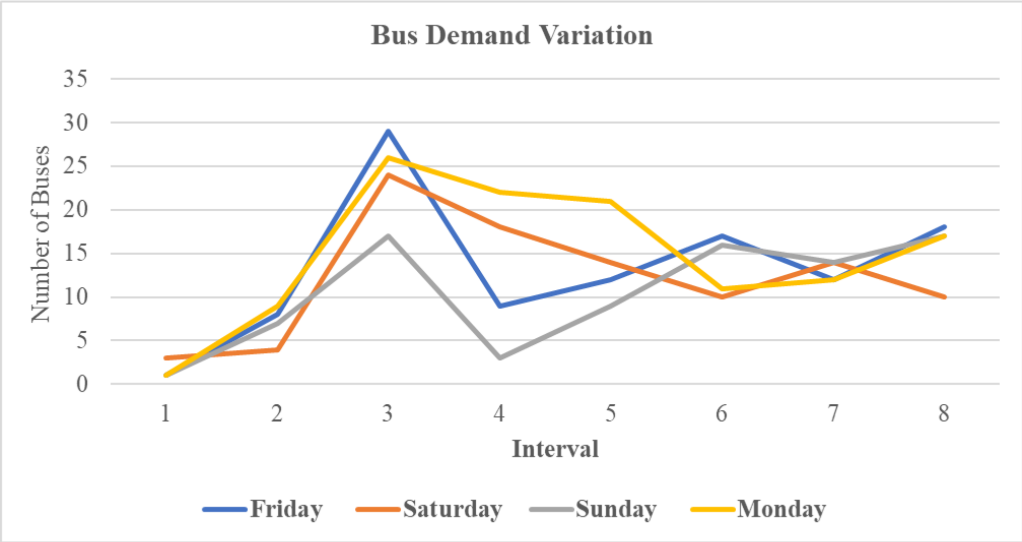
Day	Total Number of Arrivals
12/09/2016 (Monday)	128
13/09/2016 (Tuesday)	97
14/09/2016 (Wednesday)	103
15/09/2016 (Thursday)	105
16/09/2016 (Friday)	106
17/09/2016 (Saturday)	97
18/09/2016 (Sunday)	84
19/09/2016 (Monday)	119
20/09/2016 (Tuesday)	94
21/09/2016 (Wednesday)	88
22/09/2016 (Thursday)	91
23/09/2016 (Friday)	128
24/09/2016 (Saturday)	131
25/09/2016 (Sunday)	129
26/09/2016 (Monday)	115
$\sum$	1615

Source: Elaborated by the author

During the development of this study, it was observed that the arrival rates of buses significantly varied during the day. If this variable was considered constant, the model outputs would not be satisfactory, because it would not be possible to observe the effects of overload and idleness during the day. These effects occur due to demand variation. It is fundamental to understand this concept in order to achieve feasible results.

First, it is viable to identify variations during the weekdays. The period ranging from Friday to Monday is expected to follow a particular behaviour. Usually the garage is busier during Friday and Monday due to the fact that the buses should be operating during the weekend, when the demand is higher. This behaviour can be observed during 16^{th}, 17^{th}, 18^{th}, and 19^{th} of September. In order to illustrate this situation, Figure 8 shows the arrival rate variation of buses for each time interval of the period aforementioned.

Figure 8 - Arrival rate variation



Source: Elaborated by the author

During the day period, it is also possible to visualise the variation of bus arrival rates based on Figure 8. Some characteristics are very similar. First, interval 1 (from 00:00 to 02:59) usually presents lower arrival rates in comparison to other intervals. Then, the arrival rate tends to increase until interval 3 (from 06:00 to 08:59). During the morning, a higher arrival rate is expected, because most buses finish their operations during the night and return to the garage to perform maintenance services early in the morning. Next, the arrival rates start to decrease until interval 4 or 6 and increase again until interval 8, when the cycle starts again.

In order to cope with the issue of the dynamic nature of bus arrivals, it was necessary to incorporate to the model the existing data values by fitting probability distributions to them. The Arena's *Input Analyser* software was chosen to do this task. It provides numerical estimates of the appropriate parameters or fits a number of distributions to the data allowing the user to select the most appropriate one. To choose the best probability distribution, some statistical tests were performed. In this study, it was considered the Kolmogorov-Smirnov test (K-S) and chi-square goodness-of-fit hypothesis tests. These standard statistical tests are commonly used to determine whether a fitted theoretical distribution is a good fit to the data. Of particular interest, there is also the corresponding *p*-value, which always range from 0 to 1. To interpret this value, it is necessary to understand that larger values *p*-values indicate better fits. In this study, it was considered that *p*-values less than about 0.05 does not provide a good fit. It is important to mention that, as with any statistical hypothesis tests, a high *p*-value does not constitute the proof of a good match, instead, it represents the lack of evidence against the fit (KELTON; SADOWSKY; SWEATS, 2007).

The first critical decision was to choose between a theoretical distribution or an empirical one. As mentioned earlier, if a *p*-value for one distribution is fairly high (e.g., 0.05 or greater), then a theoretical distribution was chosen. However, if the *p*-values were low, an empirical distribution was chosen in order to better capture the characteristics of the data. The probability distributions for each time interval are described in Table 3

Table 3 - Probability distributions for each time interval

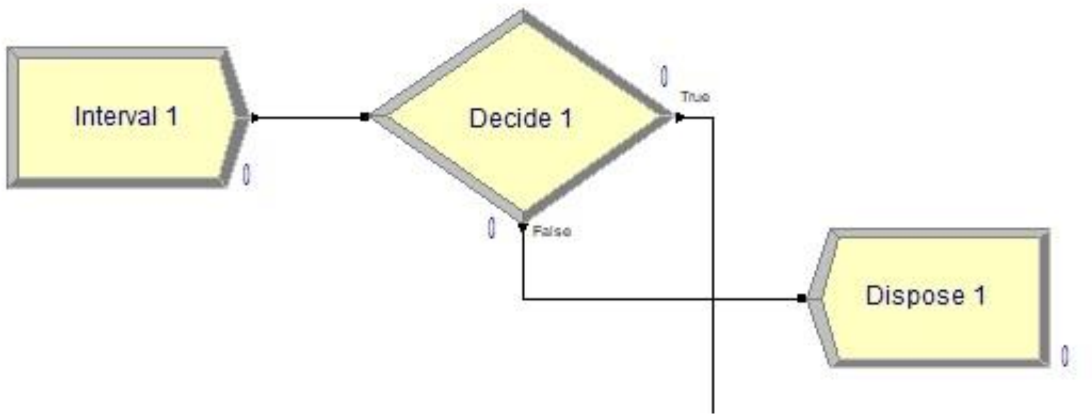
Time Interval	**Probability Distribution**	**Type of Distribution**	**Corresponding *p*-value (K-S result for fit all test)**
Interval 1 (from 00:00 to 02:59)	Weibull (17.8, 0.564)	Theoretical	$P > 0.15$
Interval 2 (from 03:00 to 05:59)	Exponential (15.7)	Theoretical	$P > 0.15$
Interval 3 (from 06:00 to 08:59)	Continuous	Empirical	$P < 0.01$
Interval 4 (from 09:00 to 11:59)	Continuous	Empirical	$P = 0.02$
Interval 5 (from 12:00 to 14:59)	Continuous	Empirical	$P = 0.02$
Interval 6 (from 15:00 to 17:59)	Continuous	Empirical	$P < 0.01$
Interval 7 (from 18:00 to 20:59)	44 * Beta (0.634, 1.46)	Theoretical	$P = 0.08$
Interval 8 (from 21:00 to 23:59)	Continuous	Empirical	$P < 0.01$

Source: Elaborated by the author

It is also important to notice that the *p*-values shown in Table 3 refer to the K-S result for *Input Analyser*'s fit all test. After setting the probability distributions, it was necessary to structure the model. The model was developed using the flowcharts modules available in ARENA. Truck arrivals were simulated by the use of three different modules: create, decide, and disposal. The create module is intended as the starting point for entities (buses) in a simulation model. Entities are generated using a schedule or based on time between arrivals. In this case, inter-arrival times were previously calculated and modelled as probability distributions.

The create module was then associated to a decide module. The decide module allows for decision-making processes in the system. It includes options to make decisions based on one or more conditions or based on one or more probabilities. Conditions can be based on attribute values, variable values, entity type, or an expression. In this case, an expression was used to interrupt the creation of entities. For the first-time interval, per example, it was utilised the expression TNOW < 180 to indicate that, after the three-hour period (180 minutes), the creation of entities should be suspended. In order to interrupt the flow, the decide module was linked to a dispose module. The dispose module is intended as the ending point for entities in a simulation model. In this particular situation, it was used to dispose the excess of entities generated by the creation module. Figure 9 shows the structure of the bus arrival event in the simulation model.

