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**RAILWAY TRAFFIC MANAGEMENT:  
SIMULATION AND HEURISTIC OPTIMIZATION**

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## RAILWAY TRAFFIC MANAGEMENT: SIMULATION AND HEURISTIC OPTIMIZATION

## CONTROLE DE TRÁFEGO FERROVIÁRIO: SIMULAÇÃO E OTIMIZAÇÃO HEURÍSTICA

Dissertation apresentada como requisito para obtenção do título de Master em Electrical Engineering da Federal University of Technology — Paraná (). Concentration Area: Instrumentation and Control Systems.

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**Ministério da Educação  
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**RAILWAY TRAFFIC MANAGEMENT: SIMULATION AND HEURISTIC OPTIMIZATION**

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To my psychologist, who provided mental conditions for this work to be done during the pandemic, under quarantine, living alone, and working from home.

Finally, to all those who contributed in some way to the realization of this project.

There is no threshold that makes us greater than the sum of our parts, no inflection point at which we become fully alive. We can't define consciousness because consciousness does not exist. Humans fancy that there's something special about the way we perceive the world, and yet we live in loops as tight and as closed as the hosts do, seldom questioning our choices, content, for the most part, to be told what to do next. *(Dr. Robert Ford, Westworld, 2016).*

*Não existe um limiar que nos torne maiores do que a soma de nossas partes, nenhum ponto de inflexão no qual nos tornamos plenamente vivos. Não podemos definir a consciência porque a consciência não existe. Os humanos imaginam que há algo especial na maneira como percebemos o mundo e, no entanto, vivemos em ciclos tão rígidos e fechados quanto os anfitriões, raramente questionando nossas escolhas, contentes, na maior parte, por saber o que fazer a seguir. (Dr. Robert Ford, Westworld, 2016).*

## RESUMO

DA SILVA, Fernando Augusto Constantino. **Controle de Tráfego Ferroviário: Simulação e Otimização Heurística**. 2021. 168 f. Dissertação (Mestrado em Engenharia Elétrica) — Universidade Tecnológica Federal do Paraná, Ponta Grossa, 2021.

As operações ferroviárias comumente requerem um planejamento das rotas dos trens de modo a cumprir com restrições físicas (como operações em linhas singelas) enquanto gerencia prioridades em cruzamentos e ultrapassagens, entre outros. De modo a facilitar o desenho das rotas, algumas ferramentas auxiliares foram construídas. Este projeto visa criar uma ferramenta de simulação de código aberto para roteamento ferroviário, aplicando uma otimização baseada em duas meta-heurísticas bio-inspiradas (Algoritmo Genético e Otimização por Nuvem de Partículas) e um outro controlador baseado em ações aleatórias. Uma revisão de literatura sobre o contexto histórico das ferrovias ao redor do mundo e principalmente no Brasil é realizada, de onde as rotas utilizadas para comparação são baseadas. Os resultados dos controladores são depois comparados sobre o melhor custo de simulação, o número total de simulações bem-sucedidas, tempo total de execução e a evolução do custo por época. Um teste de Wilcoxon pareado é executado para cada possível par de controladores de modo a determinar a diferença estatística entre os conjuntos de dados. Os resultados obtidos sugerem que o controlador RND se sai melhor nos cenários avaliados, obtendo o tempo de execução mais curto em ambos os cenários e alcançando o melhor custo de simulação global no mais difícil. A ferramenta também exporta um vídeo apresentando o painel sinóptico com toda a execução da simulação, permitindo um fácil teste e depuração da solução. Ela foi construída utilizando Python em um contêiner Docker de modo a ser executada em diferentes plataformas e arquiteturas, sendo hospedado no GitHub e disponível publicamente para futuras contribuições.

**Palavras-chave:** ferrovia. simulação. transporte. otimização. meta-heurísticas.

## ABSTRACT

DA SILVA, Fernando Augusto Constantino. **Railway Traffic Management: Simulation and heuristic optimization.** 2021. 168 p. Dissertation (Master's Degree in Electrical Engineering) — Federal University of Technology — Paraná, Ponta Grossa, 2021.

The railroad operations often require planning on the routing of the trains in order to comply with physical restrictions (like single-track operations) while handling priorities on crossings and overtakes, among others. In order to facilitate the route design, some auxiliary tools were made. This project aims to create an open-source simulation tool for railroad routing and perform an optimization based on two bio-inspired metaheuristics (Genetic Algorithm - GA and Particle Swarm Optimization - PSO) and another random-action controller (RND). A literature review about the historical context of railroads over the world and mainly in Brazil is made, from where the routes used for comparisons are based. The controllers' results are later compared over the best solution cost, the total number of successful solutions, total execution time, and the cost evolution per epoch. A Wilcoxon signed-rank test is executed for each possible pair of controllers in order to determine the statistical difference of the resulting data-sets. The obtained results suggests that the RND controller performs better in the evaluated scenarios, having the faster execution time on both scenarios and achieving the best global solution cost in the harder one. The tool also outputs a video presenting the synoptic panel with the entire execution of the simulation, allowing an easy audition and debugging of the solution. It was built using Python in a Docker container so it can run under different platforms and architectures, being hosted on GitHub and available for further public contributions after the registry process.

**Keywords:** railroad. simulation. transportation. optimization. metaheuristics.

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## 1 INTRODUCTION

This section presents a general perspective about the research, including an introduction about transportation - focusing mainly on railroads, showing the relevance and the reasons why this work was developed. The theme is also defined, as well as the objectives and the paper structure.

### 1.1 PREAMBLE

Transportation has always been a challenge for the human being. From his own arms to outer-space missions, the need to move people and/or cargo from an origin to a destination was always a theme open for structural improvements, based on well-known physical laws that described the movements needed.

As control systems evolved, transportation achieved enhancements such as automated flying systems (like the Flight Management Computer - FMC, the Flight Management Guidance Systems - FMGS, the Flight Management Systems - FMS and the Flight Director - FD), electric traction controls engine and brake systems for road vehicles (like the Engine Control Unit - ECU, Anti-lock Braking System - ABS), among others.

Most recently a particular research area began to raise, following the technological advances: the computational intelligence. Training a learning algorithm model to behave as designed under sets of previously defined scenarios allowed control systems to achieve an unprecedented level: the ability of taking actions based on the learned experience, adapting its own control parameters to reflect the ambient changes.

Railroads and highways already presents commercial autonomous vehicles by the time this document was written. In Brazil, the trains of metro line 4 (Yellow) at Sao Paulo already operates with driver-less trains, being the first one in Latin America. They are remotely controlled from the Operational Control Center (OCC) (SUZUKI, 2017).

On July 2018, the very first unmanned long-distance freight loaded train was operated, running 280km from Tom Price mine to Cape Lambert in Australia by the Rio Tinto company. Driverless operation was gradually increased over the next few months, reaching 34 trains per day and 45% of daily kilometres operated by October of that year. This had risen to more than 90% of the company operated trains by February

2019 (RIOTINTO, 2018; SMITH, K., 2019).

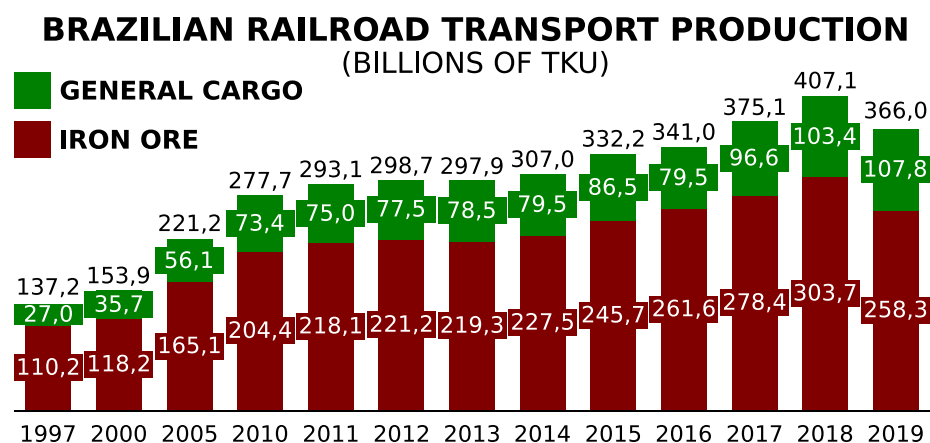
In the same context, this work aims to contribute with advances in the area of computational intelligence targeted to transportation control systems, specifically for railroad traffic management in the OCC. As freight cargo transportation in the evaluated scenarios are not constant and scheduled as the passenger transportation in the metro lines, some different approaches may be required in order to achieve an assisted traffic control that may eventually be used in fully remote operations.

Besides that, this work firstly aims to develop an open-source simulation environment for railroad traffic control models, allowing further collaboration of scientists, developers, enthusiasts, rail-fans and hobbyists that may want to contribute, developing his own version or compare the results. Bugs can be reported through issues and updates are fully described in the Version Control System (VCS) repository of this project (freely hosted at <https://github.com/ferdn4ndo/the-train-app> by GitHub). Any contribution is welcome.

## 1.2 RELEVANCE

From the start of the privatization process in 1996, Brazilian railroad network has increased its transported volume reaching a total of 493,8 millions of TKU (measurement unit equivalent to the transport of one net tonne through one kilometer) in 2019, a growth of 95% since 1997 when a total of 253,0 millions of TKU were registered (ANTF, 2020b). This evolution is shown in Figure 1.

Figure 1 – Brazilian railroad transport production, in millions of TKU.



Source: adapted from ANTF (2020b).



**Table 1 – Railroad network density among different countries.**

Country	Area millions of km <sup>2</sup>	Railroads thousands of km	Railroads/Area km/thousands of km <sup>2</sup>
USA	9,83	293,56	29,8
India	3,29	68,53	20,8
South Africa	1,22	20,99	17,2
Argentina	2,78	36,92	13,3
China	9,60	124,00	13,2
Mexico	1,96	15,39	7,8
Canada	9,98	77,93	7,8
Russia	17,10	87,16	5,1
Australia	7,74	36,97	4,8
Brazil	8,52	29,18	3,4

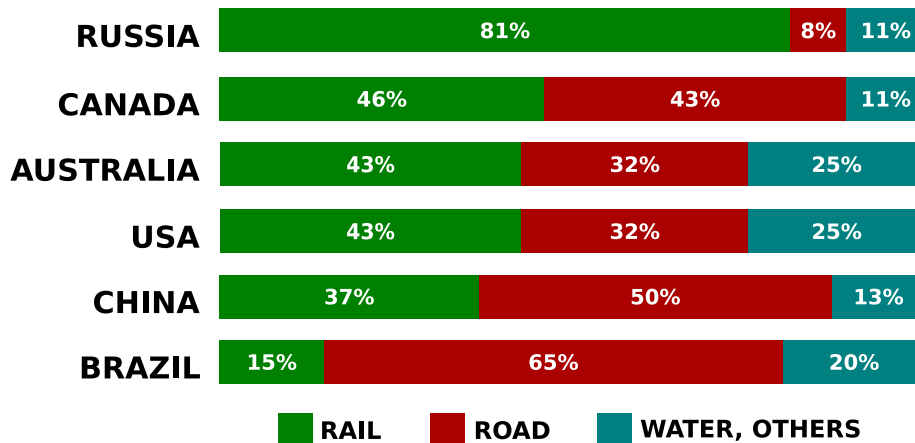
Source: ANTF (2020b).

However, compared to other countries, Brazil still has a lot to develop in terms of the amount of railroads. On Table 1 the comparison of the railroad network density (in green) against other matrices is presented.

From Figure 2, it is noted that the Brazilian railroad network usage for cargo transportation is significantly lower than other large countries.

**Figure 2 – Railroad participation in the transportation matrix for big countries.**

### COMPARISON OF CARGO TRANSPORT MATRICES



Source: adapted from ANTF (2020b).

Railroads are also more efficient than regular road transportation: one single standard 100 tons freight car replaces almost four trucks in cargo load, which helps reducing traffic jams in highways and urban areas, having as another good benefit the decreased environmental impact (ANTF, 2020b).

Another relevant purpose of this project is on disaster recovery scenarios. Unpredictable conditions may lead a section to a locked state, requiring direct intervention

in order to be moved and clear the block section. From mechanical problems to catastrophic crashes, a special unit train - called the Disaster Response Unit (DRU) - is sent from the nearest basis to the incident location.

These operations often requires a complex response plan to accommodate all trains in the route between the closest DRU and the incident location, in order to reduce the stopped time. To be able to reach that destination, there should be an available route and all the other training running towards the incident must wait for the section clearance.

The DRUs are normally composed by infrastructure equipment like cranes and tools and also the maintenance crew that will work with track recovery so the connection may be reestablished. This work could be used to help planners at Operations Control Center (OOC) defining the best strategy to recover from traffic incidents of different severity.

There could be different severity disaster scenarios considering real-life cases such as derailments with and without significant vehicles damage and/or cargo compromise, broken or cracked rails, mechanical problems in the rolling stock, and others. It could be evaluated by checking if the rescue unit(s) reaches the incident(s) location as soon as possible and if the remaining trains in the route will adapt themselves to the unexpected interdiction, taking the best decisions (either moving forward, backwards or waiting) until the situation is normalized to continue to their destination.

### 1.3 OBJECTIVES

Within the given context and relevance from the previous section, this project aims to provide an open source tool for railroad traffic management and perform an optimization based on bio-inspired metaheuristics, targeting to help in the decision-making process of the railroad dispatchers, thus allowing a reduction the planning time and in the licensing time (when a train is stops to wait a license from the dispatcher).

The specific objectives for this project includes:

- To describe each used concept in a concise resume and explaining each development step to the public from both academic and professional areas (as well as the enthusiasts) are encouraged to reproduce the results and further contribute to this project;

- To provide an open-source railroad traffic simulation tool for scientists, developers, railway employee, and enthusiasts that may want to contribute, develop his own version of the simulator or compare the results;
- To be system-agnostic, allowing further contributors to run both the simulation and the controllers in their own environments, no matter what the operating system;
- To create a basic random controller (taking only random actions while building a train's route) to validate the simulation environment and the related physics;
- To implement two different bio-inspired metaheuristic controllers: Genetic Algorithm (GA) and Particle Swarm Optimization (PSO);
- To compare the results among the different controllers based on the performance variables: best solution cost x step (evolution), final best solution cost, total time spent to compute the solution, the success and failure rate and the amount of unique valid solutions to the same scenario;

The smaller steps and the details about the development of each of the objectives will be described within the further sections of this project.

#### 1.4 PROBLEM DESCRIPTION

As stated by Fioroni (2008), the railway traffic has lower maneuverability in comparison to waterway or highway transportation, as the train must follow a predetermined path defined by the track. This implies a greater complexity for overtaking and crossings, as they need a higher level of planning and can only occur at specific locations.

Besides the direct effect on the railway traffic management that this dissertation aims to get, Brazil suffers from a historical debt from its original railroads (which still comprehends most of the active routes) that were developed for smaller/localized needs, leaving in leveling investments that could provide higher traffic in a future expansion.

Being the agriculture one of the Paraná state economy pillars, it is essential to increase the network capillarity and also provide greater connections among the main hubs. In the short term, finding improved ways to use the current network may reduce bottlenecks without infrastructural investments (NOTÍCIAS DO PARANÁ - AEN, 2020). Following this approach, this work has the premise of adopting hardware technology currently already in use at national railroads, benefiting instead of the software advances

that occurred in the last few decades.

## 1.5 DOCUMENT STRUCTURE

This document is divided into five chapters, each one of them providing information according to the following guidelines:

- **Introduction:** gave an overall perspective over the main concepts surrounding rails, focused on Brazilian-related material. It also described the main principles/objectives regarding the specific area of this research. The goal here was to situate the reader about the topics that are going to be later developed in the following sections;
- **Literature Review:** presents the description of the principles and concepts used in this document, referencing discussions about their main definitions and state-of-the-art evaluation. The general context about Brazilian railroads - from its origin to the current state - and the railway terminology is described;
- **Material and Methods:** defines the methodological approach to resolve the proposed problem, describing the principles and structures used to obtain the results discussed later. The application is described on its inner behaviors following the chosen approach, from the classes structure to the algorithms implementation;
- **Results and Discussion:** presents and discuss the results hereby obtained, from an analytic perspective (based on the data only, without the author's opinion). The performance and applicability of the simulation itself is checked, as well as the solutions obtained with the optimized controllers;
- **Conclusion and Perspectives:** discuss the general results of the work, as well as the process to reach them. Presents the author's opinion regarding the theme, the used tools and the obtained solutions. Has some suggestions for future development and expectations for its usage;

Whenever a media is presented, a QR Code (which is a matrix bar-code that is used to encode data in a visual format) that can be opened by a cellphone using any reader application. If you're already reading this document in the cellphone, the legend of the media will contain a link to the original file suffixed to it.

## 2 LITERATURE REVIEW

This chapter aims to describe the principles and concepts about railroads and railways, from the historical global scope to the one that is used as the evaluation scenario for this work. The discussions regarding the chronology about Brazilian railroads ups and downs are also noted here so the reader may take his own considerations about what took place before the actual moment.

All algorithms used as the computational intelligence behind the route optimization are explained, from the general concept to the pseudo-code.

### 2.1 HISTORICAL CONTEXT

Transportation has always been a challenge for the society. Being considered by some as the greatest human-powered railroad, the Diolkos was a paved trackway across the Isthmus of Corinth (in Greece) used to transport boats which had records from around 600 b.C. to 150 a.C. (STORY, 2020). Some sections of it still remains, like the one shown in Photograph 1.

It's based in a concept similar to the one that was later used in the modern railroads, where a heavy object is moved along a predetermined track (STORY, 2020).

Another of the very first stone roads to be used for transportation (this time, by chariots) was built in 312 B.C. during the Roman Empire and still some preserved sections (HERBST, 2006).

Up to the 17th century, wooden freight gondolas and wooden rails were the state-of-the-art of the railroads, used by coal mines in the north of England. From this point on, several remarks were present in the history of railroads, up to the point it reached Brazil.

The history of railroads in Brazil was always deeply attached to the political scenario, which had drastically changed along time. Aiming to provide a correlation between some of the most significant scenario changes - and the events related to railroads that happened in the meanwhile - the following phases were considered, based on studies of José Eduardo Castello Branco (ANTF, 2020a):

- **Earlier Moments (before 1835):** no railroads were present in Brazil, although it was possible to observe the technological evolution that led to the construc-

**Photograph 1 – Remainings of Diolkos paved road (western end).**



**Source: Diffendale (2008).**

tion and opening of the first railroads over the globe, mainly on England and USA (ANTF, 2020a);

- **Phase I (1835 – 1873):** in Brazil, the political scenario was shifting from the Regency to the Second Empire. The first Brazilian railroads were implemented in a slow process, handled by essentially private companies (ANTF, 2020a);
- **Phase II (1873 – 1889):** covering the Second Empire and characterized by a fast expansion of the Brazilian railroad network, though private investors, stimulated by the interest rate (ANTF, 2020a);
- **Phase III (1889 – 1930):** encompasses the Old Republic, still observing a fast railroad network expansion, but with the government assuming the control of several private companies suffering from financial difficulties (ANTF, 2020a);
- **Phase IV (1930 – 1960):** comprehends the Vargas Era (the period in Brazil's history between 1930 and 1945, when the country was under the dictatorship

of Getúlio Vargas) and post-war, with a slowing expansion rate and a great government control of earlier private companies (ANTF, 2020a);

- **Phase V (1960 – 1990):** situated almost entirely along the moment when the country was controlled by the military regime and having the railroad network consolidated into a few public companies. Uneconomical branches were eradicated and strategically selected projects were implanted (ANTF, 2020a);
- **Phase VI (1990 - present):** comprehends the New Republic era, characterized by the concession of the entire national railroad network. From 2016 - about a decade before their expiration - the renewal discussions are started (ANTF, 2020a);

Based on these phases, the following sections describes the most relevant events regarding railroads.

#### 2.1.1 Earlier Moments (before 1835)

From the very first railroads to the start of the discussion in Brazil regarding its implementation, the most relevant events are:

- **1776:** wooden rails are replaced by iron ones at Shropshire coal mine, in England (ANTF, 2020a);
- **1801:** British government approves the commercial exploration of the first cargo railroad: the Surrey Iron Railway (ANTF, 2020a);
- **1803:** Surrey Iron Railway starts its operations connecting Wandsworth to Croyden (both in England), using animal traction (ANTF, 2020a);
- **1804:** Richard Trevithick tries to replace animal traction by steam locomotives but failed as they were unable to move across small ramps due to low adherence caused by a low gross weight (ANTF, 2020a);
- **1807:** first passenger transportation railroad: the Oystermouth Railway, in England, using animal traction (ANTF, 2020a);
- **1812:** first steam locomotive usage, with wheels and having racks on one of the rails (similar to the rack-and-pinion system) to overcome the adherence problem, by Middleton Railway, in England (ANTF, 2020a);
- **1825:** Stockton e Darlington Railway opening for traffic, where a steam locomotive with reasonable traction and adherence conditions was used. It was

projected by George Stephenson (ANTF, 2020a);

- **1828:** José Clemente Law enacted in Brazil, authorizing the construction of roads in the country by national or foreign businessmen (ANTF, 2020a);
- **1830:** The Liverpool and Withstable Railway, in England, replaces all of its animal traction by steam locomotives (ANTF, 2020a);

### 2.1.2 Phase I (1835 – 1873)

The discussions regarding railroads implementations in Brazil starts, as well as the first railroad kilometers started operating. In the meanwhile, railroads are expanding and achieving a higher technological level around the globe. The most relevant events are:

- **1835:** Feijó Law enacted in Brazil, authorizing the concession of railroads unifying Rio de Janeiro to the provinces of Minas Gerais, Bahia and Rio Grande do Sul (ANTF, 2020a);
- **1840:** edition of Railway Regulation Act, in England, determining rules for the railroad transportation; First Brazilian railroad concession, giving the English doctor Thomas Cochrane the rights to build the connection between Rio de Janeiro and São Paulo (ANTF, 2020a);
- **1841:** railroad signaling used for the first time - in the South Eastern Railway - and of the electric telegraph - in the North Midland Railway - both on England, to control railroad traffic (ANTF, 2020a);
- **1842:** mutual traffic rules between different railroads established by Railway Clearing House, in England (ANTF, 2020a);
- **1844:** start of the track gauge standardization in England, adopting the 1.435 mm value (ANTF, 2020a);
- **1845:** opening of the first railroad in Brazil, 14.5 kilometers long, in Guanabara Bay (now the Magé city) in Rio de Janeiro - a venture from Irineu Evangelista de Souza, which would later become the Barão de Mauá (ANTF, 2020a);
- **1850:** Railroad Land Grant Act enacted in USA, granting state property lands to pioneer railroads (ANTF, 2020a);
- **1855:** start of service of the first postal train - between London and Bristol - in England (ANTF, 2020a);



- **1858:** opening of the second Brazilian railroad, the Recife and São Francisco Railway Company - between Recife and Cabo, in Pernambuco - Brazil. This railroad was also the first English company settle in the country; Conclusion of the first section - between Rio de Janeiro and Queimados, at Baixada Fluminense - of what would later become for many years the most important railroad in Brazil: a Dom Pedro II Railroad, later Central of Brazil Railroad (EFCB) (ANTF, 2020a);
- **1863:** opening for traffic of the first metro line - in London - operated by Metropolitan Railway, connecting Bishop's Road and Farringdon Street stations (ANTF, 2020a);
- **1869:** George Westinghouse receives the patent for his air brake system, which would drastically reduce the railroad accidents originated by braking failures; conclusion of the first transcontinental railroad in USA, with the union of Central Pacific Railway and Union Pacific Railway lines (ANTF, 2020a);
- **1871:** the government policy of land concession to the private railroads in the USA is discontinued (ANTF, 2020a);

### 2.1.3 Phase II (1873 – 1889)

Brazil begins to regulate the railroads construction and operation. Some great technological achievements improved the safety of railroads transportation. The most relevant events are:

- **1873:** promulgation of Law 2450, of September 24th, which grants interest warranty or - alternatively - state subsidy over the built length relative to the capital applied in the railroads construction in Brazil; automatic coupling system invented in the USA by the former slave Eli Janney, eliminating most of the serious accidents that normally occurred with railroad yard works during the coupling and decoupling of freight and passenger cars (ANTF, 2020a);
- **1878:** promulgation of Decree 6995, of August 10th, aiming to complement the previous concession regulation and resolve conflicts between the government and railroad companies (ANTF, 2020a);
- **1881:** opening for service of the first electric tram line in Berlin, Germany; George Westinghouse improves the electric signaling and blocking system,

which tremendously increases the safety level of railroads (ANTF, 2020a);

- **1882:** realization of I Congress of Railroads in Brazil, which was attended by Emperor Dom Pedro II on all of its thirteen sessions; First time a telephone was used on trains dispatch, by New York West Shore & Buffalo Railroad, in USA (ANTF, 2020a);
- **1883:** opening of the first electric railroad - the Volks Electric Railway - in England; start of service of the first long distance luxury train - the Orient Express (ANTF, 2020a);
- **1884:** start of service of the first passenger car with Air Conditioning (AC) unit, in USA (ANTF, 2020a);
- **1887:** the first railroad transport regulatory authority was created in USA at national level - the Interstate Commerce Commission (ICC) (ANTF, 2020a);

#### 2.1.4 Phase III (1889 – 1930)

Brazil government starts absorbing railroad companies that are facing financial problems. USA reaches the record of 409 thousand kilometers of railroads. Diesel-electric locomotives starts being used. Other relevant events are:

- **1889:** presented in Paris the first hydraulically operated railroad switch (ANTF, 2020a);
- **1890:** opening for traffic of the first electric metro system, in London; Brazilian government starts the receivership process for railroad companies, with the takeover of Estrada de Ferro São Paulo e Rio de Janeiro, later absorbed by Estrada de Ferro Central do Brasil (ANTF, 2020a);
- **1892:** track gauge standardization in Great Western Railway, England (ANTF, 2020a);
- **1900:** introduction of the sanding system to improve the rail x wheel adherence, in England; electrification of the Paris-Juvissey line with a 3rd rail, in France (ANTF, 2020a);
- **1903:** start of service of the first laboratory of building materials testing in Brazil, as an initiative of Estrada de Ferro Central do Brasil (ANTF, 2020a);
- **1904:** introduction of Eucalyptus plantation technique from Australia in Brazil by Companhia Paulista de Estradas de Ferro (CPEF) to supply firewood to

the steam locomotives (ANTF, 2020a);

- **1905:** Estrada de Ferro Sorocabana (EFS) was transferred to the São Paulo State government due to financial difficulties (ANTF, 2020a);
- **1906:** opening of the Simplon Tunnel in the Alps, as a shortcut for the Simplon Pass route, which became the longest railroad tunnel in the world until 1982, being 19.8 kilometers long (ANTF, 2020a);
- **1912:** opening of the Estrada de Ferro Madeira-Marmoré, considered one of the most challenging ventures in Brazil (ANTF, 2020a);
- **1916:** reached the peak of railroad network length in the USA of 409 thousand kilometers (254 thousand miles) (ANTF, 2020a);
- **1921:** creation of the first Retirement and Pension Fund for the private railroads sector in Brazil by Estrada de Ferro Santos a Jundiaí (EFSJ) (ANTF, 2020a);
- **1922:** entry into force of the Rules of Procedure for Safety, Police and Traffic of Railroads, replacing the previous one dated from 1857; Electrification of the Campinas-Jundiaí section, by Companhia Paulista de Estradas de Ferro (CPEF), being the first electric railroad in Brazil (ANTF, 2020a);
- **1923:** consolidation of the British railroads with the fusion of 123 companies into four conglomerates (The Big Four) (ANTF, 2020a);
- **1925:** the first diesel-electric locomotive of USA starts its services at Central Railroad of New Jersey (ANTF, 2020a);
- **1926:** created the Public Accounting of Transportation in Brazil, designed to organize the mutual traffic among the near 150 different railroad companies operating in the country (ANTF, 2020a);

#### 2.1.5 Phase IV (1930 – 1960)

New world rail velocity records. Brazil has a slow evolution over railroads. A major railroad accident happened in Brazil. A report indicates that passenger transportation over trains is becoming obsolete. Some relevant events are:

- **1930:** a German train sets the world rail velocity record with 230km/h; suburban lines of Rio de Janeiro are electrified by Estrada de Ferro Central do Brasil (EFCB) (ANTF, 2020a);
- **1942:** creation of Companhia Vale do Rio Doce (CVRD), which absorbed

Estrada de Ferro Vitória a Minas – EFVM, which would soon turn into the most important railroad of the country (ANTF, 2020a);

- **1945:** edition of the Decree 7632 in Brazil, from June 12th, creating taxes for improvements and asset renewal of railroads, by applying a 10% aliquot over the shipping value (ANTF, 2020a);
- **1947:** nationalization of British railroads (ANTF, 2020a);
- **1949:** first application of the continuous welding tracks, in France (ANTF, 2020a);
- **1950:** promulgation of Law 1272-A in Brazil, from December 12th, creating the National Railroads Fund; created the Joint Brazil-United States Economic Development Commission, which would prepare the base for the Brazilian railroad sector reformulation (ANTF, 2020a);
- **1952:** the major railroad accident happened in Brazil, at Anchieta downtown in Rio de Janeiro, as a result of the collision of a suburban train with a cargo one originated in a broken rail and leading to nearly 90 deaths and 200 injuries (ANTF, 2020a);
- **1955:** a French electric train sets the world rail velocity record with 330km/h (ANTF, 2020a);
- **1957:** opening of Estrada de Ferro Amapá using the international standard gauge of 1,435mm - the only one in Brazil - aiming the outflow of manganese at Serra do Navio at what would become the Amapá state; creation of Rede Ferroviária Federal Sociedade Anônima (RFFSA), as a result of the grouping of almost 20 railroads controlled by the government (ANTF, 2020a);
- **1958:** release of a report by the Interstate Commerce Commission (ICC) stating that the passenger railroad transportation is becoming obsolete and that soon the passenger cars would become part of a historical museum of transportation, along with the carriage and the steam locomotive (ANTF, 2020a);

#### 2.1.6 Phase V (1960 – 1990)

Several railroads are eradicated around the world, including in Brazil. High-speed trains starts being used in several countries. Brazil uses taxes and reorganize

public railroad companies, while some new private railroads are built. Some relevant events are:

- **1962:** Law 4102, of July 20th, was enacted in Brazil, creating the National Railroad Investment Fund (FNIF), composed of a 3% rate of the Union's tax revenue and improvement rates, the latter resulting from Law Decree 7632, of 1945, ratified by Law Decree 55651, of January 29th, 1965 (ANTF, 2020a);
- **1963:** Closing 10,000 km of uneconomic lines in Great Britain (ANTF, 2020a);
- **1964:** Opening of Tokaido Shinkansen (Japanese high-speed line) (ANTF, 2020a);
- **1967:** Law Decree 343 of 28th December was enacted in Brazil, which allocates a 8% rate of the fuel tax to RFFSA (ANTF, 2020a);
- **1968:** Over 72,000 km of railroad tracks have been eradicated in the US (ANTF, 2020a);
- **1969:** The first program contract between the French government and SNCF was signed; Law Decree 615 of 9th September, 1969 was issued in Brazil, which established the Federal Railroad Development Fund, essentially composed of RFFSA's participation of 8% the IUCLG and 5% of the importation tax (ANTF, 2020a);
- **1970:** Creation of the public passenger railroad company in the USA: Amtrack, aimed at relieving the private railroads of this type of service, considered to be a deficit; the RFFSA training program for the transportation of iron ore - supported by Bird - has started in Brazil (ANTF, 2020a);
- **1971:** Creation of São Paulo State Railroad Company (FEPASA), by the agglutination of five state railroads (Sao Paulo Company - CP, Sorocabana Railroad - EFS, Mogiana Railroad Company, Araraquara Railroad and São Paulo-Minas Railroad) (ANTF, 2020a);
- **1974:** Creation in Brazil of the National Development Fund, channeling resources previously linked to sectorial applications; The Railroad Engineering Company (Engefer) was created in Brazil, for the implementation of railroad undertakings in the country (ANTF, 2020a);
- **1978:** Start of the implantation of Trombetas Railroad, aiming at the transport of bauxite in the state of Pará, Brazil (ANTF, 2020a);
- **1979:** Inaugurated Jari Railroad, designed to support and shipment of raw

material and the production of cellulose in the state of Pará, Brazil (ANTF, 2020a);

- **1980:** The first Talgo-type Pendular Train circulates in Spain; Deregulation of the North American railroad sector, with the edition of the Staggar Law; about 8,000 km of railroad lines are eradicated in Brazil, a process that started in the early 1960s (ANTF, 2020a);

**Figure 3 – Talgo pendular train project in 2009 (video).**



Source: Talgo (2012).

- **1981:** A French high-speed train sets the world rail velocity record with 380km/h (ANTF, 2020a);
- **1984:** Created by the split of RFFSA and absorption of Engefer, the Brazilian Company of Urban Trains (CBTU), through the law decree 2178, which concomitantly transfers RFFSA's debts to the national treasury (ANTF, 2020a);
- **1985:** Inauguration of Carajás Railroad (EFC) - in Northern Brazil - owned by Vale do Rio Doce Company, destined to transport iron ore from the state of Pará (ANTF, 2020a);
- **1987:** Construction began in Brazil of the Norte-Sul Railroad, linking the states of Goiás, Tocantins, Maranhão and Pará; privatization of the Japanese Railways, with its subdivision into six private regional companies: JR Hokkaido, JR East, JR Central, JR West, JR Shikoku and JR Kyushu (ANTF, 2020a);

### 2.1.7 Phase VI (1990 - present)

The later years are marked by several privatization process around the world and mainly in Brazil. Several companies suffer merge-and-split transitions to form conglomerates. Investments are made into new lines but only a few of the unused ones are recovered.

- **1991:** Parana State Railroad (Ferroeste) construction was started, interconnecting Guarapuava and Cascavel, both in Paraná state, Brazil (ANTF, 2020a);
- **1992:** Construction started on the initial section of Brazil North Railroads Corporation (Feronorte), connecting the states of São Paulo and Mato Grosso do Sul, Brazil (ANTF, 2020a);
- **1993:** Privatization of British Rail, after its segmentation into about 100 different companies; privatization of Ferrocarriles Argentinos in Argentina (ANTF, 2020a);
- **1994:** Inauguration of the Channel Tunnel, linking England to France (ANTF, 2020a);
- **1996:** In Brazil, the RFFSA center-east, southeast and west lines were privatized and granted to Centro-Atlântica Railroad (FCA), MRS Logística and Novoeste Railroad, respectively (ANTF, 2020a);
- **1997:** Privatization of RFFSA south lines and Teresa Cristina to Sul-Atlântica Railroad (América Latina Logística) and Teresa Cristina Railroad (FTC), respectively; Privatization of part of the Parana State Railroad (Ferroeste), assumed by Paraná Railroad (Ferropar) (ANTF, 2020a);
- **1998:** Privatization of the RFFSA northeast and Sao Paulo State lines to Northeastern Railway Company (CFN) and Bandeirantes Railroad (Ferroban), respectively (ANTF, 2020a);
- **2002:** Novoeste Railroad was merged to Bandeirantes Railroad Company (Ferroban) and to Brazil North Railroads Company. (Feronorte), forming the Brazil Railroads Group (ANTF, 2020a);
- **2006:** With the acquisition of Brazil Railroads and Novoeste Railroad, ALL also started to operate in strategic areas of the Midwest and São Paulo State, becoming the largest railroad logistics company in Brazil; (ANTF, 2020a);
- **2007:** The operation of North-South Railroad (FNS) - Northern Section (from

Açailândia-MA to Porto Nacional-TO, with 722 km) was granted to Vale for a period of 30 years (ANTF, 2020a); A French electric train sets the new world speed record with a velocity of 574,8 km/h using the standard rail-wheel design with catenaries (SÁNDOR, 2009);

**Figure 4 – French electric train sets world speed record of 574,8 km/h using standard rail-wheel system in 2007 (video).**



Source: Sándor (2009).