Figure 9 - Structure of the bus arrival event in the simulation model



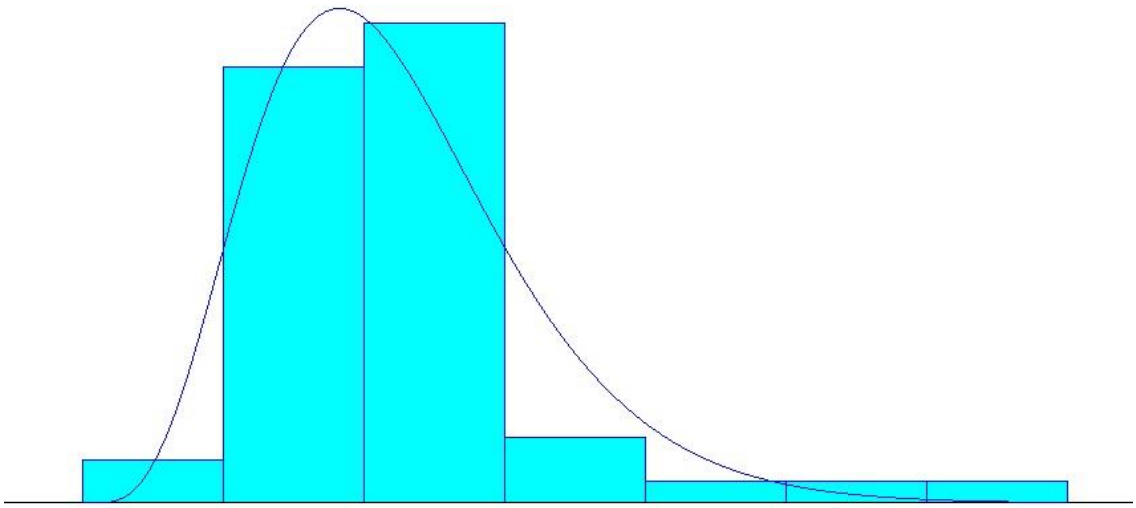
Source: Elaborated by the author

4.3.2 Fuel station

The first process at the garage occurs at the fuel station. The employees responsible for this process have to perform the lubrification of some mechanical components as well as load the buses' tank with fuel. Another important task performed at the fuel station is related to the analysis of the travel form. After analysing the travel form, the responsible employee is requested to open a service order for maintenance inspection. When a service order is opened, it is sent to the maintenance department, where the staff has to assign the buses to inspection pits.

The company did not control the operations time for the tasks performed at the fuel station. Then, it was necessary to measure the times for each operation. Due to the fact that several processes occur at the same time, thus it was considered the time counting from the moment the bus arrive to the moment it leaves the station. A total sample size of 50 was taken into consideration. Each sample was manually measured with a stopwatch during the morning period, when the bus flow is usually higher. The time for each sample was then transferred to a computer spreadsheet so it could be read by the *Input Analyser*. It is important to mention that the probability distribution passed the K-S test with a *p*-value greater than 0.05. The final result of the probability distribution used to model the activities of the fuel station is depicted in Figure 10.

Figure 10 – Gamma distribution for the fuel station process



Source: Elaborated by the author

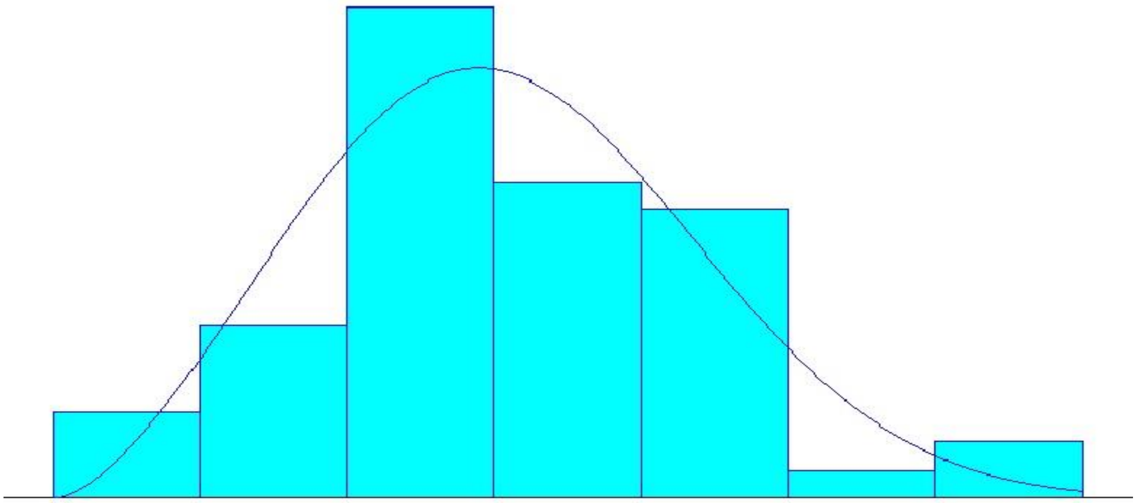
The activity was modelled using a process module. This module is intended as the main processing method of a simulation project. There are options for seizing and releasing resource constraints. The module was then set to a seize delay release action and the probability distribution depicted on Figure 10 was determined as the expression for time delay. The expression of the probability distribution is defined as: 2 + GAMM (0.466, 5.47).

4.3.3 External washing

The second process at the garage occurs at the external washing platforms. The employees responsible for this process have to perform several tasks in order to remove the gross dirty present on the buses. As soon as the bus stop at the external washing platform, an employee starts washing the windshield and the bodywork using a foam hose. Then, another employee opens the engine compartment to clean any dirty component. The toilets also undergo a cleaning process. After performing these procedures, the bus needs to be entirely washed. Finally, the responsible crew has to finish cleaning the tires, empty the black water tank, and refill the fresh water tank so the bus can proceed to the next process.

Despite of the importance of this process to the customer's perception of added value, the company did not control the operations time for the activities executed at the external washing platform. It was necessary to measure the time for each activity. In the external washing platforms, there is a number of tasks occurring at the same time. The responsible crew usually divide the tasks in order to reduce the total time of the process. For this reason, it was considered the time from the moment the bus arrives at the platform to the moment it leaves. It was considered a total sample size of 50. Each sample was manually measured using a stopwatch during the morning period, when the bus flow is commonly higher. As in the previous process, the time for each sample was transferred to a spreadsheet so the information could be read by the *Input Analyser*. The probability distribution chosen after performing the K-S test passed with a corresponding *p*-value greater than 0.05.

Figure 11 – Weibull distribution for the external washing processes



Source: Elaborated by the author

The activity was then modelled using a process module. The process module was set as an action of size delay release and the expression that defines the delay time for the process is defined as: 6 + WEIB (4.99, 2.6). Figure 11 shows the probability distribution chosen to simulate the operations time of the tasks performed at the external washing platforms.

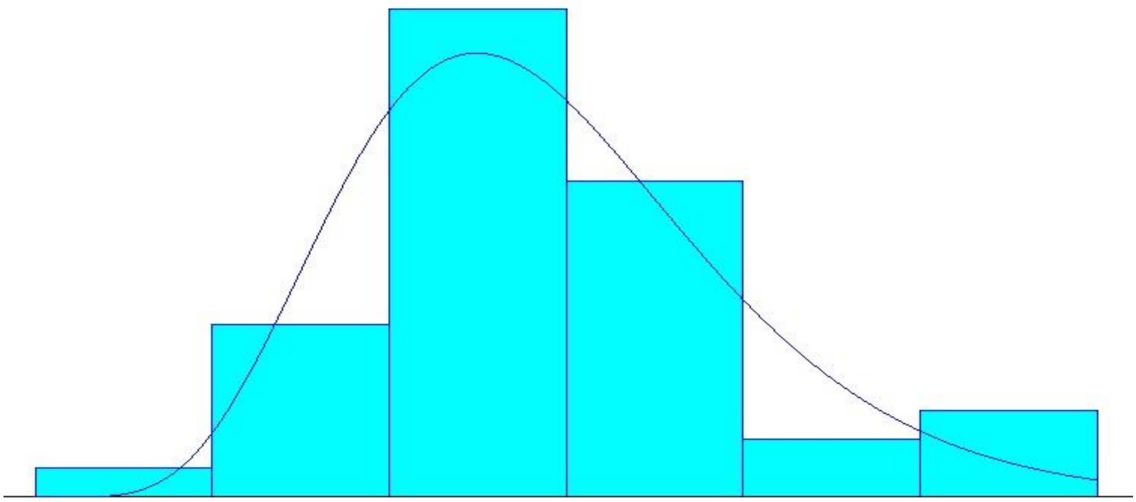
4.3.4 Machine wash

The final process before the bus being assigned to the maintenance department is performed at the washing machines. There are two washing machines that are employed in order to remove any remaining dirt on the buses' bodywork. The machines are capable of washing the buses' roof. It is impossible to reach this part in the previous process of external washing.

The washing times were monitored by the company. Then, a total of 40 available samples containing the time of each wash was extracted from the company's monitoring system. The samples contemplate the moment the bus start the washing process until the moment the bus leaves the machine. The samples were manually measured by the maintenance engineering team. The modelling process followed the same procedure described in the past two subsections. The probability distribution chosen also passed the K-S test with a *p*-value greater than 0.05.

The activity was also modelled using the process module. The expression generated by ARENA's *Input Analyser* is described as follows: 0.54 + GAMM (0.141, 7.14). The expression was used as the delay time for the machine-washing process. The process module was also configured as a seize delay release action. Figure 12 shows the utilised probability distribution.

Figure 12 - Gamma distribution for the washing machine process

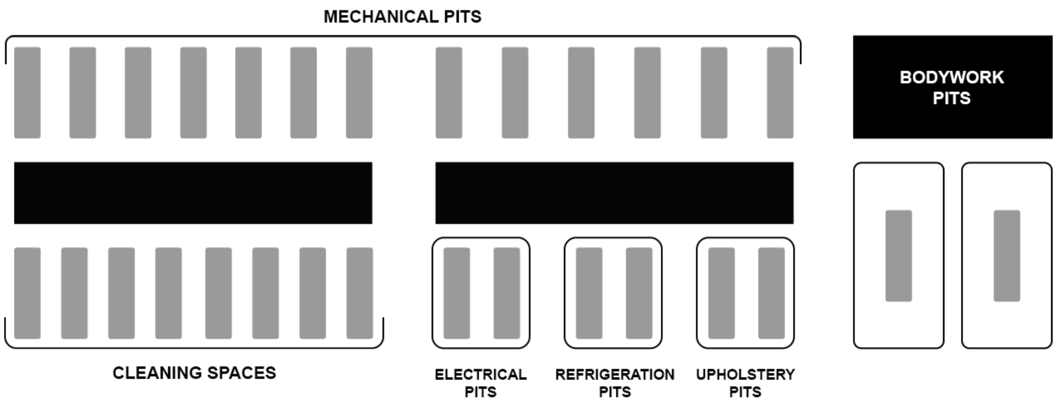


Source: Elaborated by the author

4.3.5 Inspection pits

After undergoing processes related to lubrification, fuel loading, and washing, the buses are ready to move to mechanical pits to perform an overall inspection. The garage coordinator receives the inspection service orders previously opened at the fuel station. He is responsible for assigning the buses to inspection pits. Figure 13 shows the layout of the maintenance department. There are 13 mechanical inspection pits. These pits are used for general inspection as well as to perform corrective and preventive maintenance services.