- **2008:** A corporate name of CFN (Companhia Ferroviária do Nordeste S.A.) changed to Transnordestina Logística S.A. (ANTF, 2020a);
- **2011:** The General Cargo Logistics Directorate of Vale create the company VLI (Valor da Logística Integrada), which incorporated the railroads FCA (acquired by Vale during RFFSA privatization), FNS Tramo Norte (acquired by Vale in 2007) as well as grain transfer terminals and port terminals in Maranhão, São Paulo, Espírito Santo and Sergipe (ANTF, 2020a);
- **2014:** in April, Vale finished selling 20% and 15,9% of its VLI actions to Mitsui and Fundo de Investimento do Fundo de Garantia do Tempo de Serviço (FI-FGTS), respectively. In august, it sold others 26,5% to Brookfield Asset Management, losing the control position of VLI (ANTF, 2020a);
- **2015:** Rumo Logística was created as the result of a fusion of Rumo Logística Operadora Multimodal S.A., a brand of logistics owned by Cosan Group, and América Latina Logística (ALL). It was then split into Rumo Malha Norte (735 km), Rumo Malha Oeste (1,973 km), Rumo Malha Paulista (2,055 km) and



Rumo Malha Sul (7,223 km) (ANTF, 2020a);

- **2017:** Brazilian Public Prosecution Service (MPF) recommends not automatically renew the concessions of lines Rumo Malha Paulista, MRS Logística, Estrada de Ferro de Carajás, Estrada de Ferro Vitória-Minas and Ferrovia Centro-Atlântica to guarantee that the operation would be economically interesting for the government, as well as the companies are able to solve the several process they have regarding abandoned lines, scrap of equipments and others (REUTERS, 2017);
- **2019:** Rumo signs the contract of concession of Ferrovia Norte-Sul Tramo Central (from Porto Nacional-TO to Estrela d'Oeste-GO, with 1,547 km) as a result of company winning the bidding by offering R\$ 2.72 billion in grants, a 100% increase over the minimum amount of R\$ 1.35 billion set by the government (KAFRUNI, 2019);
- **2020:** Rumo renews Malha Paulista concession until 2058 (MONEYTIMES, 2020); Sao Paulo State government announces an investment plan of R\$ 6 billions to recover two inactive routes (Colômbia-Pradópolis with 185,6 km and Panorama-Bauru with 369,1 km), aiming to interconnect with Ferrovia Norte-Sul (FNS) (FRONTEIRA, 2020);

## 2.2 RAILROAD CONCEPTS

Railroads are characterized as a self-guided system, not allowing the vehicles to change the route or direction by themselves. That way, they travel from one point to another on a track consisting of two continuous longitudinal beams, the rails.

The railroad, as itself, represents the whole set of tracks that interconnects two or more places. Its divided into the main route (from a starting location to another one, having its inner sidings and terminals) and the branches (connecting a point in the main line with another location, also with its sidings and terminals). It may also contain variants, which are part of routes that have been remodeled and may coexist with its previous version.

The railroad modelling considered for this project has the following main physical elements: tracks; rolling stock; signaling and communication systems, and railway operation. Each of them are described in the following sections.

### 2.2.1 Tracks

The track structure can be divided into two groups: infrastructure and superstructure. The superstructure has the function of absorbing the force loads transmitted by the rolling stock and, through its structural elements, transfer them in a uniform and dissipated to the railway platform (A. ROSA, 2016).

Infrastructure, on the other hand, is the basis on which superstructure and is composed by the viaducts, tunnels, and of earthworks, guaranteeing the preservation of the clearance area, transposition of the slopes and adequate drainage (STEFFLER, 2013).

V. Coimbra (2008) explains that the tracks aims to receive loads - both vertical and horizontal - of the rolling stock and unload them on the ground. In order for this transfer to occur properly, it is necessary that the line is maintained under constant evaluations and inspections throughout the period of use and, when wear reaches tolerance determined by technical standards, has an active maintenance plan, in addition to the preventive one.

The tracks components will be divided into: rails, ties, fasteners, ballast, joints, single and double tracks, turnouts, sectioning, main line and yards, crossing grades and other superstructures. Each of them are described in the upcoming sections. Some of them may also be seen in Figure 5.

**Figure 5 – Single crossover simplified representation.**



**Source: RailJoint (2020).**

2.2.1.1 Rails

The rail (also known as Steel Rail due to its composition) is the most important part of the track, and its function is to withstand the pressure of the wheels exercised by the rolling stock moving or stopped over it.

They shall provide a smooth, stable and continuous rolling surface for passing the train wheels. Steel rails can be divided into different types, including railway rails, crane rails, coal mine rails and different standards, including: American, UIC, DIN, JIS, and Australian rails.

The distance between the parallel rails is called gauge. In Brazil, the active railroads (considering the data available from 2016) are divided into three groups, as stated on Frame 1.

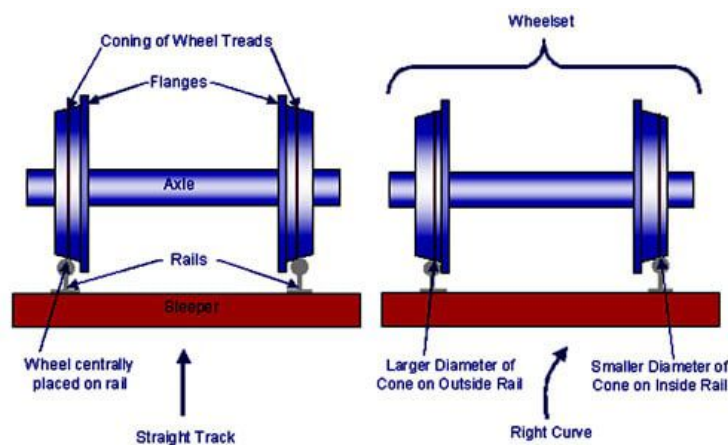
**Frame 1 – Railroad gauges in Brazil (2016).**

Name	Distance	Total length	Percentage
Metric	1.00 m	22.096 km	76,0 %
Large	1.60 m	6.454 km	22,2 %
Mixed	1.00 m and 1.60 m	523 km	1,8 %

**Source: Transporte (2018).**

It allows a rolling-stock piece to be guided in one direction over this setup, by the usage of wheels with a conic shape and flanges that keeps itself into a an alignment that compensates curves super-elevation between a safe radius range, as seen on Figure 6.

**Figure 6 – Coning of wheels – Straight and Curved Tracks.**



**Source: Paul (2014).**

### 2.2.1.2 Ties

The conjunct of two (on metric and large gauges), three or more (on mixed gauge) parallel steel rails are fixed on rectangular sections of wood, concrete or plastic. These pieces are called ties.

Their main function is to operate as a base for the rails, acting as an elastic support between the track and the ballast, ensuring that the gauge remains uniform throughout the length of the railroad and dissipating the loads coming from the tracks in a larger area of the ballast, in addition to ensure the transverse and longitudinal stability of the track. They are mainly made of wood, concrete, steel or plastic (PAIVA, 2016).

### 2.2.1.3 Fasteners

On the studied railroad, the fixation of the rails over the ties is done either by tie plates with clips or spikes (on wooden ties) or by clips fixed into the structure (on concrete ties). The spikes can be also a screw version, known by its french name *tirefond*. The fasteners also aims to maintain the track gauge.

### 2.2.1.4 Ballast

Paiva (2016) explains that the railroad ballast is composed of granular material capable of supporting the grid, the ties and rails of the railway line. In addition to the support of the grid through contact with the underside of the ties, the ballast wraps them longitudinally and laterally, minimizing movement in these directions.

Steffler (2013) also points out that it must consist of a material that allows adequate drainage of surface water while resisting to abrasion, avoiding the formation of fines that can impair the leveling of layers and surface drainage. In addition, to ensure that the grid remains stable, it is interesting that its granularity is composed of stones of different diameters.

Marcuz (2017) states that the ballast has the following objectives:

- to guarantee the draining of the superstructure;
- to act as an elastic support minimizing the vibrations originated by the moving rolling stock;

- to eliminate possible irregularities in the platform, forming a continuous surface for the arrangement of the ties and rails;
- to prevent ties from moving vertically and horizontally;
- to distribute the loads originated from rolling stocks evenly on the platform, reducing their work rate;

Paiva (2016) also describes the sub-ballast: when needed, a layer of ballast with an intermediate granularity is added between the granular layer of the ballast and the soil of the superficial layer of the platform. It acts as a complementary layer that assists in dissipating tensions. The platform, in turn, is the surface layer of the infrastructure and must be prepared to respond appropriately to loads.

#### 2.2.1.5 Joints

The rail joint - also known as fishplate - is a metal bar used to connect the end of two rails together. It's also used to reserve a space for hotter weathers when the metal expands and can cause a sun kink, as the one view in Photograph 2.

The rail joints themselves are normally made of metal, however there are some special plastic and rubber ones for electric insulation and signaling. Some standard models are shown in Figure 7

**Figure 7 – Different standard of common rail joint**

*Different Standard of Common Rail Joint*



**Source: RailJoint (2020).**

There's also the welding process that allows longer continuous tracks. They handle the expansion problems by using fasteners that allows the rails to move along the track direction, thus increasing their thermal flexibility. A continuous rail welding

**Photograph 2 – Severe sun kink in a yard.**



**Source: Kstrebor (2009).**

procedure using the aluminothermic process may be seen in the video indicated on Figure 8

#### 2.2.1.6 Single and double tracks

The combination of the rails, ties, fasteners, ballast and joints is considered a track. It may also have the ties directly fixed on the structure - without the ballast - as seen on metal bridges like the one registered by the author in Photograph 3.

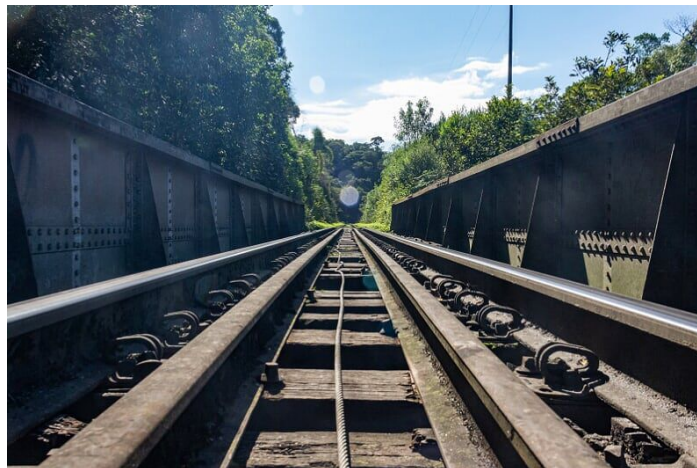
A single-track is composed by the previous components, arranged over a prepared soil that will support the forces exercised by the tracks themselves and by the rolling stock. In this condition, the train (or trains) moving over it may go only in one direction in order to avoid a collision, as there's no possibility of changing the route. It's

**Figure 8 – Continuous rail welding by aluminothermic process on the Serbian Railways in Serbia and Croatia (video).**



Source: Dulevoz (2017).

**Photograph 3 – Metal railroad bridge without ballast, near Banhado (LBH).**



Source: Own authorship (2021).

analogue to a one-way one-lane road.

A double-track is composed by two single-tracks built in parallel, allowing a flow of trains in both directions. Double-tracks usually implements a one-way movement policy for each side of the track, similar to highways. It normally allows, however, a counter-hand operation on overtakes and maintenance conditions.

### 2.2.1.7 Turnouts

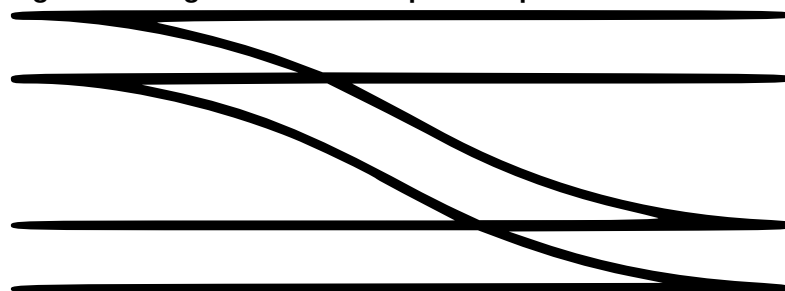
Turnouts are the basic way to merge or split two or more tracks. It's the base for crossings and yards. They're consisted of both fixed and moving parts, allowing an operator (or a machine) to set it to a different position - combining a different pair of tracks which will allow the rolling stock to pass through.

Its composed by switches, frogs, guard rails, stock rails, and closure rails. They have unique rail fastening assemblies and other miscellaneous components associated, including switch rods and gauge plates. The ties that support the turnouts (and their combinations) may also be considered as part of its components, as they often require more fabrication effort than ordinary ones, having different dimensions and/or design.

The combination of one or more turnouts allows the creation of crossover tracks, double crossovers and single and double slip switchers, in which:

- **Single Crossover:** Consists of two turnouts (one right-hand and another left-hand arranged sequentially) located in a double-track design allowing a rolling stock to switch between the tracks. The two tracks are usually parallel, although this is not mandatory. They normally use identical turnout sizes (RAILSYSTEM, 2015). A simplified representation may be seen in Figure 9.

**Figure 9 – Single crossover simplified representation.**

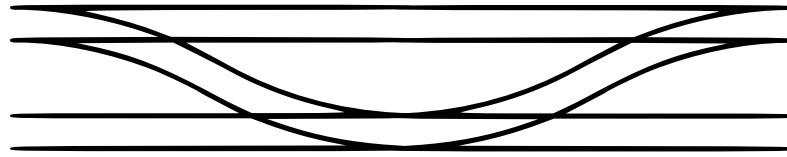


**Source: Own authorship (2021).**

- **Universal Crossover:** Consists of two single crossovers, one right-handed and one left-handed arranged sequentially, allowing the rolling stock to switch between the tracks in both directions. A simplified representation may be seen in Figure 10.
- **Double Crossover:** Consists of a combination of two single crossovers within the same length of the tracks, creating a diamond crossing section by the



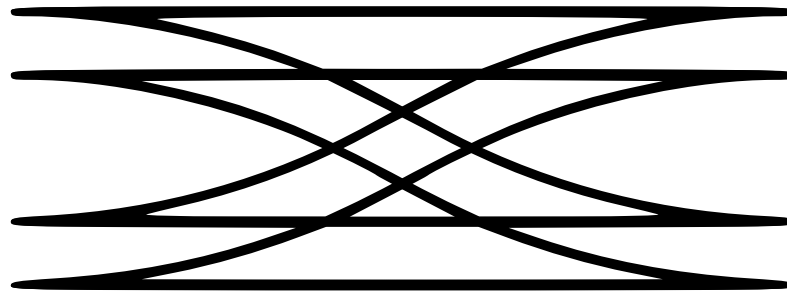
**Figure 10 – Universal crossover simplified representation.**



Source: Own authorship (2021).

superimposition of them. It's also known as scissors crossover due to the opposite hand direction of the turnouts. A simplified representation may be seen in Figure 11 (RAILSYSTEM, 2015).

**Figure 11 – Double crossover simplified representation.**



Source: Own authorship (2021).

#### 2.2.1.8 Sectioning

The railroad, as itself, represents the whole set of tracks that interconnects two or more places. It's divided into identified sections in order to allow their safe occupation during the operations. In Brazil, railroads operates on either single-track or double-track sections.

In order to allow the dispatching and routing, tracks are virtually divided into sections, named Block Section (BS). Under normal conditions only one train is allowed per section, ensuring that no collisions will occur within it.

A BS is considered occupied if there's one or more rolling stocks on it. A train may occupy several BS, depending on its length and position and on the length of the section.

The BS can be of two types: by track electrification signaling system - where the BS is the length of track between two pairs of insulating joints - or by GPS system - in which the BS comprises the length of track between two crossing yards (A. ROSA, 2016).

For this project, the turnouts will also be considered also as independent BS as they'll be used as decision points on whether the train will follow one direction or another, different than a regular BS (either a main or deviated line). On regular operations, however, railroads consider the turnout as part of the forked (main) line BS.

#### 2.2.1.9 Main line and yards

The Main Line (ML) is understood as the line that crosses yards and connects stations, responsible for the transit of rolling stock that travels following a schedule obeying licenses. The permission to advance on the main line is governed by the signaling system, blocking sections or other forms of control (MARCUSZ, 2017).

The ML is normally used to interconnect different blocks of tracks and turnouts named yards, that are classified according to the operations they perform, being either one of the following:

- **Receiving Yard (RY):** also known as Arrival Yard, where locomotives are detached from the freight cars, which are inspected for mechanical problems, and sent to a Switching Yard (SY);
- **Switching Yard (SY):** also known as Sorting Yards, Classification Yards and Marshalling Yards, defines a conjunct of tracks where the rolling stock is sorted and assembled into blocks for different destinations.
- **Crossing Yard (CY):** on single-track railroads, trains from both directions travel on the same line and, for the crossings to happen, secondary or by-passed lines are necessary. That way, a train may be diverted to the secondary line - also known as Deviated Line (DL) - of the yard, making it possible for the train in the opposite direction to have its passage guaranteed by the main line and, after the passage of the train on the main line, the other train leaves the yard and continues its journey. The group of these tracks, from the entrance (inbound) to the exit (outbound) turnout, comprises a Crossing Yard (CY) (A. ROSA, 2010).
- **Departure Yard (DY):** where freight cars blocks are assembled into trains;
- **Maintenance Yard (MY):** also known as Car Repair Yard, where the freight cars and passengers cars receive maintenance and cleaning;
- **Engine House (EH):** also referring to a roundhouse (when present), is used

to fuel and service locomotives (KRAFT, 2002);

- **Station:** where passenger cars are loaded and unloaded, as well as small cargo operations may occur. It's also a point for crew shifting;
- **Terminal:** comprises one or more siding tracks used to load and unload cargo for a local service and/or industry. Normally operated by other companies than the railroad itself, who normally only drops or picks the freight cars (FIORONI, 2008);
- **Transfer Yard (TY):** a yard where rolling stock is dropped off or picked up in groups, for services that uses Unit Trains (UT), but handled locally by surrounding switching services;
- **Unit Yard (UT):** a yard reserved for Unit Trains (trains composed by groups of rolling stocks - usually of the same model - having the same origin and destination) so the traffic may flow easily as there's no sorting. Such trains often stop in another yard for other purposes: inspection, engine servicing, switching and/or crew changes (KRAFT, 2002);

Freight yards may have multiple industries adjacent to them where the freight cars are loaded and/or unloaded and can be safely stored before moving for another trip.