Figure 13 - Layout of maintenance department



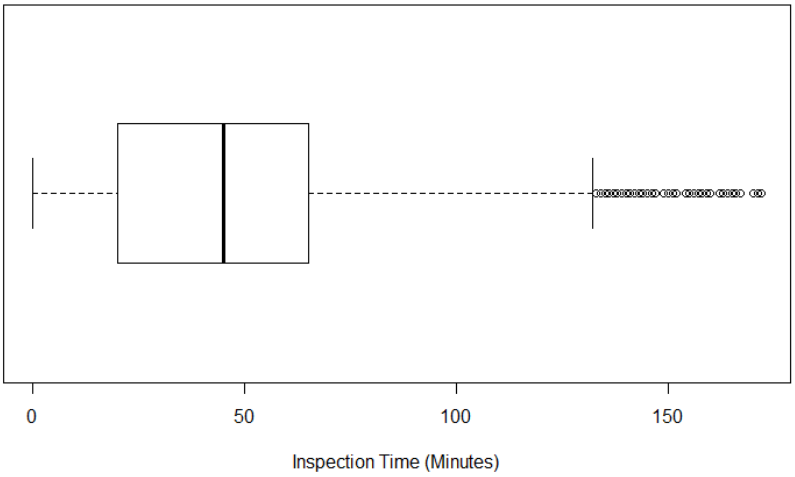
Source: Elaborated by the author

As soon as the bus arrives at an inspection pit, a team specialized in different maintenance areas checks the overall state of the vehicle. The teams are composed of maintenance professionals, which try to identify any possible failure, unexpected functioning, or damaged components of the following areas: refrigeration, electric, upholstery, bodywork, and mechanics. The inspection tasks always occur at the mechanical pits. It is also important to mention that this process is crucial since it is capable of detecting failures, therefore influencing important performance indicators such as safety and vehicle availability, which are key aspects for the customer's perception of added value.

In order to model this process, a sample size of 3925 inspections was extracted from the company's maintenance management software. Due to the large amount of data there were several outliers that needed to be removed from the sample space to obtain a better representation of the real system. A statistical analysis was conducted by using the R software. First, the data was represented in a box plot chart. Second, it was identified any possible outliers. Third, the outliers were removed based on the values that were out of the chart. Finally, the data was transferred to ARENA's *Input Analyser*. Figure 14 shows the sample space containing outlying observations (small circles represent extreme values) and Figure 15 the box plot distribution analysis after removing them.

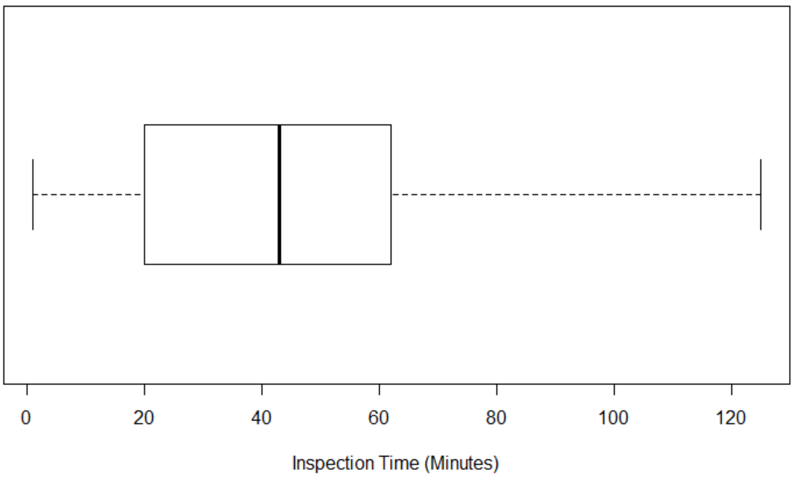
Ultimately, the data represented on Figure 15 was fit into a probability distribution. After conducting *Input Analyser*'s fit all test, it was not possible to obtain a reliable *p*-value for any theoretical distribution. Then, a continuous empirical distribution, which is represented in Figure 16, was chosen to simulate the inspection times.

Figure 14 - Boxplot representation with outlying values



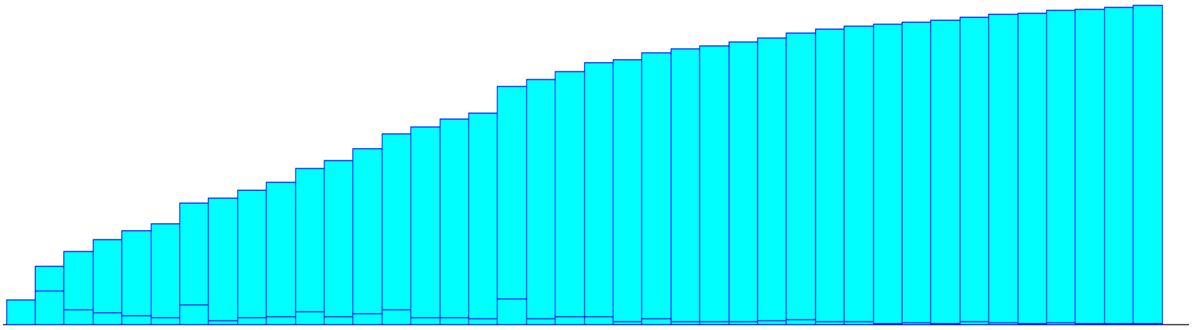
Source: Elaborated by the author

Figure 15 - Boxplot representation after outlier removal



Elaborated by the author

Figure 16 - Continuous empirical distribution for inspection pits



Source: elaborated by author

4.3.6 Maintenance services

In case of unexpected behaviour or vehicle malfunction, it is necessary to perform corrective and preventive maintenance actions. Commonly, the defects are detected during the inspections at the mechanical pits. As mentioned earlier, the company divides the maintenance services into five different groups according to the type of failure: mechanical, electrical, refrigeration, upholstery, and bodywork. As reproduced in Figure 13, each type of service has a specific department and a delimited number of inspection pits.

Table 4 - Probability distributions and proportion of vehicles assigned

Service type	**Probability Distribution**	**Proportion of vehicles assigned to process (%)**
Mechanical	Continuous	67.92
Electrical	Triangular (15.0, 45.0, 300.0)	15.09
Refrigeration	Triangular (60.0, 90.0, 300.0)	9.40
Upholstery	Triangular (30.0, 45.0, 120.0)	1.89
Bodywork	Triangular (60.0, 100.0, 120.0)	10.69

Source: Elaborated by the author

In order to model the execution of maintenance services, it was necessary to establish the proportion of buses that are redirected to perform them. First, a fifteen-day period of historical data including all the maintenance services executed during the time period ranging from 12nd to 26th of September 2016 was analysed. From this data, it was possible to estimate the total number of buses that needed to perform preventive or corrective actions. The reports extracted from the maintenance management system contained information regarding to the type of service that was performed. An interview was conducted with the maintenance personnel to define each type of service. After defining the types of services, the proportion of vehicles assigned to each process was calculated based on the total number of service orders from the period under consideration. Second, the model was constructed using a sequence of process and decide modules. The decide modules were set as 2-way by chance and the process modules were configured according to the characteristics of each activity. After the analysis, it was concluded that 75.67% of the buses need to perform a maintenance service. Finally, it was stipulated the proportion of vehicles that require each type of maintenance service and the probability distributions for simulating the process time. Electrical, refrigeration, upholstery, and bodywork processing times were estimated based on interviews due to the fact that the company did not monitor the times of these activities. The mechanical services were estimated based on information from the computerised management system and had enough samples to fit into an empirical continuous distribution. Table 4 shows the probabilities as well as the proportion of vehicles assigned to each one of the maintenance services.

4.3.7 Cleaning services

The final processes that occur within the garage are cleaning procedures. These procedures are executed in a delimited area as shown in Figure 13. There are 3 different types of tasks that need to be performed. First, it is necessary to clean the interior of the buses. Seats, dashboard, windows, curtains, and other interior components undergo a cleaning process. Second, the exterior also passes through cleaning procedures. Specially the luggage compartment, windshield, the exterior windows as well as the tyres. Third, a final inspection is executed to search for any missing objects left by passengers, or to detect any defect that can compromise the customer’s experience.

These activities were modelled using the process module. Three modules were set with the respective probability distribution to simulate the execution times for each procedure. The characteristics of the probability distributions are described in Table 5. It is important to mention that the data was extracted from the company’s monitoring system.

Table 5 - Probability distributions for cleaning services

Process	Probability Distribution	Sample Size	Max./Min. (Minutes)	Standard Dev.	*P*-value (K-S Test)
Luggage Compartment and Tyres Cleaning	Triangular (1, 2.17, 3.23)	31	3.03/2.13	0.47	$P > 0.15$
Dashboard cleaning	3 + 6.91 * Beta (1.47, 2.62)	42	9.30/3.23	1.47	$P > 0.15$
Final Inspection	2 + Erlang (1.22, 3)	40	11.90/2.52	2.06	$P > 0.15$

Source: Elaborated by the author

4.3.8 Resources

In order to define the capacity for each process, it was necessary to establish the number of resources necessary to accomplish each task. Important characteristics should be formulated such as whether the capacity is fixed or varies according to a schedule. It is also possible to force the resource to fail according to a pattern. In this study, failures were not contemplated, only schedules. Table 6 specifies the characteristics of the resources utilised in the model.

The loading platform and the washing machine have a fixed capacity because they work in 24 hours a day. The external washing platform usually have one hour break from 00:00 to 01:00, which was translated in the schedule. The rest of the resources work in full capacity from 08:00 to 18:00 in a normal day shift. It was also considered the one hour break from 12:00 to 13:00. For quicker operations, like the ones that take place on the cleaning spaces and external washing platforms, the schedule rule was set to “wait”. In longer operations like the ones that happen on the pits, the schedule rule was set to “pre-empt”. The “wait” option basically sets the model to wait until the in-process entities release their units of the resource before starting the actual capacity decrease. Whereas the “pre-empt” option attempts to pre-empt the last unit of the resource seized by taking it away from the controlling entity (KELTON; SADOWSKI; SWETS, 2007). The visualisation of the final version of the model containing all the modules, processes, and resources is available in Appendix B.

Table 6 - Resource list

Resource	**Operations**	**Type**	**Capacity (units)**	**Schedule Rule**
Loading Platform	Fuel loading	Fixed capacity	2	-
External Washing Platform	External wash	Based on schedule	2	Wait
Washing Machine	Machine washing	Fixed capacity	2	-
Mechanical Pit	Inspection/Mechanical services	Based on schedule	13	Pre-empt
Electrical Pit	Electrical services	Based on schedule	2	Pre-empt
Refrigeration Pit	Refrigeration services	Based on schedule	2	Pre-empt
Bodywork Pit	Bodywork services	Based on schedule	2	Pre-empt
Upholstery Pit	Upholstery services	Based on schedule	2	Pre-empt
Cleaning Spaces	Luggage compartment and tyres cleaning/Dashboard cleaning/Final inspection	Based on schedule	8	Wait

Source: Elaborated by the author

5. RESULTS AND DISCUSSION

In this chapter, the results of the simulation experiments are described in detail. First, the real simulated scenario is tested and the results for the performance indicators are shown as well as the queue formation process. Next, an alternative scenario is verified with increased number of inspection pits. It was selected an additional number of four mechanical pits for simulation purposes. The impacts on queue formation, capacity, and performance indicators are evaluated. Then, the performance of the system is assessed for different numbers of mechanical pits to evaluate the benefits of a potential expansion project. Finally, another scenario is tested considering the reallocation of upholstery pits to mechanical pits.

5.1 Simulation results

In this subsection, it will be discussed the overall results of the simulation model after the validation process. First, it is important to understand that there are two types of performance indicators. The first one concerns to the entity itself as well as a predefined time variable. This variable is associated with the behaviour of the entities. In this study, there is only one entity, which are the buses. These performance indicators were defined as entity related indicators.

The second one refers to resource utilisation. The resources are always associated to the process modules of the simulation project. As mentioned earlier, it is possible to define both instantaneous utilisation and scheduled utilisation for these resources. Some resources are based on schedules and others work 24 hours a day, therefore having a fixed capacity. These performance indicators were defined as resource related indicators. An overview of the resources and their characteristics were previously shown in Table 6.

5.1.1 Performance results for entity related indicators

This subsection only refers to entity related indicators, which are associated to a predefined time variable. These performance indicators are useful to the company because they permit future planning and evaluation of process efficiency. It is important to mention that the company stipulates a minimum average time of three and a half hours for each bus in order to execute all the operations within the garage. Moreover, there are also the performance indicators related to the entity itself. Examples of these performance indicators are: the number in, number out, and the work-in-progress (WIP). The outputs of the simulation model are described in Table 7.

Table 7 - Performance outputs for entity related indicators

Performance indicator	**Average - 95% confidence level (minutes)**	**Half width (minutes)**	**Minimum average (minutes)**	**Maximum average (minutes)**
Value-added time	92.83 (88.19; 97.47)	3.18	70.56	106.25
Wait time	126.73 (120.39; 133.07)	13.94	45.98	209.51
Total time	219.57 (208.59; 230.55)	16.57	124.32	312.59
Number in	150.13 (142.62; 157.64)	0.49	147.00	151.00
Number out	104.70 (99.47; 109.94)	1.73	95.00	113.00
WIP	25.12 (23.86; 26.38)	1.42	17.10	33.58

Source: Elaborated by the author

From the table above it is possible to conclude that the average total time of the entities in the model is close to the company's established limit of three and a half hours (210 minutes). If it is considered the 95% confidence interval, the simulated system accurately represents the behaviour of the real one. Another important consideration is regarding to the number out of buses. As previously stated, this number also represents the amount of buses that daily leaves the terminal. According to the maintenance engineering team, these outputs faithfully depict the behaviour of the real system.

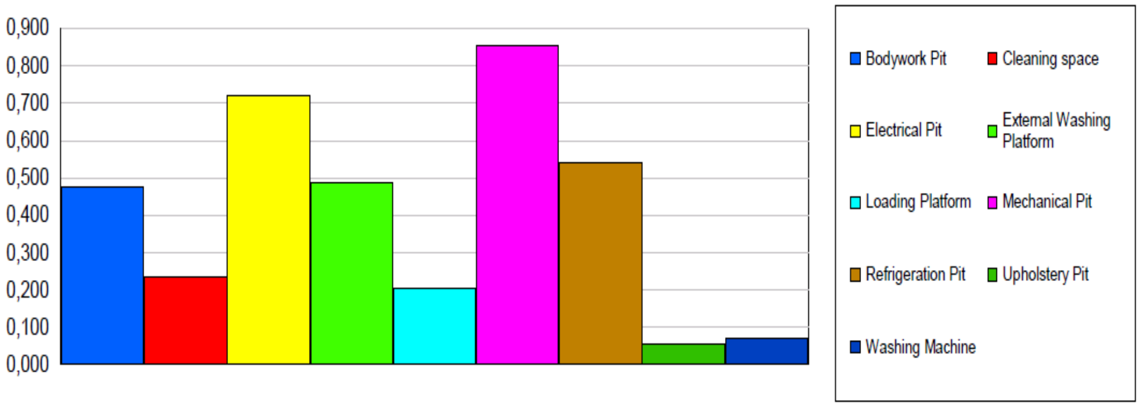
Another important consideration is relative to the wait time. This performance indicator is very important to the company under consideration. During the high season period, it is important to estimate these numbers in order to determine the efficiency of the operations and to identify possible bottlenecks.

The value-added time concerns to the amount of time that the entities spend on value-adding activities. The objective of the company is to keep the value-added time as close as possible to the total average time. Furthermore, since the company in question is a service provider, it is important to keep the value-added time greater than the wait time for more efficiency.

5.1.2 Performance results for resource related indicators

One of the most important tasks of the model is to assess the capacity of the facility under study. In the real scenario, it is possible to observe that the mechanical pits are the busiest of the resources. This occurs due to the fact that two of the most important operations depend on them, which include the overall inspections and the mechanical services. The demand for these resources are usually higher than others. Figure 17 depicts the resource utilisation and Table 8 shows the related results.

Figure 17 - Resource utilisation



Source: Elaborated by the author

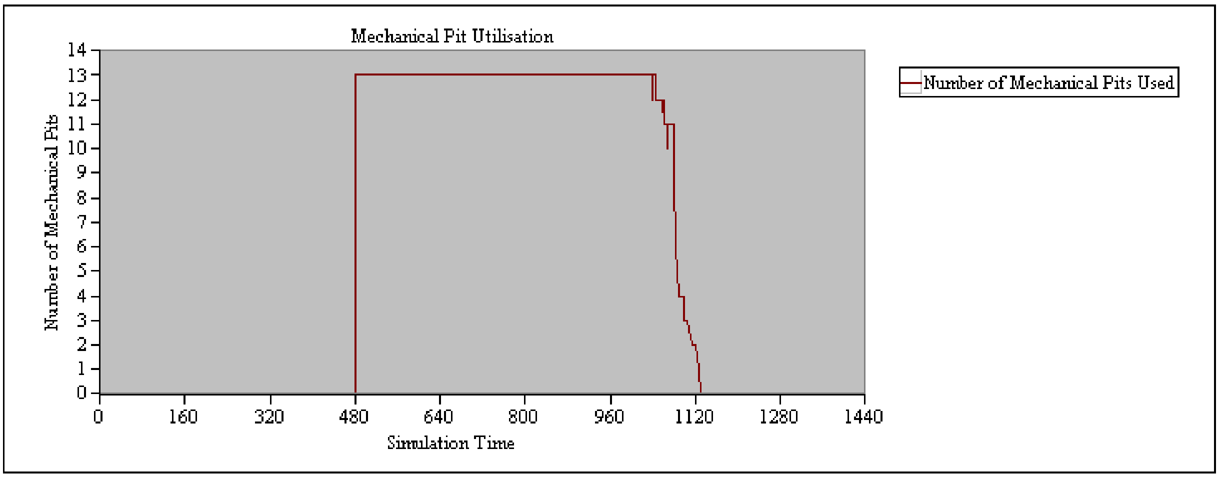
Table 8 - Scheduled utilisation of resources

Resource	Average	Half Width	Minimum average	Maximum Average
Bodywork Pit	0.47	0.07	0.13	0.77
Cleaning Spaces	0.23	0.01	0.20	0.26
Electrical Pit	0.72	0.05	0.49	1.00
External Washing Platform	0.49	0.01	0.43	0.55
Loading Platform	0.20	0.00	0.18	0.24
Mechanical Pit	0.85	0.03	0.70	1.00
Refrigeration Pit	0.54	0.08	0.13	0.94
Upholstery Pit	0.06	0.02	0.00	0.20
Washing Machine	0.07	0.00	0.06	0.08

Source: Elaborated by the author

As expected, the mechanical pits are by far the resources with the greatest utilisation rate. The average scheduled utilisation reaches 85% with a minimum average of 70% and maximum average of 100%, which means that it is overloaded during some periods of the day. In order to have a better understanding of these parameters a chart containing the utilisation of the mechanical pits over the day is provided in Figure 18.