A. Rosa (2010) states that the lines that make up the Crossing Yard must have at least the length of the longest train planned for the section and a length to ensure the safety of the operation. On the railroad subject of the scenarios describe in this project, however, there are different CY lengths, which often lead to conditions where a small train waits the crossing in the deviated line while a longer train (which wouldn't fit the deviated line) crosses using the main line - occupying the BS immediately before the yard, the main line inside the yard and the BS immediately after the yard, simultaneously.

For the development of this work, only Crossing Yards (CY) will be considered in the comparison scenarios.

#### 2.2.1.10 Crossing Grades

Crossing Grades (CG) are defined by Federal Law 9503 of September 23rd, 1997 as "any crossing between a track and a railway line or tram track with its own track at the same height". Therefore, CGs are the point of intersection of main Brazilian

transportation modals: road and rail. Although the frequency of rail accidents is not as high as other modals, CGs are considered to be critical points in the operation due to the severity of the accidents that occur (CARMO, 2006).

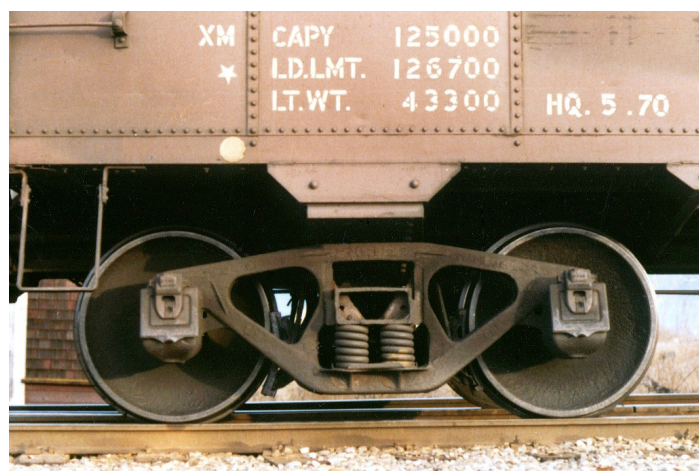
#### 2.2.1.11 Superstructures

The superstructures comprehends the bridges, tunnels and other specific rail-road constructions. However, the study of those subjects goes beyond the scope of this project and won't be detailed here.

#### 2.2.2 Rolling Stock

Over the track there are different type of vehicles that moves themselves, being propelled or propelling units. These are called rolling stock, as they are moved above a pair of frameworks that holds a wheelset each one. They are known as bogies, although in the United States the term "truck" is used designating Bettendorf-style three-piece bogie with axle boxes. As the name suggests, it was basically composed by two rail wheels constrained by four boxes to a structure formed by two sideframes and one crossed section.

**Photograph 4 – Bettendorf variety truck.**



**Source: Moses (2006).**

The Bettendorf Co. was the first company to develop a boogie using this setup in 1903, an hence being referenced on the "Bettenford-style" term. A model can be seen in Photograph 4. As they needed inspection and lubeoil addition on the journal box

(the point where the frame support the axle) at every stop, they were later replaced by the roller bearing trucks after 1920. They may also have originated the term "hot box", which nowadays designate a compromised roller bearing causing too much friction and therefore being dissipated as heat.

**Photograph 5 – Roller bearing truck with painted caps.**



**Source: Own authorship (2021).**

The roller bearing model is spread used until nowadays, being easily identified by its journal caps (the rolling plate fixed on the planar end faces of the axle). Sometimes they receive a different painting, as registered by the author in Photograph 5.

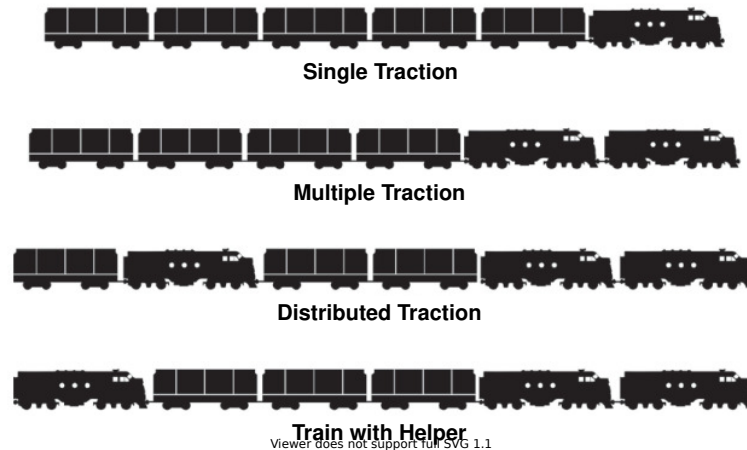
Powered units, passenger cars and maintenance equipment use different bogies, as they're also a different type of rolling stock. They are divided into: locomotives, freight cars, passenger cars, maintenance-of-way and special types. Each of them are describe in the upcoming subsections.

A. Rosa (2016) presents the wagon (either a freight car or a passenger car) as the minimum transport unit and the locomotive as the minimum traction unit. Thus, trains can be composed of one or more locomotives coupled to one or more wagons. Therefore, the compositions can be classified according to their traction in simple, multiple, distributed or train with helper, as seen in Figure 12.

#### 2.2.2.1 Locomotives

Locomotives are the self-propelling units which provides traction force to move the train. They're mainly classified by its power source. In Brazil, the following were used: steam, electric and diesel-electric

Figure 12 – Train traction types.



Source: Marcuz (2017).

- **Steam Locomotives:** the earliest models of locomotives used a steam engine to provide mechanical power directly to the traction axles. It usually had a boiler to generate the steam which was pressurized to move against pistons which were connected to the wheels. Its heating energy came from the burning of a combustible material, such as coal and wood;
- **Electric Locomotives:** electric locomotives normally capture energy from suspended wires (in a building or catenary) through a pantograph - or from a third track through a side shoe - and through a control equipment feeds the traction motors located in the bogies. The same principle applies to passenger unit trains used in metropolitan transport systems. In Brazil, most electrification systems with suspended wires operate with direct current at  $3\text{ kV}_{DC}$ , and with a third rail with direct current at  $750\text{ V}_{DC}$ ;
- **Diesel-electric Locomotives:** in diesel-electric locomotives, the diesel engine drives a generator that produces the electricity required for the traction motors located in the bogies and coupled to the driving wheels by gears. Especially from the 1970s on, the alternator started to be used, producing alternating current to be rectified and sent to direct current traction motors, being widely used in Brazil since then;

### 2.2.2.2 Freight Cars

Each product must be transported by a specific type of wagon according to its characteristics. The five different basic types of wagons used to transport cargo (ROSA, 2011) are:

- **Box Cars:** as their name indicates, have as their main characteristic the protection of their cargo against the weather. Loading and unloading can be done through the side doors. Products such as cement, cellulose and even grains can be transported (ROSA, 2011);
- **Gondolas:** it is the type of wagon that carries products that do not need protection from the weather. It is the most common type in Brazil because of its usage for ore transport. Loading and unloading must be carried out from the top of the wagon. Wagon dumpers are usually used to unload them (ROSA, 2011);
- **Platforms:** platform wagons are the most flexible type for operations, since they can transport all types of contained cargoes. Loading and unloading can be carried out either from the top or from the side and some may have complements on the sides and headboards (ROSA, 2011). The main products transported are steel coils, long steels and containers. They are also used to transport rails, some special maintenance rolling stock and/or equipment;
- **Hopper Cars:** Hopper cars are characterized by their unloading system. The structure is a large funnel in which there are lower openings for the discharge. They can be either closed or open, similar to gondola cars. The main products transported are grains, bran and even ores (ROSA, 2011);
- **Tank Cars:** Tank cars are those specific to liquid bulk of all types, whether corrosive or not, even with an alternative to powdery products. It is formed by a cylindrical structure - usually supported on a metallic platform - being the cylindrical structure itself part the main frame of the freight car (ROSA, 2011). The main products transported includes liquid fuels and chemicals (both liquid and gaseous);

### 2.2.2.3 Passenger Cars

A passenger car (also known as a passenger coach) is a rolling stock designed to exclusively transport passengers and their luggage, however there are different types designed for different purposes. They may be separated in the following types:

- **Standard (Coach):** it's the regular passenger car, designed with seats that allows the passengers to comfortably travel in a rest position;
- **Dining Car:** also known as Restaurant Car is used to serve meals to the passengers. It may have its interior partitioned off for a galley, which is off-limits to passengers and where the meals are prepared;
- **Sleeping Car:** these cars provide sleeping arrangements for the passengers, normally on long-distance trains traveling at night. Some earlier models were convertible into standard cars during the day. The modern ones usually contains separate bedrooms for the passengers, which may vary in size being small for only one bed or large enough to contain a private bathroom;
- **Baggage Car:** a special car designed to transport the passengers' baggage, having its interior normally wide open as in a box freight car. It's normally placed between the locomotive and the passenger cars, allowing a better acoustic insulation from the engines. They can also include restroom facilities for the train crew;
- **Post Office Car:** a special type of passenger cars designed to transport and sort mail en route. They are not accessible to the regular paying passengers. These cars are normally placed between the locomotives and the baggage cars, in order to inhibiting their access by passengers, as the mail packages could contain valuable products. The interior of these cars were designed with sorting facilities normally used in conventional post offices around the world;
- **Control Cab:** a control cab car is a special passenger car that allows the train to run in the reverse direction with the locomotive at the back, remotely operated by the train driver that sits in a cab partitioned from the rest of the car, which is normally a standard one;
- **Lounge Car:** the lounge cars usually have a bar and public seating. On the side of the car, they normally have benches, armchairs or large swivel chairs. They also normally have small tables to drink, or even to play cards. Some



lounge cars include musicians to entertain the passengers;

- **Observation Car:** the observation car usually operates as the last car in a passenger train. Its interior may include features of a coach, lounge, dining, or sleeping car. The main spotting feature was at the tail end of the car, where an observation open deck is present. At this deck, the passengers can enjoy the view of the track rapidly recede into the distance;

#### 2.2.2.4 Maintenance-of-way

The maintenance-of-way rolling stock may include (but is not limited to):

- Ballast regulators;
- Tie cranes;
- Tie replacers;
- Tie plate sweepers;
- Bridge cranes;
- Scarifiers;
- Shoulder ballast cleaners;
- Sand and snow removal machines;
- Brush cutters;
- Rail heaters;

#### 2.2.2.5 Special Types

There are some special types of rolling stock for specific usages, such as prisoner transport cars, funeral cars, inspection cars and others, but their definition goes beyond the scope of this project and will be skipped.

#### 2.2.2.6 Train Types

According to Fioroni (2008), the trains may be divided in the following types:

- **Direct Trains:** freight trains with origin and destination, formed periodically in a yard (its origin yard), going for the main line at a predetermined time and following a fixed route through the railroad until reaching the destination yard

or terminal, where it is disassembled. This kind of train carries may carry different types of cargo and may or may not be linked to a specific customer of the railway management company. The Direct Trains may be considered as Express Trains if they have higher priority over the others;

- **Unit Trains:** composed by groups of freight or passenger cars of the same (or complementary) model, having the same origin and destination and not being disassembled in the yards, except for maintenance;
- **Cyclic Trains:** a freight train dedicated to the transport of a specific cargo between loading and unloading terminals. This type of train is formed only once in the network, has a fixed size (varies only in case of a unit repair), and follows a closed cycle loading at the loading terminal, leaving and following a fixed path to the unloading terminal, unloading, returning to the cargo terminal by a fixed path, and continuously repeating this cycle. This train is not disassembled. A Cyclic Train is normally also a Unit Train;
- **Scout Locomotives:** the term "scout" is used to describe a locomotive running without passenger or freight cars. This movement occurs when a train is dismembered in one yard and its locomotives are needed in another - where a new train is being formed - or when a traction exchange occurs between different yards, either for maintenance or relocation;
- **Helper Train:** presents a set of one or more auxiliary locomotives, positioned in some strategic yards, normally at the lowest level of section where the slope is very steep. Its purpose is to be coupled to a train that needs to overcome the slope. Once the steep section is covered, the auxiliary locomotive is decoupled from the train (normally automatically through a remote device operated by the train driver) and must return to the starting yard. It can return "scout" or attached to another train that is circulating in the same direction. Depending on the circulation intensity on the section - or its length - there may be several auxiliary locomotives, and their return can be made in a single train (with several scout locomotives);
- **Passenger Trains:** trains that have characteristics similar to the Cyclic Trains, circulating between two or more Stations. These trains usually have a higher speed than other trains and should have a higher priority compared to freight trains, according to the Brazilian concession rules.

- **Maintenance Trains:** Trains composed by maintenance-of-way rolling stock. Some common maintenance compositions includes
  - **Track Maintenance:** a set of maintenance-of-way rolling stock including self-propelled vehicles that performs different operations on the track maintenance, such as ballast regulation, tampering, ties and rails replacement, turnout maintenance and others;
  - **Vegetation Control Train:** a special type of train used to control the vegetation along the tracks. Normally consists in a chemical weeding system, with tank freight cars carrying both water and pesticides, a passenger car for the crew, a regular freight car for equipment and a special manned freight car connected to the tanks that sprays the compound over the tracks while the train is moving;
  - **Rescue Train:** normally consisted by one or more cranes and their respective platform freight cars, one or more freight cars for equipment and one or more passenger cars for the crew. It's used on accidents and incidents with derailment of other rolling stock;
- **Other trains and equipment:** other trains that circulates through the railroad for conducting tests on the tracks or special repairs. Usually they work during the passage intervals of the other trains, avoiding causing interference (FIORONI, 2008).

### 2.2.3 Signaling and Communication Systems

The railroad signaling may be divided into two different types: static (traffic signs) and dynamic (section occupancy).

#### 2.2.3.1 Static Signs

It comprises the services, materials and equipment related to the railway signaling by plates (signs), crossing grades signaling, mileage marks and safety marks in turnouts, in order to provide a higher safety level, not only for the circulation of railway trains, but as well as for the road traffic at crossing grades. They are described as:

- **Signaling by Signs:** in Brazil, the signaling system by signs consists of

regulation signs, warning and indication signs, arranged along the railway, always on the right side of the direction of traffic, positioned on the earthwork platform, immediately after the clearance area, in places that allow the best visibility condition to train driver.

Regulatory signs are intended to guide train drivers towards the compliance with operational rules and regulations. The warning signs are intended to draw the drivers' attention to the imminent situations whose nature requires precautionary measures.

The indication plates serve the purpose of providing complementary information to the driver for the safe circulation of trains;

- **Crossing grades signaling:** consists of signs in the area of influence of the crossing grade, necessary to inform train drivers about the existence of the CG and other rail traffic conditions, while, in the same way, road signaling is directed to pedestrians and drivers of road vehicles.

Signaling is divided into two basic groups comprising active signaling and passive signaling, the basic characteristic of active signaling being the fact that the information given to users varies over time, always indicating the situation that is currently occurring, or that is, the existence or not of a train when approaching the level crossing, whereas in passive signaling, the information remains unchanged over time, only indicating the existence of the level crossing.

The active signaling, normally installed on all roads for public use, preferably comprises a set of warning signs, placed both on the railroad and on the highway, complemented by traffic lights, bells and gates, equipped with sensors installed next to the tracks whose activation occurs in the approach of a train;

- **Mileage marks and safety marks in turnouts:** the kilometer marks are intended to materialize the mileage of the railroad in a reliable and visible way - along its entire length - in order to facilitate the identification of the sections, and are placed immediately after the clearance area.

The safety marks are implanted in the turnouts, indicating the point from where the safety distance between the clearance area of the two tracks that are being merged is no longer respected. This indicates the maximum point where a train may go before invading the turnout section. It's also used to determine

the useful length of a Crossing Yard, by measuring the distance between the inbound turnout safety mark and the outbound one;

### 2.2.3.2 Dynamic Signs

According to Theeg and Vlasenko (2009), the two main characteristics of a railway are: the path traveled by vehicles is guided by the tracks - requiring special devices to change the track - and the vehicles have great braking distances due to the low friction between wheels and rails.

Allied to this, the fact that the trains are guided by the track (that is, the system has only one degree of freedom) means that collisions can be avoided only when the vehicles are in a certain location at different times (FENNER, 2007).

The role of the railroad signaling is to guarantee the maximum number of trains traveling through the same given structure and, at the same time, to ensure that two vehicles do not reach the same location at the same time, potentially leading to a collision (FENNER, 2007).

As the volume of traffic increased, it became necessary to increase the number of mandatory crossings between trains of opposite directions. This increase made the operation increasingly complex and there was a need for greater control over traffic. In addition, the increased speed of some trains made it necessary to start overtaking maneuvers. Thus, the use of communication between stations and the recording of train departures and arrivals at stations was required (CAZELLI, 2012).

Simultaneously, the concept of licensing arises. Licensing is an authorization for movement. In the later ages, when a license was issued to a train, it was informed to the following stations so that the operators of those stations would not license trains for the same stretch (CAZELLI, 2012).

Mechanical signals were developed with the functionality to provide drivers with an indication of the turnouts position. A raised sign indicated that the turnout was correctly positioned and that the driver could proceed (CAZELLI, 2012).

With the advent and reduction of the cost of using electricity, it was possible to replace the mechanical signals with luminous ones. The main advantage of light signals is their better visualization, especially at night. Also, the light signals can have different aspects according to color, color combination or flashing. Each aspect indicates

a maximum speed and an operating mode until, normally, the next signal (CAZELLI, 2012).

The most commonly used light signals are colored ones, that is, the color of the light on indicates its appearance. Such signals can be constructed in two ways:

- **Single-point signals:** the signal is represented by only one focus, internally there was a set of lenses of different colors that moved to form the aspect. Also known as a searchlight signal. Nowadays it uses different LEDs (Light Emitting Diode) with no moving parts;
- **Multi-focal signals:** each signal has more than one focus, that is, it has a focus for each color;

The aspects of signs and their meanings vary according to the railway on which they are installed. The aspects are regulated according to the Railroad Operational Regulation (ROR) of each railroad.