Figure 18 - Mechanical pit utilisation over time



Source: Elaborated by the author

Figure 18 was extracted from a simulation run. It shows the number of mechanical pits utilised during a one-day period. It is possible to observe that the mechanical pits are being used in full capacity from the beginning of the work shift to a moment close to the end, when the utilisation starts to drastically decrease. On the next day, a new queue is formed for inspection and execution of mechanical services, keeping the utilisation rates high again. The company is operating in full capacity at the moment. For this reason, it is important to look for alternatives in order to reduce the utilisation of the mechanical pits in order to buffer future demand increases.

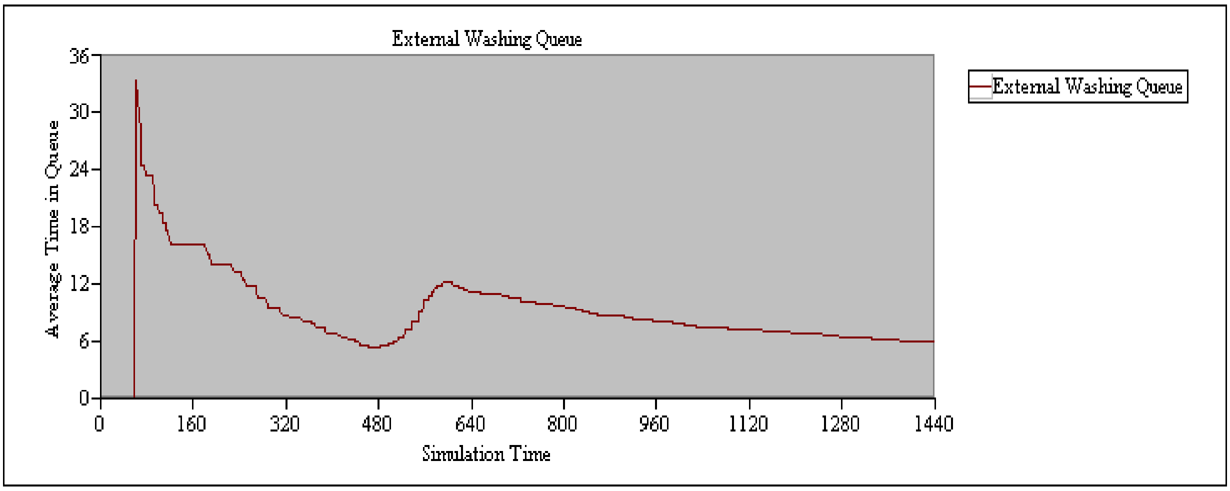
Another resource with high utilisation rates are the electrical pits. This may happen due to the frequent occurrence of electrical problems. These problems vary according to several factors. But kilometrage and the age of the buses are two of the main reasons. To tackle this problem, the company tries to maintain the fleet with an average age of only two years. After two years, the buses start to require more maintenance services, which can affect the operations of the company.

The other resources maintain acceptable levels of utilisation, such as the bodywork pit, refrigeration pit, external washing platforms, cleaning spaces and fuel loading platforms. However, an important factor to consider is the utilisation of the washing machines and upholstery pits. The low level of utilisation of washing machines may occur because of the fast execution times and their high availability. On the other hand, the upholstery pits follow a ten-hour schedule, but are rarely used.

5.1.3 Queues

The company under study is interested in determining the average time in queue for two important processes. The first one concerns to the queues for the external washing platforms. The process time of the external washing is considerably higher than the previous process of fuel loading. During the morning, it is common to form queues between the fuel station and the external washing platforms. The other one regards to the inspection pits queue. Due to the high number of vehicles during the morning (beginning of the work shift), it is frequent that buses must be assigned to the parking area to wait for a free space at the mechanical pits. The average time in queue to perform the external wash as well as the inspections are respectively depicted in Figures 19 and 20.

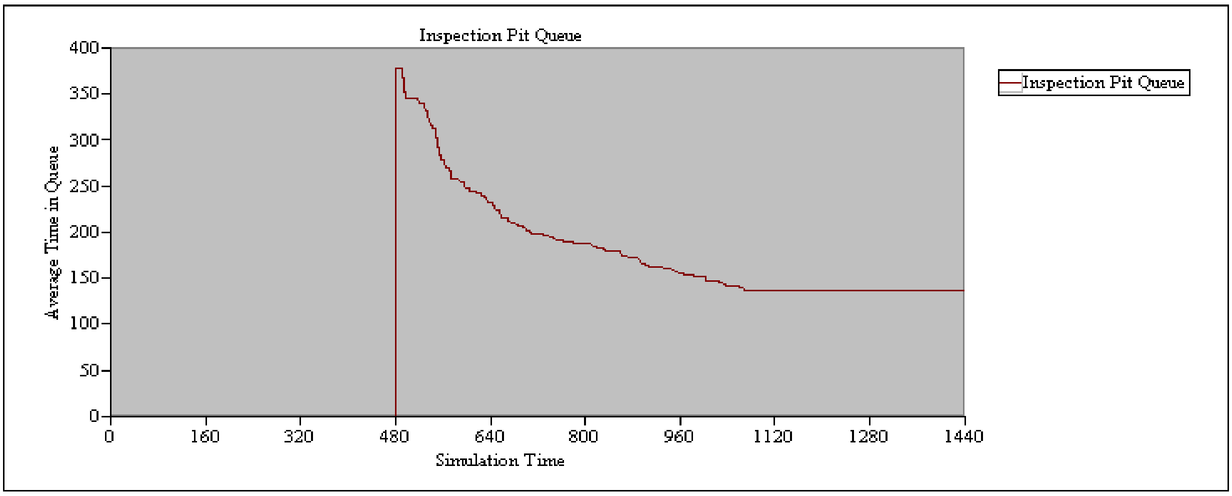
Figure 19 - Average time in external washing queue



Source: Elaborated by the author

From Figure 19, the waiting times are greater at 01:00, when the external washing platforms start to operate. It should be taken into consideration that any remaining buses from the last day and the ones that arrive before one o'clock are already waiting. The average time start to decrease until approximately 08:00, when the arrival rates are higher. Although, it keeps an acceptable rate during the rest of the day. From Figure 20, it is clear to see that the average waiting time is higher during the beginning of the work shifts because the buses that arrive earlier are waiting to be allocated to an available pit. Then, the average time tends to decrease along the day. The average time and number of waiting units at the queues are shown in Table 9.

Figure 20 - Average time in inspection queue



Source: Elaborated by the author

Table 9 – Queue performance evaluation for real scenario

Queue	Average waiting time (minutes)	Average number waiting (units)
External washing	3.79	0.34
Inspection Pit	103.57	10.75
Perform bodywork services	14.05	0.22
Perform Electrical services	52.24	0.87
Perform mechanical	51.65	2.23
Perform refrigeration	25.72	0.33
Perform Upholstery	0.15	0.01

Source: Elaborated by the author

5.2 Alternative scenario: Increasing the number of inspection pits

As mentioned in the last section, the utilisation of inspections pits reached high values. In order to test the impact over the performance indicators previously mentioned, the model was set to operate with an additional number of mechanical pits. The total number of mechanical pits was increased from 13 to 17. The mechanical pits were chosen due to the fact that two of the most important operations depend on them (overall inspections as well as the execution of mechanical services). The results over the performance measures will be described and compared with the real system in the following subsections.

5.2.1 Performance results for entity related indicators with the increased number of mechanical pits

First, it will be discussed the impact over entity related indicators. A comparison with the results shown in Table 7 is important to analyse different behaviour of the real system and the modelled scenario. With an increased number of mechanical pits, it is expected to see alterations mostly in the performance in the time related performance measures such as: lead time, value-added time, and wait time. Another important consideration regards to the number in, number out, and WIP performance measures, which are expected to remain similar.

Table 10 - Impact over entity related indicators

Performance indicator	Average - 95% confidence level (minutes)	Half width (minutes)	Minimum average (minutes)	Maximum average (minutes)
Value-added time	95.02 (90.27; 99.77)	3.68	71.86	113.56
Wait time	100.30 (95.29; 105.32)	11.33	33.74	153.83
Total time	195.32 (185.55; 205.09)	14.44	105.59	267.40
Number in	149.63 (142.15; 157.11)	0.69	146.00	151.00
Number out	105.00 (99.75; 110.25)	1.50	97.00	112.00
WIP	23.24 (22.08; 24.40)	1.26	15.59	29.40

Source: Elaborated by the author

From Table 10, it is possible to conclude that the impact over the wait time, and total time are the greatest. The wait time reduced from 126.73 (120.39; 133.07) to 100.30 (95.29; 105.32). The time spent on queues significantly diminished in comparison to the real scenario. In relative terms, the wait time dropped 20.86%. In relation to the total time, it reduced from 219.57 (208.59; 230.55) to 195.32 (185.55; 205.09), which represents a reduction of 24.25

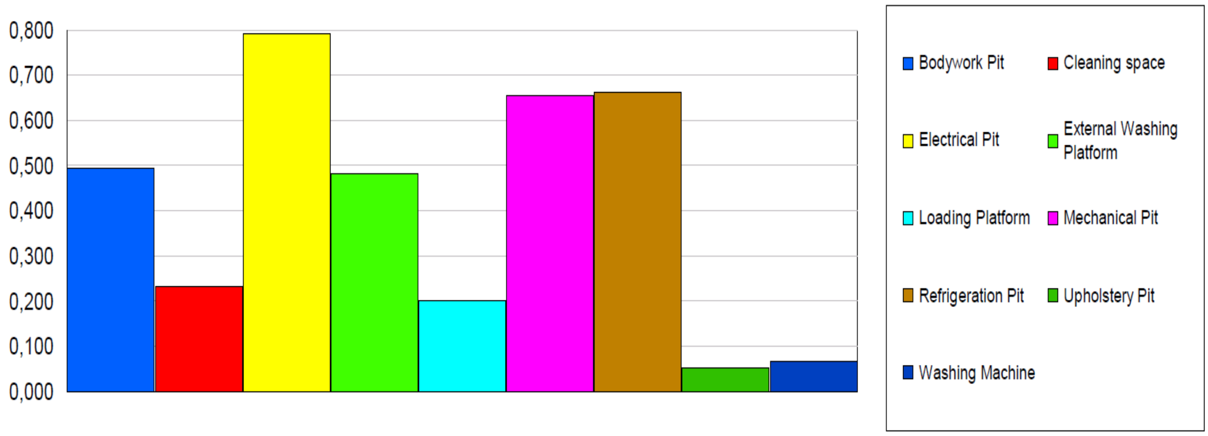
minutes and 11.04% in relative terms. It is also important to mention that the value-added time increased.

The number in and number out performance indicators did not suffer any alterations. Although, the number of work in progress entities reduced in comparison to the real scenario. This might occur due to the fact that the buses are leaving the garage quicker. From this perspective, the installation of new mechanical pits would bring positive results for the company.

5.2.2 Performance results for resource related indicators with the increased number of mechanical pits

Another important scenario to test is relative to the utilisation of resources after adding 4 new mechanical pits. The utilisation of the mechanical pits is expected to drop since the number of buses remain the same. To draw some conclusions about the utilisation of the mechanical pits, Figure 21 is provided. The detailed outputs for the new scenario is shown in Table 11.

Figure 21 - Resource utilisation with increased number of mechanical pits



Source: Elaborated by the author

From Table 11, it is possible to conclude that the utilisation of mechanical pits significantly dropped in relation to the real scenario. According to Table 12, the scheduled utilisation of the mechanical pits is 85%. In comparison to the alternative scenario, there was a 20% reduction. The reduction of the scheduled utilisation allows the company to buffer any additional demand more comfortably. However, it is costlier to acquire and maintain an additional number of resources. In this case, a specific analysis should be conducted in order to evaluate whether the acquisition of new mechanical pits is beneficial to the company under study. To understand the scheduled utilisation behaviour of the alternative scenario during the day, Figure 22 is provided.

Table 11 – Impact over scheduled utilisation of resources

Resource	Average	Half Width	Minimum average	Maximum Average
Bodywork Pit	0.49	0.07	0.23	0.89
Cleaning Spaces	0.23	0.01	0.19	0.26
Electrical Pit	0.79	0.07	0.37	1.06
External Washing Platform	0.48	0.01	0.41	0.53
Loading Platform	0.20	0.01	0.17	0.23
Mechanical Pit	0.65	0.02	0.54	0.77
Refrigeration Pit	0.66	0.09	0.09	1.01
Upholstery Pit	0.05	0.02	0.00	0.24
Washing Machine	0.07	0.00	0.06	0.08

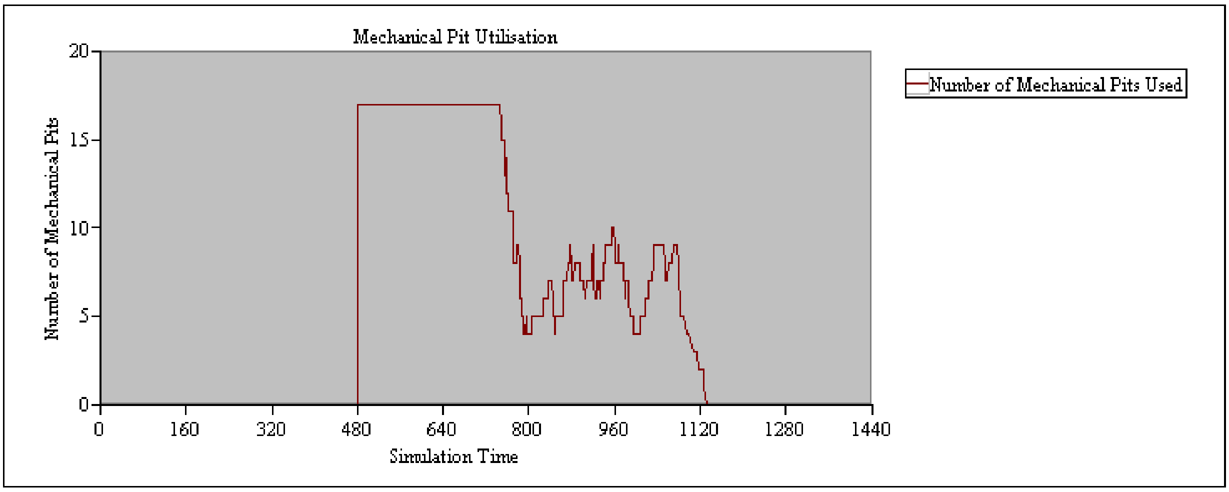
Source: Elaborated by the author

Table 12 - Comparison between real and alternative scenarios for scheduled utilisation

Resource	Scheduled utilisation (real scenario)	Scheduled utilisation (alternative scenario)
Bodywork Pit	0.47	0.49
Cleaning Spaces	0.23	0.23
Electrical Pit	0.72	0.79
External Washing Platform	0.49	0.48
Loading Platform	0.20	0.20
Mechanical Pit	0.85	0.65
Refrigeration Pit	0.54	0.66
Upholstery Pit	0.06	0.05
Washing Machine	0.07	0.07

Source: Elaborated by the author

Figure 22 - Mechanical pit utilisation over time with increased number of inspection pits



Source: Elaborated by the author

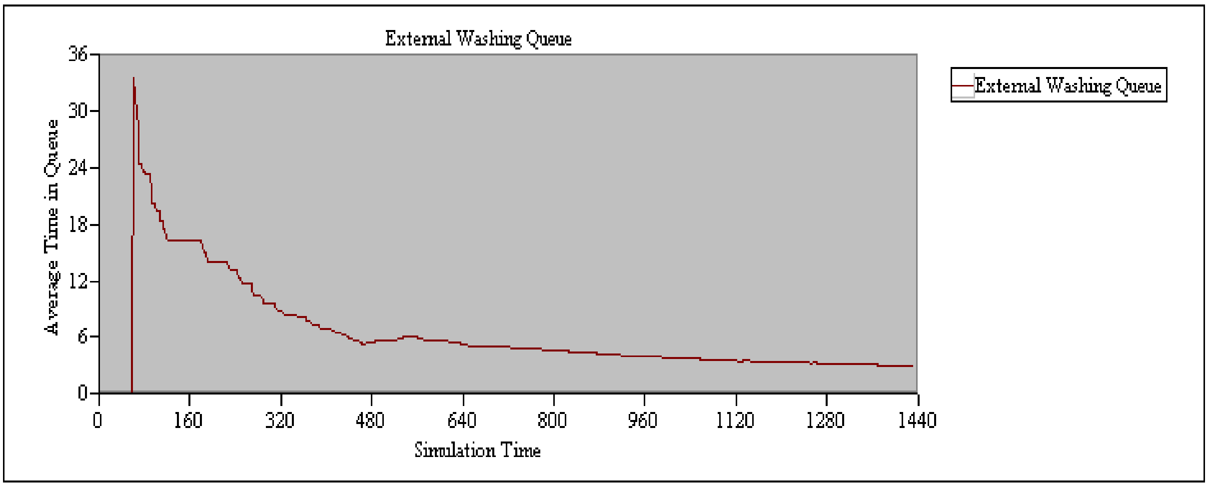
In Figure 22, the number of mechanical pits utilised start to decrease from around 720 minutes. In comparison with Figure 18, it is a significantly reduction. There are extra pits to buffer possible demand increases more comfortably. From around 800 minutes and 1120 minutes there is a considerable variability until the end of the work shift, when the next queue starts to be formed.

In comparison to the real scenario, the utilisation of the other resources remains almost the same. There are no significant alterations. It is important to mention that electrical pits become the most utilised resource. The company can consider the reallocation of buses in case of overload. The reallocation consists of assigning the entities to resources that are working under the expected capacity.

5.2.3 Queues with the increased number of inspection pits

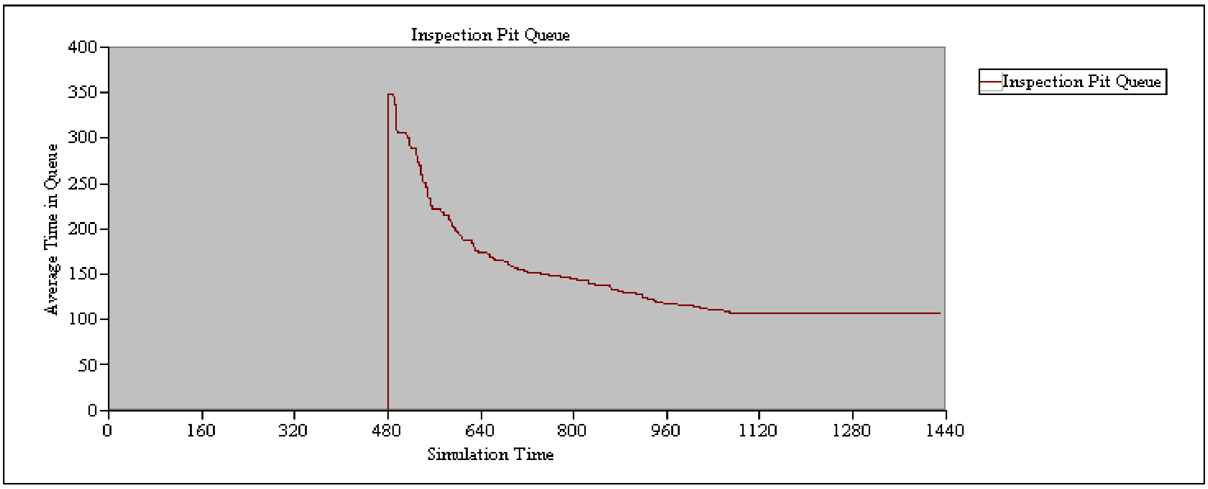
After setting adding four new mechanical inspection pits, it is expected the reduction in the total waiting time. For this reason, the queue formation process should be diminished in comparison with the real scenario. As mentioned earlier, it is important to assess the performance of two most important queues. The queue at the external wash as well as the one for inspection. Figure 23 and 24 depict the average time in queue for external wash and inspection.