With the advent of the technologies described in this topic, it was possible to invent the CTC (Centralized Traffic Control). This control model allowed a significant increase in speed and traffic density in the network.

#### 2.2.4 Railway Operation

The railroad operations will be divided into: basic operation, routing and operational safety. Each of them are described in the following sections.

##### 2.2.4.1 Basic Operation

The basic operation of the railroad is done by the crew members directly and indirectly over the rolling stock and the route. The railroad crew operators (regarding the scope of this project) are divided in the following roles:

- **Train Driver:** responsible for conducting one or more locomotives in a train, adjusting the speed through throttling/breaking while performing side operations such as general monitoring of the train and track conditions, activating horn/bell when needed and communicating with the Operational Control Center (OCC) as well as with other trains when required;
- **Train Engineer:** despite not being used in Brazil - where the Train Driver

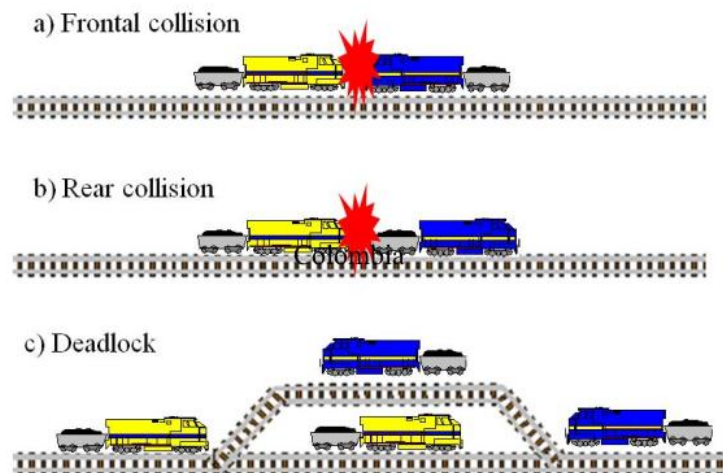
conducts the whole train alone - this role is normally responsible for the general and specific monitoring of the train conditions, performing real-time diagnostics and providing conduction guidelines for the Train Driver to have a safer trip;

- **Switchman:** normally acting only within the limits of yards, is responsible for the coupling and uncoupling of rolling stock - as well as their air hose connections - and for the positioning of turnouts;
- **Dispatcher:** works at the Operation Control Center (OCC) or at Stations given permissions for trains to move along the route sections, taking care to avoid unsafe and/or conflicting conditions and managing priorities;

#### 2.2.4.2 Routing

The railroad operation is composed by a series of traffic contracts to avoid conflicting conditions, like the ones shown on Figure 13.

**Figure 13 – Conflicting conditions that should be prevented in the railroad operation.**



**Source: Fioroni et al. (2013).**

The situation presented on (a) is a frontal collision that may happen on a single-track when two trains travelling in the opposite direction hits each other.

The situation (b) is a rear collision and may happen both single-tracks and double-tracks when two trains travelling the same direction, but having the train behind moving faster, hits the end of the train right ahead of it.

The (c) situation is a deadlock and may happen in single-track lines in the Crossing Yards, leading to a condition where there is no possible forward movement for any of the involved trains - and moving backwards is not a normal nor safe condition (as the train driver is normally not able to see what is ahead of the train in this situation).

All those cases are usually avoided by the Operational Control Center (OCC) which monitors every train and controls their permissions to move through the Block Sections (BS). Also, the automated signaling provides a visual feedback for the train driver regarding the occupancy of the sections ahead. The photography presented in Photograph 6 displays an OCC at Rumo Logística.

**Photograph 6 – Operation Control Center of Rumo Logística.**



**Source: Remotatec (2020).**

The constraints needed to avoid these situations directly affects the railroad capacity, and should be represented in the simulation model. Without them, it would be possible for the simulation to perform better than in the real life (for example, allowing trains to cross at the same section without collision), compromising the results. Several simulation studies focus on the evaluation on the infrastructure and traffic rules, aiming to increase the transportation capacity (FIORONI et al., 2013).

In this project, the rules are going to be written in the simulation model and the simulation output will be a video representing the OCC synoptic panel with the route and the sections occupancy - as well as some instant data about the trains - to represent the solution steps and allow a fine audition.



#### 2.2.4.3 Operational safety

The safety in the operations is the basis of any railway operation. Due to the large masses and inertia involved, railway accidents are often catastrophic and of large proportions. In addition, they cause loss of life, assets and revenue due to traffic interruption.

Every railroad has its ROR - which stands for Railroad Operational Regulation - which consists in a document that governs all rules to be followed by people directly linked to the operation. It is expected that compliance with these rules will prevent accidents, safeguarding the people, the environment and the equipment (VALEC, 2016)

In many countries there are government agencies that often outline at least the basic rules that every railroad must obey. As an example, in the United States there's the Federal Railroad Administration. In Brazil, it's regulated by the ANTT (in Portuguese: *Agência Nacional de Transportes Terrestres*).

### 2.3 SIMILAR PROJECTS

Coupal, Garver, and W. R. Smith (1960) proposed an deterministic algorithm to assist railroad traffic management by evaluating the route that a given set of trains would perform, allowing controllers (humans by the time) to check the effects of a possible change in the railway condition or train schedules. It was designed to run with punch cards in an *IBM 650* computer, a magnetic drum data processing machine first announced in 2 July 1953. Storing data and instructions in words consisted of ten decimal digits and a sign, it was called by the manufacturer as an automatic calculator, not a computer (CRUZ, 2017).

The drum-memory was used to store the signal locations, grades, curves, speed restrictions to be able to describe the track layout of the railroad. For the trains, it stored the number, weight, and type of cars, the locomotive power, both origin and destination, and the departure time. All this information was used to provide both arrival and departure time for each of the trains at each siding or station along the railroad, taking into account the time spent in conflicting route requirements, like crossings and overtakes.

For a single IBM 650 computer, the algorithm took approximately 8 minutes to

calculate one of many trains over 100 miles of railroad. It could be used to provide the predictions for up to 10 trains operating simultaneously on a route of 100 to 150 miles (161 to 241 kilometers).

It was divided into two main parts: the calculation program - used to calculate the time spent for a train to travel from one portion of the route to another - and the route logic program - used to provide a track layout numerical visualization method of the railroad so that when two trains conflict the solution could be recalculated considering an available siding. The complete algorithm of both programs can be seen in Annex A.

Saad (1999) developed a stochastic model to be able to dynamically represent a flow of trains over a single main-track line with sidings. It considers only a single route with no branches, and is capable of performing the measurement of usage of the stations and the average waiting time for the trains in each of the yards. A set of predefined rules is defined in the model to avoid blocking and deadlock situations. This approach was also used in this project.

Pater and Teunisse (1997) proposed the development of a template-based simulation tool targeted to validate the capacity of the Dutch railroad network to attend the demand previewed for 2010. It's focused on passenger trains and considers a network structure different than the one developed in Brazil.

Hooghiemstra and Teunisse (1998) continued the work started with Pater and Teunisse (1997), aiming the research in the evaluation of different timetables and the impact that changes could be made in the entire network. Some of the improvements included a higher integration level with the subject company database and a more intensive punctuality approach.

Middelkoop and Bouwman (2001) also continued the work previously developed by Pater and Teunisse (1997) and Hooghiemstra and Teunisse (1998), adding the possibility to read all the required information to build the network model from a database, automatically creating the corresponding representation. It also creates an animation, using the same template-based approach as the previous developers. This same animation strategy inspired the one presented in this project.

Nunes (2004) presents an internal tool to be used by the dispatchers to help in the decision process of the routing, aiming to reduce the waiting time in the crossings of a single-track line. The experiments showed that the tool was efficient in the network routing problem solving.

Fioroni (2008) presented an algorithm implemented in ARENA aiming to represent a rail network with closed-loop trains, using an event-based simulation. It evaluated different strategies to use in the simulator and discuss the results.

Motraghi and Marinov (2012) performs an analysis using a event-based simulation of an urban rail network to show it's a viable transportation alternative to the most popular modals in the market. It uses ARENA - an event based software, inputting a metro network and performing a set of different simulations under a predetermined number of different scenarios, evaluating the results.

This same approach was considered for this work. However, the author is a defender of the open-source community and believes that the creation of a simulation tool open for a collaborative work would be a greater way to compensate the public investment received along these years of research.

I. Chen (2013) proposed a tool called *TrainWorld* to solve timetables centrally based on the heuristic presented by Lee and Chen (2009). It evaluates the several possible alternatives for the trains routing between the stations until it reaches the best possible solution, aiming to reduce the delays in the system. The tool itself is not open-sourced, but the heuristic was replicated in other works, such as in Araujo (2013).

Paula (2017) developed an algorithm using integer linear programming and used an heuristic to solve it, based on the management of constraints along the time horizon. It was built using the *LINGO* modelling language, receiving the trains, sections and stations of the route. It outputs a timetable graph of the predicted best solution.

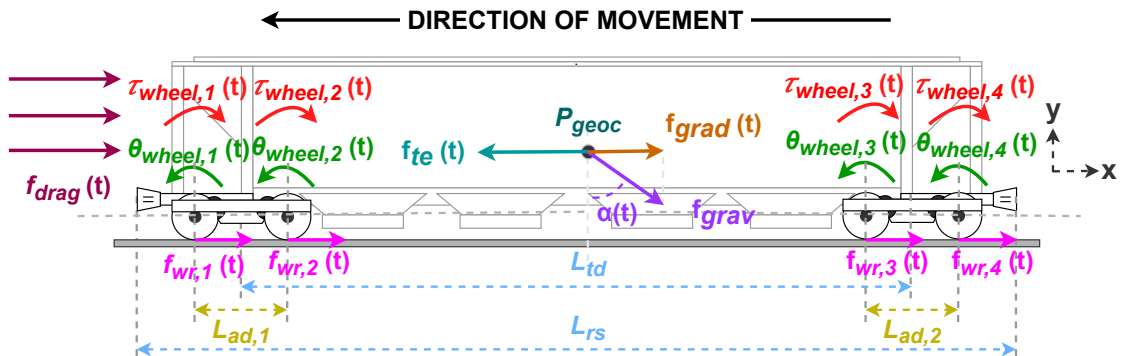
## 2.4 MATHEMATICAL MODELLING

For the rolling stock mathematical modelling, consider the forces diagram presented in Figure 14. It's based on a generic rolling stock freight car (however a prime mover force is also considered in order allow the model to represent self propelled vehicles, such as the locomotives) with a generic breaking system applying a contrary (to the direction of movement) torque to the wheelsets, presenting both the longitudinal and rotational DoF (Degrees of Freedom) and also some of the longitudinal dimensions.

From Figure 14, we have the following variables:

- $\theta_{wheel,1}(t) \dots \theta_{wheel,4}(t)$ : radial velocity of the wheelset. Its value changes over time;

Figure 14 – Forces diagram for a generic rolling stock.



Source: Own authorship (2021).

- $\tau_{wheel,1}(t) \dots \tau_{wheel,4}(t)$ : torque applied to the wheelset trough breaking - always in the opposite direction of the movement (or zero if not moving at all). Its value changes over time;
- $f_{wr,1}(t) \dots f_{wr,4}(t)$ : wheel-rail forces caused by friction in the contact between the wheel and the rail. Its value changes over time;
- $f_{grav}(t)$ : gravitational force relative to the rolling stock weight. Its value changes over time, since the position of the rolling stock (which may change the track grade) is also a time-dependant variable;
- $\alpha$ : angle formed considered the  $y$  axis that crosses the geographic center of the rolling stock and the gravitational force experienced by the vehicle;
- $f_{grad}(t)$ : parallel force (relative to the track) representing the  $x$  component of the gravitational force. As it's original force vector, it's also time-dependant;
- $f_{te}(t)$ : traction effort over the rolling stock (generated through a prime mover). Used to represent the pulling force generated by a self-propelled unit, like locomotives, multiple unit trains, motorcars, MoW (Maintenance-of-Way) vehicles or any other rolling stock that generates tractive effort by itself. Its value changes over time (as the throttle varies);
- $f_{drag}(t)$ : drag force experienced by the rolling stock (received through interaction with the air mostly - but not limited to - the frontal face). Its value changes over time;
- $L_{rs}$ : distance between the end of the couplers (total length). Its considered to be a constant value;
- $L_{td}$ : distance between the center of the trucks (bogies). Its considered to be a

constant value;

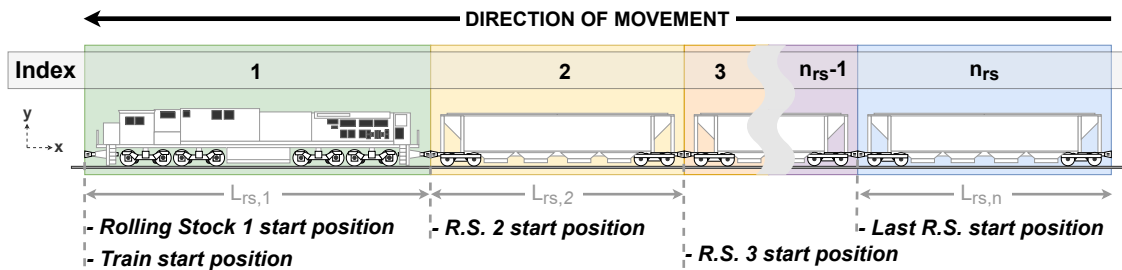
- $L_{ad,1}, L_{ad,2}$ : distance between the center of the wheels on each of the trucks (bogies). Its considered to be a constant value;
- $P_{geoc}$ : geometric center of the rolling stock. Its considered to be a constant value. As the simulator proposed in this work doesn't consider side effects like derailments caused by rollover or tipover, we'll ignore the exact center of mass location ( $P_{mass}$ ), assuming only that  $P_{mass} = P_{geoc}$ ;

#### 2.4.1 Train, rolling stock and axles positions

Alturbeh et al. (2018) used a strategy for the mathematical approach that considered  $x(t)$  (in meters) as the train position given a time  $t$  (in seconds), and  $x_i(t)$  as the rolling stock position, considering  $i$  as the rolling stock index in the train (so that  $1 \leq i \leq n_{rs}$ , being  $n_{rs}$  the total count of rolling stock in the train).

Note that the summation operator presents the coefficients in a way that requires a zero-based index (the first unit has  $i = 0$ ). It's also counted ascending from the leading unit to the trailing one - which would be left-to-right considering that the train is pointing to the left. This is represented in Figure 15.

**Figure 15 – Rolling stock indexes and positions in a generic train.**



Source: Own authorship (2021).

Considering this, we have Equation 1,

$$x_i(t) = x(t) + \sum_{n=1}^{n_{rs}} L_{rs,i} \quad (1)$$

where:

- $x_i(t)$ : Rolling stock position - considering the face of the frontal coupler - at index  $i$  in the train. Its value changes over the time [ $m$ ];

- $x(t)$ : Train position (from the first coupler). Its value changes over the time [m];
- $i$ : Rolling stock index in the train, within the range  $1 \leq i \leq n_{rs}$ ;
- $n_{rs}$ : Total count of rolling stock units in the train;
- $L_{rs,i}$ : Rolling stock (at index  $i$ ) length, from coupler-to-coupler [m];

Thus, we can define the wheelsets' position  $x_{ij}(t)$  in a similar way that Alturbeh et al. (2018) did, considering  $j$  as the rolling stock wheel index, so that  $1 \leq j \leq n_{ax}$ , being  $n_{ax}$  the total count of axles in that particular rolling stock (usually four).

For the model defined in Figure 14, these positions are defined by Equation 2, Equation 3, Equation 4, and Equation 5,

$$x_{i,1}(t) = x_i(t) + \frac{1}{2} \times (L_{rs} - L_{td} - L_{ad}) \quad (2)$$

$$x_{i,2}(t) = x_i(t) + \frac{1}{2} \times (L_{rs} - L_{td} + L_{ad}) \quad (3)$$

$$x_{i,3}(t) = x_i(t) + \frac{1}{2} \times (L_{rs} + L_{td} - L_{ad}) \quad (4)$$

$$x_{i,4}(t) = x_i(t) + \frac{1}{2} \times (L_{rs} + L_{td} + L_{ad}) \quad (5)$$

where:

- $x_{ij}(t)$ : Rolling stock axle position (considering rolling stock index  $i$  in the train and axle index  $j$  in the rolling stock) [m];
- $x_i(t)$ : Rolling stock position (at index  $i$  in the train) [m];
- $x(t)$ : Train position (from the first coupler) [m];
- $L_{rs}$ : Total length of the rolling stock, from couplers ends [m];
- $L_{td}$ : Distance between the center of the trucks (bogies) [m];
- $L_{ad}$ : Distance between the center of the axles in the trucks (bogies), considering that  $L_{ad,1} = L_{ad,2}$  in the Figure 14 [m];

They also defined the horizontal geometric centre of the rolling stock, which will be used in the calculation of the effect of the track gradient, seen in Equation 6,

$$x_{geoc,i}(t) = x_i(t) + \frac{1}{2} \times (L_{rs} + L_{td}) \quad (6)$$

where:

- $x_{geoc,i}(t)$ : Rolling stock geometric center horizontal position (considering rolling stock index  $i$  in the train) [ $m$ ].
- $x_i(t)$ : Rolling stock position (at index  $i$  in the train) [ $m$ ];
- $L_{rs}$ : Total length of the rolling stock, from couplers ends [ $m$ ];
- $L_{td}$ : Distance between the center of the trucks (bogies) [ $m$ ];

For the axles we also have the axle radial position for a given time  $t$ , defined by  $\theta_{i,j}$  (in radians) considering  $i$  as the rolling stock index in the train - so that  $1 \leq i \leq n_{rs}$  - being  $n_{rs}$  the total count of rolling stock in the train - and  $j$  as the rolling stock wheel index - so that  $1 \leq j \leq n_{ax}$ , being  $n_{ax}$  the total count of axles in that particular rolling stock (usually four). For the model defined in Figure 14, they'd be  $\theta_{wheel,1} \dots \theta_{wheel,4}$ .