Figure 23 - Average time in external washing queue with increased number of mechanical pits



Source: Elaborated by the author

Figure 24 - Average time in inspection queue with increased number of mechanical pits



Source: Elaborated by the author

From Figure 23, it is possible to conclude that the average time in queue has diminished in comparison to the real scenario. A significant change is observed when the simulation run reaches 480 minutes, when the arrival rate of buses is intensified. In the real scenario, the average waiting time starts to increase and reaches a peak of 12 minutes of waiting time at 640 minutes of simulation run. Meanwhile, in the alternative scenario, the average waiting time is about 6 minutes and tends to continuously decrease afterwards.

The most significant changes occur on the inspection pit queue, which is represented in Figure 24. In comparison with the real scenario, there is a reduction of approximately 35 minutes in the average time in queue at 480 minutes of simulation run. Then, the behaviour of the curve tends to be the same, however the average wait time is considerably reduced. Table 13 shows the queue performance evaluation for the alternative scenario.

Table 13 – Queue performance evaluation for alternative scenario

Queue	Average waiting time (minutes)	Average number waiting (units)
External washing	3.79	0.34
Inspection Pit	83.62	9.29
Perform bodywork services	17.26	0.23
Perform electrical services	60.16	0.99
Perform mechanical services	26.24	1.25
Perform refrigeration services	45.49	0.53
Perform upholstery services	0.00	0.02

Source: Elaborated by the author

5.3 System behaviour for different numbers of mechanical pits

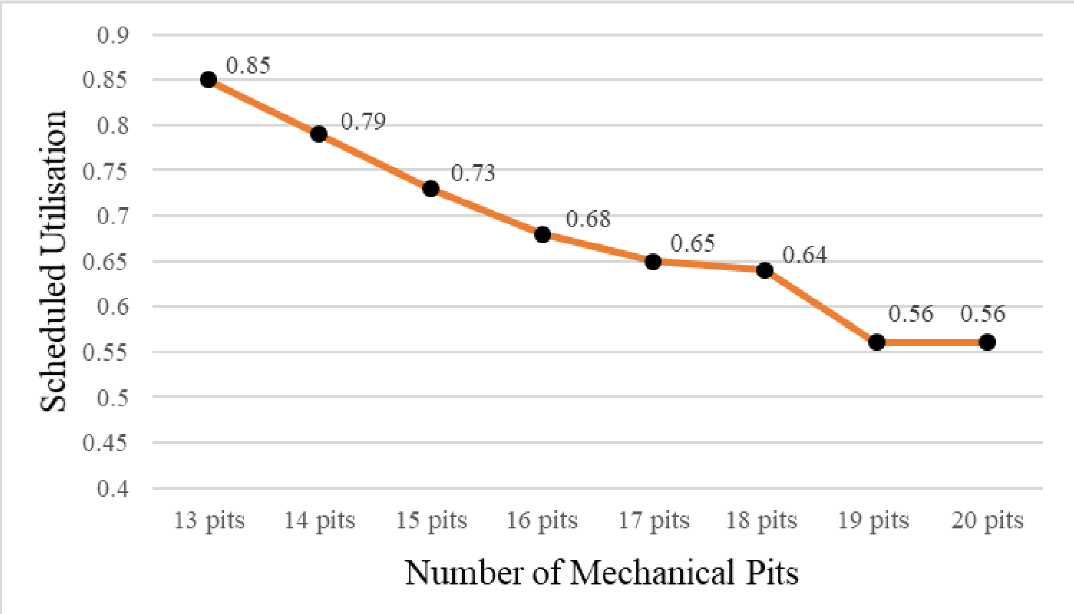
Another feasible alternative to check the behaviour of the system is to determine the variations of performance measures for different scenarios and evaluate which circumstances provide the best results. For this reason, it was necessary to estimate the values of these measures considering different numbers of resources. As previously stated, the mechanical pits were chosen due to the impact that they generate in the performance measures of the system. Table 14 shows the results of the performance indicators for alternative scenarios for different numbers of mechanical pits.

Table 14 - Performance measures for different numbers of mechanical pits

Performance indicator	13 pits	14 pits	15 pits	16 pits	17 pits	18 pits	19 pits	20 pits
Value-added time (minutes)	92.83	93.20	93.40	95.25	95.02	94.43	95.99	95.21
Wait time (minutes)	126.73	117.46	109.68	102.24	100.3	93.28	93.55	88.86
Total time (minutes)	219.57	210.65	203.08	197.49	195.32	187.71	189.54	184.07
Mechanical Pit Scheduled Utilisation (%)	0.85	0.79	0.73	0.68	0.65	0.64	0.56	0.56

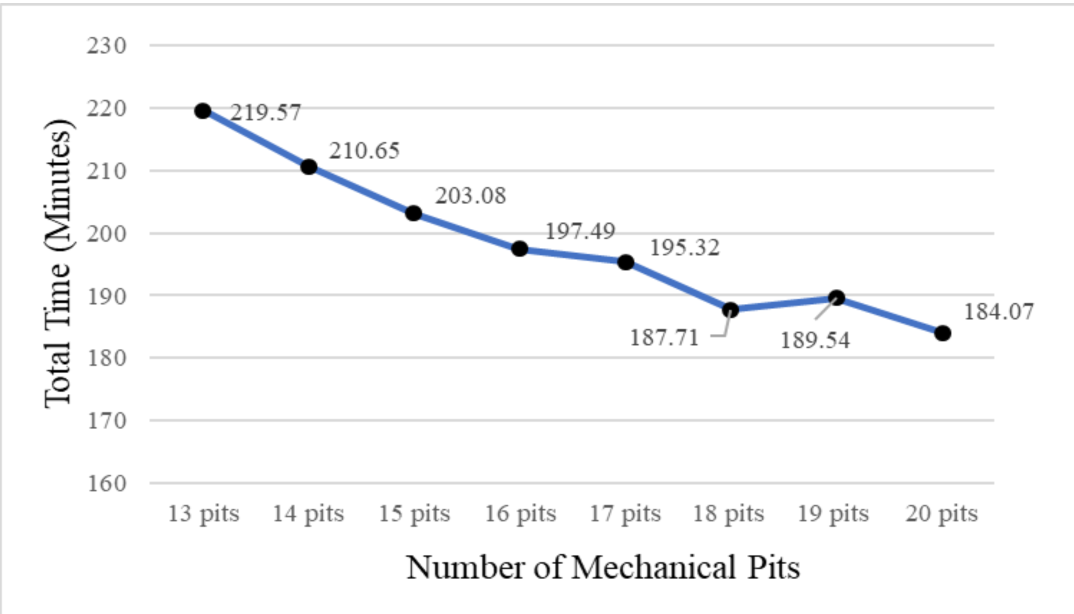
Source: Elaborated by the author

Figure 25 - Scheduled utilisation for different numbers of mechanical pits



Source: Elaborated by the author

Figure 26 - Total time for different numbers of mechanical pits



Source: Elaborated by the author

From Table 14, one can observe that the most significant gains occur for the scenarios with 17 or 18 mechanical pits. In order to facilitate the comprehension of this results, Figures 25 and 26 are provided. They show the variations of two of the most meaningful performance measures: the lead-time and the scheduled utilisation of the mechanical pits. These charts allow a cost-benefit analysis for the operational gains in comparison to the number of additional mechanical pits necessary for a potential expansion project. It is also important to notice that there is a stabilisation of the scheduled utilisation for 19 and 20 mechanical pits. For the total time, there is a small increase for 19 pits and then it starts to decrease again to a value close to the one obtained with 18 pits. The greatest diminishment rate occurs for the interval from 13 to 18 pits.

5.4 Testing the reallocation of resources

From the scenarios previously tested, there is a clear variation of the utilisation of resources. For example, the scheduled utilisation of upholstery pits is commonly the lower one, which is usually around 5%. This type of service is rarely performed at the garage. Another way to test the efficiency of the operations is to reallocate resources with greater demands to less utilised ones. In this case, it is viable to evaluate whether it is worth or not to reallocate the upholstery pits. In other words, the activities that take place in the upholstery pits can be changed to fit the extra demand that overloads the mechanical pits. In this case, there was a substitution of the 2 upholstery pits to mechanical ones. The number of mechanical pits increased from 13 to 15 and the upholstery services were set to be performed also at the mechanical pits. The results for entity related indicators in the alternative scenario is depicted in Table 15.

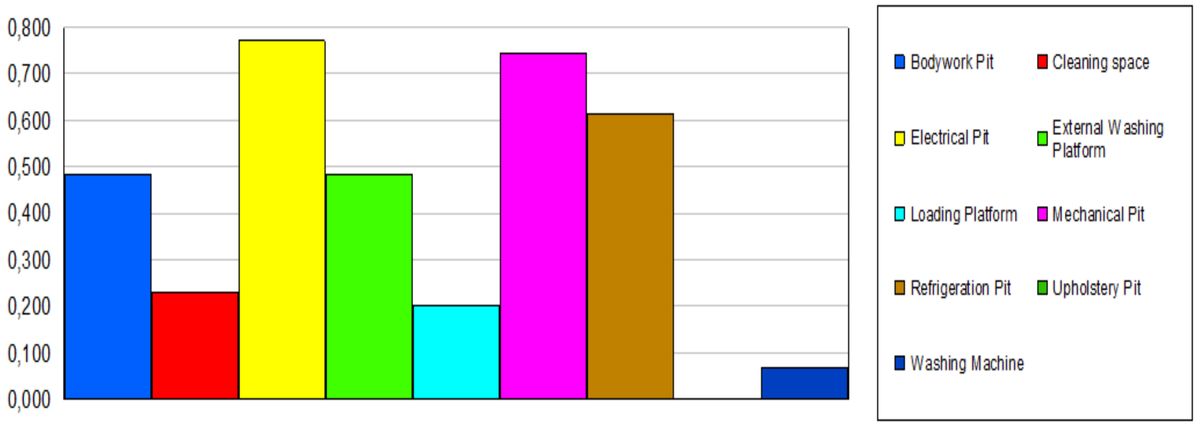
Table 15 – Entity related indicators after resource reallocation

Performance indicator	**Average - 95% confidence level (minutes)**	**Half width (minutes)**	**Minimum average (minutes)**	**Maximum average (minutes)**
Value-added time	93.69 (89.01; 98.37)	3.22	77.64	108.26
Wait time	110.11 (104.60; 115.62)	12.04	37.38	167.80
Total time	203.80 (193.61; 213.99)	14.50	115.02	265.85
Number in	149.67 (142.19; 157.15)	0.70	144.00	151.00
Number out	104.43 (99.21; 109.65)	1.52	97.00	112.00
WIP	24.10 (22.90; 25.31)	1.22	17.28	30.56

Source: Elaborated by the author

Table 15 shows that a reduction of approximately 15 minutes in the average lead-time of the buses in comparison to the real scenario. The results were close to the ones represented in Figure 26 for 15 mechanical pits. It may occur because there was a substitution of the 2 upholstery pits for an additional number of mechanical pits that increased from 13 to 15. Therefore, reallocating vehicles for upholstery pits may be a feasible solution for buffering the extra demand in moments of high season. The values for the utilisation rates are illustrated in Figure 27 and in Table 16. The results also support the idea that the reallocation of upholstery pits is a feasible alternative for buffering increased demands.