#### 2.4.2 Longitudinal dynamics

Based on the approach used by Alturbeh et al. (2018), a single vehicle model is considered for the dynamics, composed by the wheel-rail forces, the drag forces, the pulling force and the horizontal component of the gravitational force.

Considering this, it is possible to describe Equation 7 as the sum of the longitudinal forces divided by the rolling stock mass in order to find its total acceleration (Newton's second law),

$$\ddot{x}(t) = \frac{1}{M_{rs}} \times (f_{te}(t) - f_{wr,1}(t) - f_{wr,2}(t) - f_{wr,3}(t) - f_{wr,4}(t) - f_{drag}(t) - f_{grad}(t)) \quad (7)$$

where:

- $\ddot{x}(t)$ : Rolling stock acceleration for a given time  $t$  [ $ms^{-1}$ ];
- $M_{rs}$ : Total mass of the rolling stock [ $kg$ ];
- $f_{wr,1} \dots f_{wr,4}$ : Wheel-rail forces caused by friction in the contact between each of the wheelsets and the rails - so we have  $f_{rw,j}$  for  $1 \leq j \leq n_{AX}$ , being  $n_{AX}$  the total count of axles in that particular rolling stock. We are considering a default rolling stock with four axles [ $N$ ];
- $f_{drag}$ : Drag forces resulted from the interaction of both aerodynamic and gravitational force [ $N$ ];
- $f_{te}$ : Traction effort over the rolling stock (received through the couplers or

self-propelled) [ $N$ ];

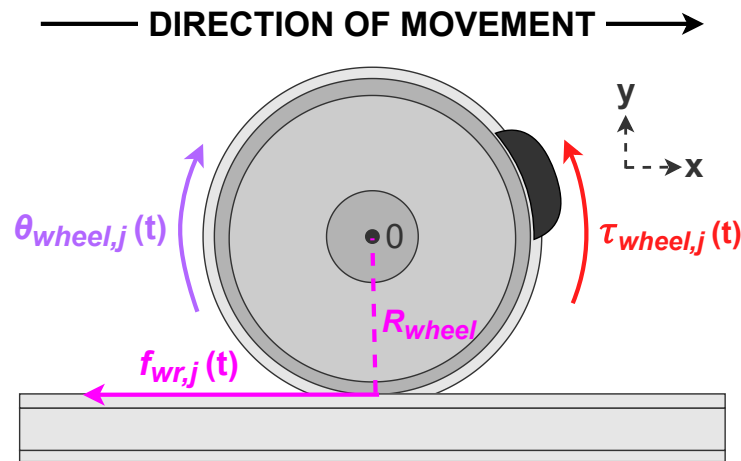
- $f_{grad}$ : Horizontal component of the gravitational force over the rolling stock weight due to the track gradient [ $N$ ];

To be able to determine the wheel-rail forces, it's necessary to first consider the rotational dynamics of the wheel, as presented in the following sub-section.

### 2.4.3 Rotational dynamics

In order to calculate the rotational dynamics of the wheelset, consider the diagram presented in Figure 16.

Figure 16 – Rotational dynamics in a wheelset.



Source: Own authorship (2021).

From this diagram, it's possible to determine that two torques are present in each wheelset  $j$ : the resultant torque from the wheel-rail friction force  $f_{wr,j}(t)$  with an arm of moment with the length of the wheel radius ( $R_{wheel}$ ) - not considering the wheel flange - and the torque applied to the wheel trough braking ( $\tau_{wheel,j}(t)$ ), always in the opposite direction of the movement (or zero if not moving at all). By summing both torques and dividing them by the rotational inertia  $J_{wheel,j}$  of the wheelset, we are able to determine its rotational acceleration  $\ddot{\theta}_{wheel,j}(t)$  (Newton's second law), as represented in Equation 8,

$$\ddot{\theta}_{wheel,j}(t) = \frac{1}{J_{wheel,j}} \times (f_{wr,j}(t) \times R_{wheel} - \tau_{wheel,j}(t)) \quad (8)$$

where:



- $\ddot{\theta}_{wheel}(t)$ : rotational acceleration of the wheelset for a given time  $t$  [ $rad \times s^{-2}$ ];
- $J_{wheel,j}$ : rotational inertia  $J$  of the wheelset (for  $1 \leq j \leq 4$ ) [ $kg$ ];
- $f_{wr,j}(t)$ : wheel-rail forces caused by friction in the contact between each wheelset and the rails (for  $1 \leq j \leq 4$ ) for a given time  $t$  [ $N$ ];
- $R_{wheel}$ : wheel radius from the center of the axle to the rail contact face - not considering the wheel flange [ $m$ ];
- $\tau_{wheel,j}(t)$ : torque applied to the wheelset (for  $1 \leq j \leq 4$ ) through braking always in the opposite direction of the movement (or zero if not moving at all) [ $N \times m$ ];

The wheel-rail forces results from the interaction of an adhesion model which turns into a complex calculation, even in the simplified versions as presented by Piotrowski and Kik (2008). Popov et al. (2002) proposed a macro-level analysis for the wheel-rail contact problem considering both being perfectly elastic bodies, bounded by smooth surfaces. It considered a typical slip rate in the contact region varying in the range of 1 to  $5ms^{-1}$  for a rolling velocity of  $50ms^{-1}$ , representing a loss from 2 to 10% of the tractive effort.

We'll consider only a maximum value for  $f_{wrmax,j}(t)$  as the wheel-slip boundary limit in the logic implementation of a locomotive - for both braking and throttling - as Equation 9 from Jayakumar and Kumar (2012) suggests,

$$f_{wrmax,j}(t) = \mu(t) \times \frac{\tau_{wheel,j}(t)}{R_{wheel}} \quad (9)$$

where:

- $f_{wrmax,j}(t)$ : maximum tangential force produced by the wheel before slipping for a given time  $t$  in seconds [ $N$ ];
- $\mu(t)$ : coefficient of friction of the track for a given time  $t$  in seconds;
- $\tau_{wheel,j}(t)$ : torque applied to the wheel through braking [ $N \times m$ ];
- $R_{wheel}$ : wheel radius from the center of the axle to the rail contact face - not considering the wheel flange [ $m$ ];

The wheel-slip phenom can be seen in a real-world situation video by GottliebPins (2019) that can be accessed through the Figure 17.

Consider  $1 \leq j \leq n_{AX}$ , being  $n_{AX}$  the total count of axles in that particular rolling stock (assuming a default four-axle rolling stock). It is also assumed that the wheel-rail forces caused by friction in the contact between each of the wheelsets and the rails are

Figure 17 – SD40-2 in a wheel-slip condition (video).



Source: GottliebPins (2019).

already considered together with the drag force  $f_{drag}(t)$ , in order to form a single rolling resistance force  $f_{rr}(t)$  (SZANTO, 2016). That way it will be considered that  $f_{wr,j}(t) = 0$  in Equation 8, rewriting it into Equation 10,

$$\ddot{\theta}_{wheel,j}(t) = -\frac{\tau_{wheel,j}(t)}{J_{wheel,j}} \quad (10)$$

where:

- $\ddot{\theta}_{wheel,j}(t)$ : rotational acceleration of the wheelset for a given time  $t$  [ $rad \times s^{-2}$ ];
- $J_{wheel,j}$ : rotational inertia  $J$  of the wheelset (for  $1 \leq j \leq 4$ ) [ $kg \times m^2$ ];
- $\tau_{wheel,j}(t)$ : torque applied to the wheelset (for  $1 \leq j \leq 4$ ) trough braking for a given time  $t$  [ $kg \times m^2 \times s^{-2}$ ];

Considering that  $\ddot{x}(t) = \ddot{\theta}_{wheel,j}(t) \times R_{wheel}$  and having in mind that this acceleration is no longer dependant in the rolling stock weight, we may rewrite Equation 7 into Equation 11.

$$\ddot{x}(t) = \frac{1}{M_{rs}} \times (f_{te}(t) - f_{drag}(t) - f_{grad}(t)) - \ddot{x}_{tan}(t) \quad (11)$$

And  $\ddot{x}_{tan}(t)$  is defined in Equation 12,

$$\ddot{x}_{tan}(t) = K_{comp} \times \sum_{j=1}^{n_{ax}} \frac{\tau_{wheel,j}(t) \times R_{wheel}}{J_{wheel,j}} \quad (12)$$

where:

- $\ddot{x}_{tan}(t)$ : resultant tangential acceleration considering all the wheelset in the rolling stock for a given time  $t$  in seconds [ $m \times s^{-2}$ ];
- $K_{comp}$ : compensation constant for the energy loss due to the slip rate in the contact region (0.95 will be used, representing a 5% loss), following the results obtained from Popov et al. (2002);
- $\tau_{wheel,j}(t)$ : torque applied to the wheelset at position  $j$  trough braking for a given time  $t$  in seconds [ $kg \times m^2 \times s^{-2}$ ];
- $R_{wheel}$ : radius of the wheel from the center of the axle to the rail contact face - not considering the wheel flange [ $m$ ];
- $n_{ax}$ : number of axles in the wheelset;
- $J_{wheel,j}$ : rotational inertia  $J$  of the wheelset at position  $j$  [ $kg \times m^{-2}$ ];

#### 2.4.4 Traction effort

The next variable to be defined is the  $f_{te}$ , which represents the traction effort (force) produced by the rolling stock. Coupal, Garver, and W. R. Smith (1960) considered this as a constant (either with the maximum value or zero). A more realistic approach could be used considering discrete tractive effort values for each of the APs (Acceleration Points) of the self-propelled rolling stock (we'll consider a locomotive for convention, but it could be any powered-unit) or even a speed function, considering real gathered data. It could even consider the dynamic breaking steps as negative values.

Story (2018) presents a didactically simplified approach to the explanation between the relation of the tractive effort, the horsepower and the APs for a diesel-electric locomotive. The video can be accessed through the Figure 18.

Coupal, Garver, and W. R. Smith (1960) assumed a route restricted to diesel-electric locomotives operation, which also applies for the scenarios considered in this research. This allows  $f_{te}$  for a single rolling stock self-propelled unit to be simplified to Equation 13,

$$f_{te|bf}(t) = \frac{300 \times w_{locoh_p}(t)}{v_{hp_{mph}}} \quad (13)$$

where:

**Figure 18 – Relation between Tractive Effort, Horsepower and APs (video).**



**Source: Story (2018).**

- $f_{te_{lbf}}(t)$ : tractive effort [ $lbf$ ];
- $w_{loco_{hp}}(t)$ : locomotive output horsepower [ $hp$ ];
- $v_{hp_{mph}}$ : train speed or minimum speed for the maximum horsepower, whichever is larger [ $mph$ ];

However, this equation is not SI compatible. With few conversion constants, we may then have Equation 14,

$$f_{te}(t) = K_{lbf2N} \times \frac{300 \times w_{loco}(t) \times K_{w2hp}}{v_{hp} \times K_{ms^{-1}2mph}} \quad (14)$$

where:

- $K_{lbf2N}$ : conversion factor from pound-force to Newtons [ $N \times lbf^{-1}$ ];
- $K_{ms^{-1}2mph}$ : conversion factor from meters per second to miles per hour [ $mph \times m^{-1} \times s$ ];
- $K_{w2hp}$ : conversion factor from watts to horsepower [ $hp \times W^{-1}$ ];
- $f_{te}(t)$ : tractive effort [ $N$ ];
- $w_{loco}(t)$ : locomotive output horsepower [ $W$ ];
- $v_{hp}$ : train speed or minimum speed for the maximum horsepower, whichever is larger [ $m \times s^{-1}$ ];

Consider the constants defined in Equation 15, Equation 16, and Equation 17.

$$K_{lb f2N} = 4.4482 \quad (15)$$

$$K_{w2hp} = 1.3410 \times 10^{-3} \quad (16)$$

$$K_{ms^{-1}2mph} = \frac{1}{0.4470} \quad (17)$$

By replacing Equation 15, Equation 16 and Equation 17 in Equation 14, Equation 18 is obtained,

$$f_{te}(t) = 4.4482 \times \frac{300 \times w_{loco}(t) \times 1.3410 \times 10^{-3}}{v_{hp} \times 0.4470^{-1}} \simeq \frac{0.8 \times w_{loco}}{v_{hp}} \quad (18)$$

where:

- $f_{te}(t)$ : tractive effort [ $N$ ];
- $w_{loco}(t)$ : locomotive output horsepower [ $W$ ];
- $v_{hp}$ : train speed or minimum speed for the maximum horsepower, whichever is larger [ $m \times s^{-1}$ ];

Note that for non-powered units (such as the freight cars considered in the scenarios) will have  $F_{TE} = 0$ .

#### 2.4.5 Train resistance and drag force

Another variable to determine is the drag force ( $f_{drag}$ ) often called as rolling resistance. This later naming however, comprehends both the forces caused by aerodynamic forces ( $f_{drag}(t)$ ) and the wheel-rail forces caused by friction in the contact between each of the wheelsets and the rails ( $f_{wr,j}(t)$ ). Thus we'll consider:

$$f_{rr}(t) = f_{drag}(t) + \sum_{j=1}^{n_{ax}} f_{wr,j}(t) \quad (19)$$

This force directly affects the journey time and the fuel consumption, being a research area by itself. It results from the interaction of both aerodynamic and gravitational force, being substantially higher in tunnels than in open air (M.H. BIGHARAZ, 2014).

Several studies in the area were made in the last two centuries. According to (M.H. BIGHARAZ, 2014), the first detailed researches were made during the 1840's by W. (1846) and GOOCH (1848). It led to predictive equations on later studies by Clark (1855). The velocity on these early measurements reached about 100 km/h and later up to 210 km/h by W. (1846).

These measurements are taken typically at constant speed, like in W. (1846), GOOCH (1848) or by run-down like in R. (1908), Bernard (1974), (BROCKIE, 1988), Rochard and Schmid (2000), Lukaszewicz (2001), Lukaszewicz (2007), Lukaszewicz (2009) and S. W. Kim, Kwon, and T. W. Kim Y. G. Park (2006). Brockie and Baker (1990), Brockie and Baker (1991) and Schetz (2001) used a reduced scale model in wind-tunnel tests to perform the measurements, however a correction was needed to compensate the difference between the scaled experiment to full-scale conditions.

Several equations were developed by different authors, like W. (1846), Clark (1855), Barbier (1898), Borries (1904), Frank (1907), Schmidt (1910) and Strahl (1913). They're all based in an equation quadratic in velocity, as described in its general form in equation Equation 20. It's commonly known as the Davis equation, as published by W. J. jr Davis (1926) (ROCHARD; SCHMID, 2000),

$$\rho_{unit} = A + B \times v + C \times v^2 \quad (20)$$

where:

- $\rho_{unit}$ : resistance value for a single rolling stock unit.
- $v$ : velocity of the unit;
- $A$ : coefficient (from theoretical considerations or measurements);
- $B$ : coefficient (from theoretical considerations or measurements);
- $C$ : coefficient (from theoretical considerations or measurements);

The coefficients values depends on different contributions, like the rolling resistance on  $A$ , the association between the drag and ingest air on  $B$  and the aerodynamic resistance on  $C$  (SCHETZ, 2001; BROCKIE; BAKER, 1990). W. J. jr Davis (1926) proposed Equation 21 with the constants defined to calculate the resistance for freight trains, which become well-known and is still widely used (SZANTO, 2016). It was also

used by Coupal, Garver, and W. R. Smith (1960),

$$\rho_{unit}(t) = 1.3 + \frac{29}{w_{ax}} + 45 \times 10^{-3} \times v_{mph}(t) + \frac{5 \times 10^{-4} \times a}{w_{ax} \times n_{ax}} \times v_{mph}^2 \quad (21)$$

where:

- $\rho_{unit}(t)$ : resistance value for a single rolling stock unit [ $lb \times ton^{-1}$ ];
- $w_{ax}$ : load per axle [ $ton$ ];
- $n_{ax}$ : number of axles;
- $a_{unit}$ : frontal area of the unit [ $sq.ft.$ ];
- $v_{mph}(t)$ : velocity [ $mph$ ];

Association of American Railroads (2001) defined a slightly modified version of the Davis equation, as represented in Equation 22. Note that in this version, the second term depends also on the number of axles. W. J. jr Davis (1926) considered this with a constant value of  $29lb_f$  per axle (approx.  $13kg_f$  per axle) with  $n \simeq 2$ . Association of American Railroads (2001) instead consider  $18lb_f$  per axle (approx.  $8kg_f$  per axle) and the number of axles appears as a new constant. Also, the aerodynamic drag term  $C$  defaults to a cross-sectional area of  $110sq.ft.$  (approx.  $10m^2$ ). There are also other variants of the equation for different wagon types (SZANTO, 2016),

$$\rho_{unit}(t) = 1.3 + \frac{72.5}{w_{ax} \times n} + 15 \times 10^{-3} \times v_{mph}(t) + \frac{55 \times 10^{-3}}{w_{ax} \times n_{ax}} \times v_{mph}^2(t) \quad (22)$$

where:

- $\rho_{unit}(t)$ : resistance value for a single rolling stock unit [ $lb \times ton^{-1}$ ];
- $w_{ax}$ : load per axle [ $ton$ ];
- $n_{ax}$ : number of axles;
- $v_{mph}(t)$ : velocity [ $mph$ ];

Szanto (2016) also proposes a metric version of the equation, considering  $g = 10m \times s^{-2}$  - used for convenience as the constants have an accuracy of less than two decimal places - which can be seen in Equation 23,

$$\rho_{unit}(t) = 6.5 + \frac{320}{w_{ax} \times n_{ax}} + 15 \times 10^{-3} \times v_{ms}(t) + \frac{96 \times 10^{-3}}{w_{ax} \times n_{AX}} \times v_{ms}^2(t) \quad (23)$$

where:

- $\rho_{unit}(t)$ : resistance value for a single rolling stock unit [ $N \times ton^{-1}$ ];
- $w_{ax}$ : load per axle [ $ton$ ];

- $n_{ax}$ : number of axles;
- $v_{ms}(t)$ : Velocity [ $m \times s^{-1}$ ];

Engineering and Maintenance-of-Way Association (1999) proposed a different set of values for the aerodynamic coefficient based on the rolling stock type, as compared by Szanto (2016) in Table 2.

**Table 2 – Air Drag as per Canadian National.**

	Coeff (C) $\frac{lbf \times s}{ton \times sq.ft.}$	Area (A) $sq.ft.$	C x A (original) $\frac{lbf \times s}{ton}$	C x A (metric) $\frac{kg^2}{m}$
AAR RP548	0.0005	110	0.055	0.096
Coal Gondola	0.00042	105	0.044	0.077
Empty Gondola	0.0012	105	0.126	0.219
Lead Locomotive	0.0024	160	0.384	0.670
Trailing Locomotive	0.00055	160	0.088	0.154

**Source: Engineering and Maintenance-of-Way Association (1999).**

By multiplying Equation 23 by a  $1 \times 10^{-3}$  factor, we'll have the value expressed in  $N/kg$  (considering  $1ton = 1 \times 10^{-3}kg$ ). Then it'll be multiplied by the rolling stock mass  $M_{rs}$  (also in kilograms), so that we end-up with a function that returns a force scalar value.

We'll also consider that  $W_{axle} \times n_{ax} = M_{rs}$ , as the weight per axle ( $W_{axle}$ ) multiplied by the number of axles ( $n_{ax}$ ) must be equal the total weight of the rolling stock ( $M_{rs}$ ), as the wheelsets are the only supporting surfaces under normal conditions. That way we'll have Equation 24,

$$f_{rr}(t) = M_{rs} \times K_{ton^{-1}2kg^{-1}} \times (6.5 + \frac{320}{M_{rs}} + 15 \times 10^{-3} \times v_{ms}(t) + \frac{96 \times 10^{-3}}{M_{rs}} \times v_{ms}^2(t)) \quad (24)$$

where:

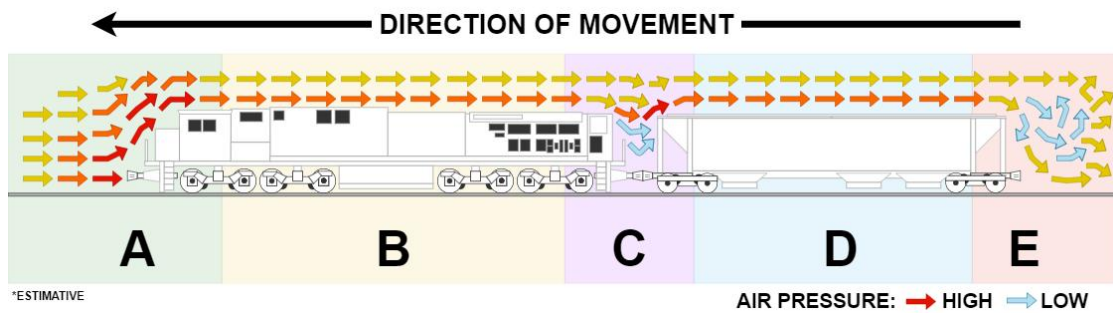
- $f_{rr}$ : resultant rolling resistance force in the rolling stock unit [ $N \times kg^{-1}$ ];
- $K_{ton^{-1}2kg^{-1}}$ : conversion factor from  $ton^{-1}$  to  $kg^{-1}$ , evaluated to  $1 \times 10^{-3}$  [ $ton \times kg^{-1}$ ];
- $M_{rs}$ : total mass of the rolling stock [ $kg$ ];
- $V_{ms}$ : velocity [ $m \times s^{-1}$ ];

This force is however designated to the first frontal face of first rolling stock of the train. Consider the air flow simplification presented in Figure 19. The total force  $f_{drag}$  is applied fully to the frontal surface (area) of the train in section A. It'll be considered also that the tail drag force of section E is compensated in  $f_{drag}$  of the first unit in the



Davis equation. Sections *B* and *D* will be considered to have  $f_{drag} = 0$  for simplification. We may see, however, a surface exposure to the air flow in the gaps of the rolling stock couplers, such as in section *C*. The analysis of the winds and air flow surrounding the trains and between the rolling stocks is complex and out of the scope of this project. For simplification, a value of 30% of the original rolling stock  $f_{drag}$  will be assumed when it's not the first unit. This value is a suggestion and will be kept as a constant in every simulation condition (in order to avoid any interference), but a better approach could be used in the future.

**Figure 19 – Drag forces surrounding a train (simplified).**



**Source: Own authorship (2021).**

That way, we may consider a constant  $K_{drag}$  that will be 1.0 if the rolling stock is the first unit, 0.3 otherwise. Then we may rewrite Equation 24 into Equation 25, which also replaced  $K_{ton^{-1}2kg^{-1}}$  for  $1 \times 10^{-3}$ . Consider Equation 25 and Equation 26,

$$f_{rr}(t) = M_{rs} \times K_{drag} \times (6.5 \times 10^{-3} + \frac{3.2 \times 10^{-6}}{M_{rs}} + 1.5 \times v_{ms}(t) + \frac{9.6 \times 10^{-5}}{M_{rs}} v_{ms}^2(t)) \quad (25)$$

$$K_{drag} = \begin{cases} 1.0, & \text{if first unit} \\ 0.3, & \text{otherwise} \end{cases} \quad (26)$$

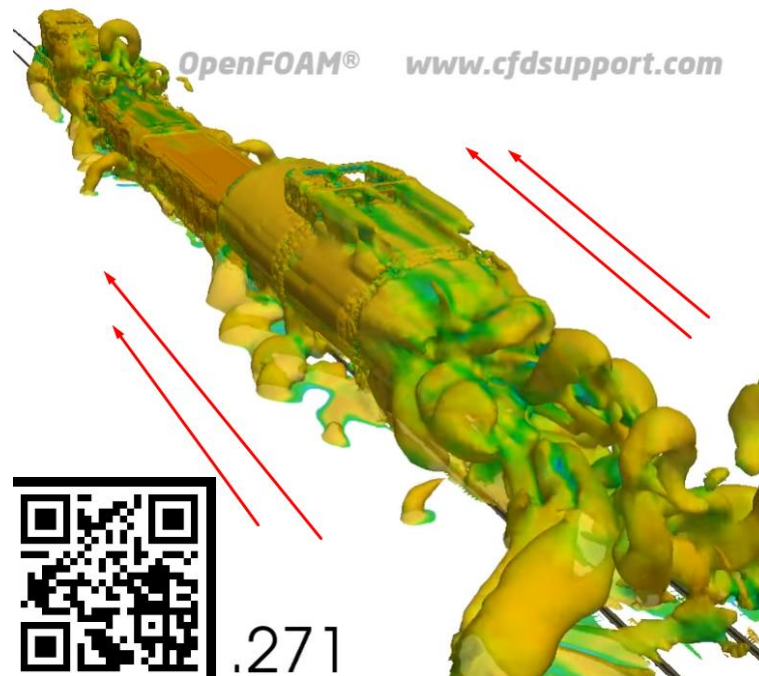
where:

- $f_{rr}(t)$ : resultant rolling resistance force in the rolling stock unit [ $N \times kg^{-1}$ ];  
 $1 \times 10^{-3} [ton \times kg^{-1}]$ ;
- $M_{rs}$ : total mass of the rolling stock [ $kg$ ];
- $v_{ms}(t)$ : velocity [ $m \times s^{-1}$ ];

These assumptions were made based on the work presented by Khayrullina et al. (2015). There were also two Computational Fluid Dynamics (CFD) simulation

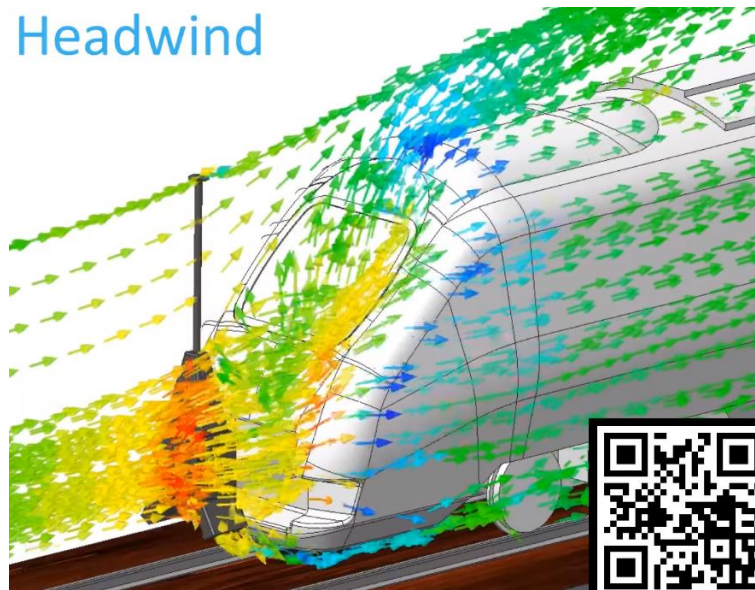
videos considered, one published by CFDSupport (2014) which can be seen in Figure 20 and the other by Linders (2016) which is available in Figure 21.

**Figure 20 – Train aerodynamics simulation (video).**



Source: CFDSupport (2014).

**Figure 21 – CFD Simulation RILA with train - Wind drag (video).**



Source: Linders (2016).

#### 2.4.6 Track grade and gravitational force

Being the last force to determine - but not the least important - comes the gravitational force. Due to the train weight (in the order of  $6 \times 10^9 kg$  for a bulk regular loaded train that runs in the studied scenarios) the track grade (which is the percentage of elevation/length for a given section) affects directly the required amount of tractive effort (and therefore the amount of fuel) required to move a cargo from one place to another.

Considering  $\alpha$  as the angle formed by the y axis (from the rolling stock geographic center referential) with the gravitational force perceived by the rolling stock  $f_{grav}$  - as represented in Figure 14 - we may define the track grade force  $f_{grad}$  as in Equation 27,

$$f_{grad}(t) = f_{grav} \times \sin \alpha(t) \quad (27)$$

where:

- $f_{grad}(t)$ : horizontal component of the gravitational force over the rolling stock weight due to the track gradient [ $N$ ];
- $\alpha(t)$ : gravitational force angle relative to the vertical y axis, normally represented as a percentage from the elevation/length ratio for a given section (called track grade);
- $f_{grav}$ : gravitation force perceived by the rolling stock, based on it's mass [ $N$ ];

We'll consider that  $\sin \alpha = \alpha$  as this is valid for angles up to about 14 deg (where the equality occurs). This represents a gain of about 250m for a 1000m section, or a grade of 25%. That's more than two times the biggest grade registered in Brazil - at *Estrada de Ferro Campos do Jordão* (Campos do Jordão Railway) which is approximately 10% at the peak. We'll also assume that  $f_{grav}(t) = M_{rs} \times \ddot{G}$ , where  $\ddot{G}$  is the gravitational acceleration considered to be a constant of  $9.71m \times s^{-2}$ . Thus we'll have Equation 28,

$$f_{grad}(t) = M_{rs} \times \ddot{G} \times \alpha(t) \quad (28)$$

where:

- $f_{grad}(t)$ : horizontal component of the gravitational force over the rolling stock weight due to the track gradient [ $N$ ];
- $M_{rs}$ : total mass of the rolling stock [ $kg$ ];

- $\ddot{G}$ : gravitational acceleration (considered to be a constant of  $9.71m \times s^{-2}$ ) [ $m \times s^{-2}$ ];
- $\alpha(t)$ : gravitational force angle relative to the vertical  $y$  axis, normally represented as a percentage from the elevation/length ratio for a given section. It'll be variable over time;

#### 2.4.7 Final Train Acceleration Equation

Consider the replacement of Equation 12, Equation 18, Equation 25 and Equation 28 in Equation 11. Consider also that  $f_{drag} = f_{rr}$ , as the rolling resistance force ( $F_{RR}$ ) incorporates wheel dynamics considerations that were ignored in the negative (braking) acceleration term. We'll then have Equation 29 and Equation 30,

$$\ddot{x}(t) = \frac{0.8 \times w_{loco}(t)}{\dot{x}_{hp}(t)} - K_{drag} \times \ddot{x}_{davis}(t) - \ddot{G} \times \alpha(t) - K_{comp} \times \sum_{j=1}^{n_{ax}} \frac{\tau_{Bj}(t) \times R_{wheel,j}}{J_{wheel,j}} \quad (29)$$

$$\ddot{x}_{davis}(t) = 6.5 \times 10^{-3} + \frac{3.2 \times 10^{-6}}{M_{rs}} + 1.5\dot{x}(t) + \frac{9.6 \times 10^{-5}}{M_{rs}} \quad (30)$$

where:

- $\ddot{x}(t)$ : rolling stock acceleration for a given time  $t$  [ $m \times s^{-1}$ ];
- $w_{loco}(t)$ : locomotive power output [ $W$ ];
- $\dot{x}_{hp}(t)$ : train speed or minimum speed for the maximum horsepower, whichever is larger [ $m \times s^{-1}$ ];
- $K_{drag}$ : drag compensation constant for coupled rolling stock (will be 1.0 if the rolling stock is the first unit, 0.3 otherwise);
- $\ddot{x}_{davis}(t)$ : Davis equation rolling resistance force (separated for styling) [ $m \times s^{-1}$ ];
- $\ddot{G}$ : gravitational acceleration (considered to be a constant of  $9.81m \times s^{-2}$ ) [ $m \times s^{-2}$ ];
- $\alpha(t)$ : gravitational force angle relative to the vertical  $y$  axis, normally represented as a percentage from the elevation/length ratio for a given section. It'll be variable over time;
- $K_{comp}$ : compensation constant for the energy loss due to the slip rate in the contact region (0.95 will be used, representing a 5% loss), following the results obtained from Popov et al. (2002);

- $n_{ax}$ : total amount of axles in the rolling stock;
- $\tau_{Bj}(t)$ : torque applied to the wheelset at position  $j$  trough braking for a given time  $t$  in seconds [ $kg \times m^2 \times s^{-2}$ ];
- $R_{wheel,j}$ : radius of the wheelset at position  $j$  from the center of the axle to the rail contact face - not considering the wheel flange [ $m$ ];
- $J_{wheel,j}$ : rotational inertia  $J$  of the wheelset at position  $j$  [ $kg \times m^{-2}$ ];
- $M_{rs}$ : total mass of the rolling stock [ $kg$ ];
- $\dot{x}(t)$ : rolling stock velocity [ $m \times s^{-1}$ ];

## 2.5 COMPUTATIONAL INTELLIGENCE

Computational intelligence comprehends a set of practical adaptation and self-organization concepts, paradigms, algorithms and implementations that enable or facilitate appropriate actions (intelligent behavior) in complex and changing environments. It is commonly divided into artificial neural networks, fuzzy systems, evolutionary computation and hybrid systems. For this project, two metaheuristics were considered as the optimization method for the proposed controllers, being one an evolution-based algorithm and the other a swarm-based one.

Metaheuristics are methods used to generically solve optimization problems. They use combinations of random choices and historical knowledge of the previous results to guide and conduct their searches through the research space in neighborhoods within the research space. This is useful to avoid premature stops in great locations (greedy behavior), being often applied to find multiple optimal solutions, although its parameters must be tuned to achieve this purpose.

Two metaheuristics algorithms are applied on this work: the Genetic Algorithm and the Particle Swarm Optimization, being each of them described in the following subsections. Both of them assume the accumulated simulation cost as the inverse fitness function, thus referring to *cost* instead of the usual *fitness* in the controllers' implementation. This consideration was taken to simplify the analogy with the real-world scenario (a train accumulates expenses as the time passes - either stopped or moving).

### 2.5.1 Genetic Algorithm

Over time, populations evolve in nature to ensure their survival. This evolution takes place according to the principles of natural selection, postulated by Darwin (1859). The genetic evolution occurs in chromosomes, which are responsible for coding living beings. The chromosomes that coded successful structures reproduce at a higher frequency than the chromosomes that coded unsuccessful structures. This evolution occurs at every new offspring generation process. During this process, however, mutations can cause changes in the chromosomes of the new generation - caused by the combination of the parents' chromosomes - leading to characteristics in the offspring that were not present in the ancestors (DAVIS, L., 1989).

These genetic information are contained in the genomes of individuals and do not have a biological memory, which means that they do not know the genetic chains of the original individuals that were used for the generation of this new offspring.

Genetic Algorithms were inspired by this process of natural evolution and are used to solve search and optimization problems found in the real world. They seek the best solution for optimization problems, using an iterative searching process. The search starts from an initial population and obtains a new one - combining the best representatives of this population - replacing the original one (partially or totally).

These algorithms began to be studied by John Holland in the early 1970s, when the research was started on algorithms that manipulated strings of 0 and 1, which he called chromosomes. These algorithms performed the simulated evolution of these chromosome populations, efficiently solving the problem of finding good chromosomes by manipulating the material contained in them.

The algorithm is usually divided into three operators:

- **Selection:** used to determine the individuals that are going to be persisted and/or used as parents for the next generation;
- **Crossover:** used to combine the genes of the selected parents to generate new individuals;
- **Mutation:** used to add some randomness to the individuals and increase the number of different solutions, avoiding local convergences.

Each of the operators are describe below.

### 2.5.1.1 Selection Operator

The selection operator in an algorithm is used to pick the individuals of the population that will participate in the new offspring generation process, which means that it selects the parents of the individuals that will be present in the new population. This choice must be made in such a way that the members of the population more adapted to the environment have a greater chance of participating in the offspring generation - those who have a higher fitness value.

The most known way to make the selection of individuals is the Monte Carlo algorithm, also known as the roulette wheel selection algorithm, where each individual of the population will occupy a portion of the roulette wheel, proportional to their fitness value. By doing that, individuals who have a high aptitude will occupy a larger portion than individuals who have a lower aptitude.

This roulette wheel is spun several times, where the amount of spins varies according to the size of the population. At each turn of the roulette, an individual is selected to participate in the process of generating the new population.