Figure 27 - Resource utilisation after upholstery pit reallocation



Source: Elaborated by the author

Table 16 - Scheduled utilisation after upholstery pit reallocation

Resource	Average	Half Width	Minimum average	Maximum Average
Bodywork Pit	0.48	0.07	0.16	0.83
Cleaning Spaces	0.23	0.01	0.19	0.25
Electrical Pit	0.77	0.06	0.38	1.01
External Washing Platform	0.48	0.01	0.44	0.53
Loading Platform	0.20	0.00	0.18	0.22
Mechanical Pit	0.74	0.03	0.56	0.87
Refrigeration Pit	0.61	0.08	0.14	1.04
Washing Machine	0.06	0.00	0.06	0.08

Source: elaborated by the author

6. CONCLUSION

Through a consistent analysis of the maintenance operations that occur within the garage, it was possible to build a computerised model that faithfully represents the real system. The process modules required a great amount of data collected directly in the company by means of the maintenance management software, hand filled data, or interviews conducted with the maintenance engineering personnel.

The model development phase involved the application of diverse concepts and tools addressed in the field of simulation and operational research. It was essential to adapt the reality of the bus garage to the logic of the computerised model based on discrete-event simulation. The model was robust enough to replicate the maintenance operations and, at the same time, simplified to make its development feasible as well as to efficiently run the necessary replications in Arena.

Different scenarios were tested to explore the potential modifications in the behaviour of the real system and the effects over operational performance. It was verified that the increments in the number of mechanical pits is definitely the best alternative in terms of gains, especially for the number of 17 mechanical pits (the impacts over entity and resource based indicators were measured in detail for this number) as well as for 18 pits. The reduction in the scheduled utilisation becomes inexpressive for 19 and 20 pits (these results are demonstrated in Figure 26). For the lead-time the behaviour is similar, although the results for 18 pits is even better in comparison to the one for 19 pits (refer to figure 27). Both performance indicators confirm that the most significant benefits are achieved for a number of 17 and 18 pits.

As demonstrated in subsections 5.1.3 and 5.2.3, the queues also diminish with the increase on the number of mechanical pits. In comparison with the current scenario, adding four mechanical pits can significantly reduce the time in queue. The results show a 35-minute reduction for the inspection queues, which can be translated into operational performance improvements. It is also possible to observe the reduction in queues of previous processes such as the external washing that dropped the average waiting time from 12 minutes to 6 minutes at 480 minutes of simulation run.

Increasing the number of inspection pits can be costly to the company in case of a possible expansion. Due to this reason, this study also suggests the reallocation of resources, which can be considered a less expensive alternative. This reallocation consisted of substituting the upholstery pits, which had a scheduled utilisation of only 5% for mechanical pits. It was taken into account that the upholstery services could also be performed at mechanical pits. Significant gains also occurred, including a drop from 85% to 74% on the scheduled utilisation of mechanical pits. There was a reduction in the average lead-time of the buses that contracted from 219.57 minutes to 203.80.

Studying the capacity of the garage together with expansion forecasts can be useful to determine the optimum moment to increase the number of resources in order to avoid any possible perturbations in case of additional demands. This type of study is also important to prevent unnecessary investments that can culminate in the inefficient utilisation of the available resources.

It is also important to mention the benefits that this undergraduate thesis brought to the company in a short-term period. During the development phase of the simulation model, it was identified that the company did not electronically monitor some processes. For example, the fuel loading process was controlled by two employees who were responsible for manually filling a form containing the arrival times of the buses as well as the amount of fuel loaded. However, the procedure was susceptible to imprecisions and limited the process of data gathering. Then, the company decided to implement a new electronic monitoring system based on spreadsheets to have a better control over the information, which is essential for developing simulation models or any other type of statistical analysis. Another example regards to the company's maintenance software. This software has several functionalities, but the validation process of service orders was imprecise. In other words, the arrival time of the buses was correctly represented, but the validation of service orders could take a long time after finishing an inspection or a maintenance service, which led to inaccurate estimations of the execution time of both. After some meetings and discussions with the information technology department of the company, it was decided that a more precise maintenance management software was necessary. The company plans to implement the corrections by the end of 2017.

Even though the developed model required a significant amount of information in relation to the processes of the company, a lot of aspects of the system had to be simplified. The company under consideration has several opportunities for simulation within the maintenance department such as: working with spare parts, individual simulation modules for the cleaning sector, and sold vehicles. It is expected that the implementation of the new management system can increase the accuracy of the data from the following processes: execution of electrical, refrigeration, bodywork and upholstery services; inspection times; bus arrival time. It would also permit further investigation of variations in demand due to seasonal factors. Another possibility for future work consists on trying to estimate the impact of vehicle flow in performance measures. In other words, the system behaviour for different flow rates.

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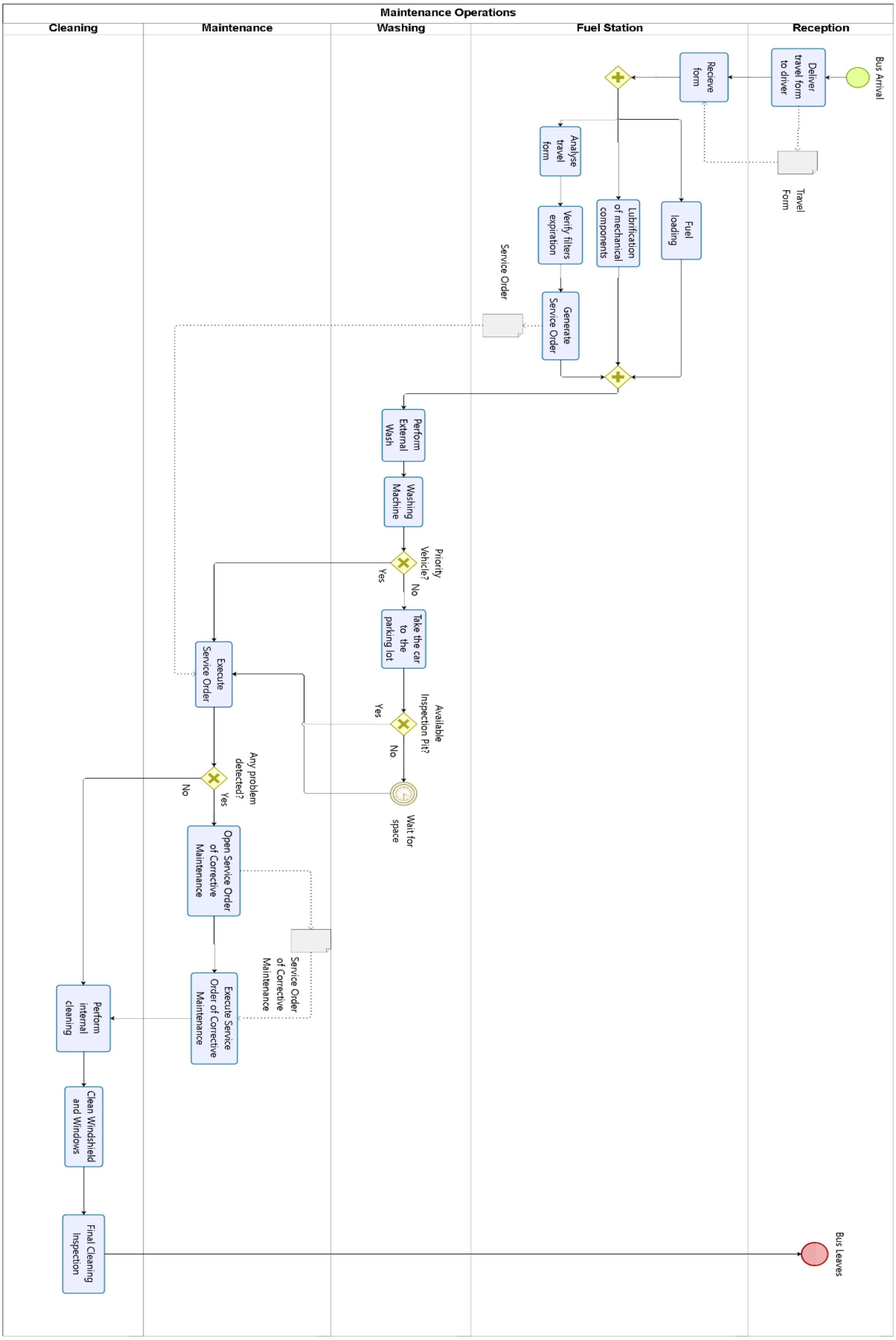
APPENDIX A – OPERATIONS FLOWCHART



APPENDIX B – SIMULATION MODEL