### 2.5.1.2 Crossover

The crossover operator presents the function of combining the chromosomes of the parents to generate the chromosomes of the children. There are different types of crossover operators, some developed to be more generic and others more suitable to a type of chromosome coding. The two more common crossover techniques are the one-point crossover and the uniform crossover, being them:

- **One-point Crossover:** consists of dividing the selected chromosomes at a randomly selected point in their chain. After that, a part of each of the selected parents' chromosomes is combined to create the new children' one. In this crossing method, it's common for the parents to generate two new children, but any number of children can be created, provided that the number of alleles allows the desired number of different combinations;
- **Uniform Crossover:** consists in generating each gene of the descendant by copying the corresponding gene from one of the parents, who is chosen according to a randomly generated mask. For each of the mask elements, a

binary value indicates if the gene is going to be copied from the mother or from the father. At the end of the process, the new descendant will be generated. An example of this process is seen on ;

**Figure 22 – Uniform crossover operator example on a binary AG topology.**

	OFFSPRING A								OFFSPRING B							
<b>FATHER</b>	1	1	0	1	0	0	1	1	1	1	0	1	0	0	1	1
<b>MOTHER</b>	0	0	1	1	0	1	1	0	0	0	1	1	0	1	1	0
<b>MASK</b>	0	0	0	1	1	1	0	0	1	1	0	0	1	1	0	0
<b>RESULT</b>	1	1	0	1	0	1	1	1	0	0	0	1	0	1	1	1

Source: Own authorship (2021).

### 2.5.1.3 Mutation

The mutation operator is responsible for inserting small random changes in the chromosomes of the children. As in the case of crossover operators, there are several types of mutation operators. This method generates a random number for each bit of the chromosome. This random number is compared to the probability of mutation. If it's lower than that value, the mutation happens, by switching the gene value to another valid one.

For this project, an approach equivalent to the bit mutation operation will be considered. However, instead of changing a binary value of one bit, a single action in the train's route will be changed by another one (randomly chosen among the possible options).

### 2.5.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a swarm-based computing technique developed by James Kennedy, a social psychologist, and Russell Eberhart, an electrical engineer, in 1995, inspired by the simulation of a simplified social system.



One of the original intention was to graphically simulate the behavior of a flock of birds in flight with their locally random but globally determined movement. Computationally, swarm algorithms are an abstraction of this natural process, where the search for the most suitable position is the search for the best solution to a problem, with the set of possible particle positions being the search space of the problem, and each position occupied by a particle is a possible solution to the problem.

The behavior of each particle is based on its previous experience and the experience of those other particles with which it relates. Similar to genetic algorithms, the set of particles tends to preserve those positions that determine greater aptitude and to discard the positions of lesser aptitude.

As in a Genetic Algorithm (GA), PSO is started with a population of random or pre-established solutions. However, it is different from GA as in each potential solution a random velocity is also designated, and potential solutions, called particles, fly through the search space of the problem.

Each particle keeps track of its coordinates in the search space, which are associated with the best solution (fitness) that it has achieved. The value of fitness is also stored. This value is called  $p_{best}$  (from personal best).

Another value that is tracked by the PSO algorithm is the best value of all values (or of a neighboring group, depending on the topology) obtained by any particle in the population. This position (solution) is called  $g_{best}$  (from global best). The principle of this metaheuristic consists of, in each iteration and change of speed, the particles fly towards their positions  $p_{best}$  and  $g_{best}$ .

Unlike other Evolutionary Computing techniques with encouraged evolution (Genetic Algorithms), PSO does not use genetic operators. Instead, each particle (individually) adjusts its flight according to its own flight experience and that of its companions. From this, it makes use of a group (population) of particles that are inserted in a solution space to search for an optimal location, based on some procedures. The particles communicate with each other informing the values of the objective function in their respective local positions. Each particle optimization movement is based on three parameters: Sociability factor, individuality factor and maximum speed. The algorithm combines these parameters with a randomly generated number to determine the next particle location. This actually means that:

- the sociability factor determines the attraction of the particles to the best

position discovered by any element of the cluster (swarm);

- the individuality factor determines the attraction of the particle with its best position ever discovered;
- the maximum speed delimits the movement, since it is directional and determined.

In addition to these three factors, there are also the number of particles in a cluster, the number of clusters in the solution space and the termination criteria. Each particle is treated as a point in a  $D$ -dimensional space. The  $i$ -th particle is represented as  $\mathbf{x}_i = (x_{i,1}, x_{i,2}, \dots, x_{i,D})$ , where  $D$  is the number of dimensions in that space.

The best previous position in the  $d$ -th dimension of the  $i$ -th particle is registered and represented as  $p_{best,i} = (p_{best,i,1}, p_{best,i,2}, \dots, p_{best,i,D})$ . The index of the best particle among all particles in the population (or a group of them) is represented by the variable  $g_{best,i}$ , which may be a one-element array if the topology assumes only one global best, or it can store region-based bests in a neighboring topology approach.

The rate of change of position (velocity) for particle  $i$  is represented as  $v_{i,d} = (v_{i,1}, v_{i,2}, \dots, v_{i,D})$ . The particles are manipulated according to Equation 31 and Equation 32,

$$v_{i,d} = \omega \times v_{id} + K_1 \times rand() \times (p_{best,id} - x_{id}) + K_2 \times rand() \times (g_{best,i} - x_{i,d}) \quad (31)$$

$$x_{i,d} = x_{i,d} + v_{i,d} \quad (32)$$

where:

- $K_1$  and  $K_2$ : two positive constants corresponding to the cognitive and social components;
- $rand()$ : a pseudo random number generator (from 0 to 1);
- $\omega$ : inertia factor;

Equation 31 is used to calculate the new speed of the particle according to its previous speed and the distances between its current position, its best position and the best position in the group. Then the particle flies to a new position according to Equation 32.

The performance of each particle is measured according to a pre-defined fitness function that is related to the problem to be solved. The weight of inertia  $W$  is used to

control the impact of the previous speed on the current speed, thus influencing the global and local exploration skills of the particles. A higher weight of inertia facilitates global exploration (looking for new areas), while a lower weight of inertia tends to facilitate local exploration to refine the current search area. The satisfactory selection of the weight of inertia  $W$  can provide a balance between global and local exploration skills, and thus may require fewer repetitions, on average, to find the optimal value.

Each particle keeps track of its coordinates, in the space of the problem that is associated with the best solution, in fact, how far the particle has shifted. This value is called  $p_{best}$ . Another value that is determined by the particles is the best value obtained among all the particles (or the neighboring particles, depending on the topology). This location is called  $g_{best}$ .

When a particle takes the entire population, that is, its neighbors, the best value is called  $g_{best}$ . The number of clusters in a space is clearly known as a factor in the probability of finding the optimum, because the greater the number of particles in a given space the higher the probability of finding the optimum. However, conversely, a larger number of particles will result in the increase of individual points that will be tested, thus increasing the computation time.

### 2.5.2.1 Discrete and Continuous PSO

All the characteristics presented so far refer to the Classic PSO, however another model can be found in the literature: the Discrete PSO. In discrete PSO the equations remain unchanged, although the algorithm has to be adapted to work with discrete intervals. The points to be modified are the operators used in the search space and the solutions found, since it will no longer be in a continuous search space.

Regarding the position of the particle, in the discrete PSO it considers the edges (knots) to be each dimension of the particle, representing them in a position vector and the change of position consists of an exchange of positions in the position vector (swap) of the particle.

In the PSO applied to continuous problems, the particles move in space through a vectorial sum, that is, an algebraic sum of the current space is made with the speed to obtain a new position. Analyzing the speed in the Discrete PSO, it can be concluded that it consists of the exchanges of information carried out on the vector positions of the

particles, the "swaps", being its sum, a concatenation of lists of "swaps".

The speed of a particle consists of a list of "swaps" that will be applied at the position of the particle to obtain a new position. In Continuous PSO the speed of a particle is a number (scalar) that will be added to its position to obtain a new position in the search space.

### 3 MATERIALS AND METHODS

Before discussing about methods evolving the two main components of this work, this section first explains the principles and guidelines adopted for the software development. The methods are then divided into two groups: the simulation environment and the optimization controller. This division is defined at the fringe between programming to reproduce the real-world problem as better as possible and programming to create a logic as intelligent as possible to achieve the optimized results. It is based on the concepts and problems proposed on the previous chapter.

It also discuss about the necessary simplifications to solve the problem, the modelling applied to the real-word scenario, the software implementation options taken during the process and also the workarounds made to solve some specific blocking points found. The source code is also available in an open source repository so anyone can reproduce the results and contribute to later development of this research.

#### 3.1 SOFTWARE DESIGN

This section presents the principles considered during the development of the project, as well as a description of the considered design strategy for the application implementation, containing a list of the classes and a brief explanation of their functionality.

##### 3.1.1 Programming Language

Programming languages have been around for decades, evolving from the earlier low-level languages like Assembly) to the modern Very High-Level Programming Language (VHLL) such as Python and Ruby. The choose for a VHLL is made taking in consideration the ease of having a solid starting point with several built-in libraries already written and tested on lower-level languages.

According to the list of most used programming languages worldwide for December 2020, Python stands in the first place with more than 30% of the market share, as seen in Table 3.

The Python language was created by Guido Van Rossum in 1991 and is currently used in large corporations such as Google and Nasa. Being the most used programming

**Table 3 – Popularity of Programming Languages for December 2020.**

Rank	Language	Share	Trend
1 <sup>st</sup>	Python	30.34 %	+1.2 %
2 <sup>nd</sup>	Java	17.23 %	-1.7 %
3 <sup>rd</sup>	JavaScript	8.65 %	+0.6 %
4 <sup>th</sup>	C#	6.44 %	-0.8 %
5 <sup>th</sup>	C/C++	6.11 %	+0.1 %
6 <sup>th</sup>	PHP	5.88 %	-0.3 %
7 <sup>th</sup>	R	3.84 %	+0.1 %
8 <sup>th</sup>	Objective-C	3.75 %	+1.2 %
9 <sup>th</sup>	Swift	2.17 %	-0.3 %
10 <sup>th</sup>	Matlab	1.77 %	-0.0 %

**Source: GitHub (2020).**

language nowadays - and probably the reason behind the first position - Python has several benefits, as listed below.

#### 3.1.1.1 Readable and Maintainable Code

Python - unlike the other listed programming languages - has an emphasis on code readability by using human-like English statements on most of its operators instead of punctuation and symbols. This simplifies the cognitive process behind the code understanding for other programmers and also for the original developer himself a while later. This allows development teams and collaborative projects to increase the maintenance and on-boarding speed.

#### 3.1.1.2 Multiple Programming Paradigms

There are different programming paradigms being used, including object-oriented and structured programming. Python fully supports both of them, as well as various concepts in functional and aspect-oriented programming. Python also supports dynamic typing and has an integrated memory management, making it easier to develop large and complex applications.

### 3.1.1.3 Compatibility with Platforms and Systems

Python supports multiple platforms as systems - such as Windows, Linux, macOS, AIX, IBMi, iOS, OS/390, Solaris, and more - running in different architectures such as ARM, x86 and x86-64. This makes python a system-agnostic language, allowing developers - and consumers - from different devices to have the same experience while developing and using the application.

Furthermore, Python is an interpreted programming language, allowing you to run the same code on different platforms without recompilation.

### 3.1.1.4 Robust Library Repository

Package Installer for Python (PIP) is the official repository for ready-to-use libraries that makes Python shine against several other programming languages.

The repository contains a wide scope of modules that adds a great level of abstraction on different areas, allowing a fast start for multiple projects, without summing up to the code thus making it easier to focus on the business logic.

For example, if you need a web application in Python, you have a variety of ready-to-use libraries that will handle administrations, perform data serialization, validation and persistence, handle requests and many other features. Also, the built-in stock libraries are well-documented in the Python Standard Library documentation.

### 3.1.1.5 Open Source Frameworks

Python is open-source, which already reduces costs. Despite that, it has several well-known open-source frameworks that allows developers to jump start the deployment of an application, from concept designs like the MVPs (Most Viable Product) to production-ready implementations. Some of them are: Django, Flask, PyQt, Kivy, PyGTK, among several others.

### 3.1.1.6 Multipurpose Development

Python is a general purpose programming language, which means that it can be used for developing both web, mobile and desktop applications. It's also widely used for numeric and scientific applications with libraries that performs data analysis and visualization with a great support for big data solutions. It's also commonly used for Computational Intelligence (CI) - as in this project - and for natural language processing.

### 3.1.1.7 Test Driven Development

Python provides a built-in suite for testing which allows developers to write the acceptance criteria (and use case tests) before starting the development of the application itself, which is the base for the Test Driven Development (TDD) strategy.

However, Python also its own downsides as well, like the execution speed (compared to other modern VHLL programming languages like Java and C++). Still, it was the chosen language for the development of this project, due to the advantages already pointed before.

## 3.1.2 Guidelines

As a guideline for the development of this project the SOLID principles where used, aiming to have an understandable and maintainable code. These principles also help the development of a cleaner code, the separation of responsibilities and a coupling reduction between different sections of the code.

SOLID stands for:

- **S** - Single Responsibility Principle (SRP): this principle defines that a class must have one - and only one - reason to change. It actually means that a class must it scope limited to a single subject and have only one responsibility in the software business logic (it must have a single task or action to perform). This facilitates the code maintenance and an eventual refactoring, making it easy to gradually apply changes and providing a greater level of confidence for the developer. Not following this principle may lead to a high coupling among different portions of the code, a harder understanding of the business logic



(and a potential loss of cohesion) and difficulties writing automated tests;

- **O** - Open-Closed Principle (OCP): this principle states that objects (or entities) must be open for extension, but closed for modification. It means that when new behaviors and features need to be added to the software, the original source code must be extended instead of changed. It can be done using interfaces;
- **L** - Liskov Substitution Principle (LSP): this principle defines that a derived class must be replaceable by its base class. It was introduced by Liskov (1987) with the formal definition: "if S is a sub-type of T, then objects of type T in a program can be replaced by objects of type S without having to change the properties of that program".

This allows a better usage of polymorphism by considering the base classes as a contract which will then be extended by its children, reducing the risk of unexpected results in the system;

- **I** - Interface Segregation Principle (ISP): this principle states that a class should not be forced to implement interfaces and methods that they will not use, meaning that it is better to create more specific interfaces instead of having a single generic one;
- **D** - Dependency Inversion Principle (DIP): This principle defines that the development should depend on abstractions, not implementations. This means that a high-level module should not depend on a low-level one. Instead, both of them must depend on an abstraction. Also, the abstraction should not depend on details, but instead the details must depend on the abstraction (MARTIN, 2020).

It's important to note that Dependency Inversion is not the same as Dependency Injection, as the first one is a principle (concept) while the other is a design pattern;

### 3.1.3 Software Design

The design strategy for the software if this application was chosen to be the Object-Oriented Programming (OOP), splitting the application into different objects:

- **ActionHistory**: this class stores the set of actions taken by each of the trains,

in order to provide a tracking of the decisions taken and to be able to reproduce the results in other tools or even in the real life;

- **BaseController**: the base class to create a controller. Implements the common functions used by them, including updating the global best solution, creation of new blank solutions, checking the stop conditions, managing the execution of the simulations and perform a status report. It's extended by the controllers classes *GeneticAlgorithmController*, *ParticleSwarmOptimizationController*, and *RandomActionController*, each of them implementing its own business logic for the operations done on each epoch;
- **BaseOptions**: a base mutable class used to store the starting options for the simulations, expanding the constructor parameters into class properties;
- **BaseScenario**: the base class to create a comparison for different controllers. It's responsible for creating the same environment for them to run, as well as the creation of the output comparison report and graphs. It's extended by each of the comparison scenarios, where the route, the trains and the run-time parameters are defined;
- **Cache**: a custom cache handling class to store the computed section relations from the route to be used by the simulations. Implements a layer of ephemeral data persistence using a temporary folder in the disk, that is clean before the start of a new scenario to ensure that there's no crossed influence;
- **Dispatcher**: the main class responsible for ensuring that the basic railroad operation rules are followed, like checking if a section is occupied before moving or adding a train, determining if a train is ready to be added to the simulation, determining if a given route (a list of Section objects) has all the sections available (not occupied), and providing the sections information for the trains: the next and previous section in the route, the closest turnout section ahead and before, the list of possible actions (taking in consideration the occupancy of the sections surrounding the train). It also computes the final cost of each train (as it has the global vision of the route and the running trains), applying penalties when the rules are not obeyed;
- **RollingStock**: this class aims to aggregate the characteristics of a generic rolling stock. The goal is to aggregate both identification/specifications used in the presentation layer and dynamic variables/calculations used in the data

access layer. Its public properties are defined below;

- **Route:** this class aims to represent a set of Block Section (BS), grouped by connections that are later interpreted by the SectionMapper class. It's extended by the route implementations for each of the scenarios to set the BS list, but this may also be defined in the base class constructor;
- **Section:** this class aims to represent the real-world equivalent Block Section (BS), storing its data (like the starting kilometer, the length, the maximum velocity, the connections and the restrictions);
- **SectionMapper:** this class is used to translate the initial input data into *Section* objects, as well as check the integrity of the route (if every endpoint exists and is interconnected through the same amount of routes for both directions). It's also responsible for the route mapping, like retrieving the sections ahead and before a given one and calculating the possible routes between two sections. These information are cached and reused by the controllers, as they're static in the comparison scope of this project;
- **Simulation:** this class aims to aggregate the characteristics of the simulation environment. Its public properties are presented on Frame 2;

**Frame 2 – Properties implemented on Simulation class.**

Name	Type	Default Value	Unit	Description
state	string	"running"	-	The state of the simulation. Can be "running", "paused", "ended", "error"
seconds	integer	0	[s]	Seconds from simulation start. Should have at least 32 bits.
stepSize	float	0.01	[s]	Calculation step size (duration) in seconds.

**Source: Own authorship (2021).**

- **ThreadingExecutor:** a wrapper for the Python *ThreadPoolExecutor* interface, allowing expensive methods to be executed in parallel using multi-threading. Its used for running different simulations in parallel and also to simultaneously render the frames for the output synoptic panel video. Its properties are presented on Frame 3;

**Frame 3 – Properties implemented on *RollingStock* class.**

<b>Name</b>	<b>Type</b>	<b>Default Value</b>	<b>Unit</b>	<b>Description</b>
type	string	"unknown"	-	The type of the rolling stock. Can be "unknown", "locomotive", "freight-car", "passenger-car", "maintenance-of-way", "other"
number	integer	999999	-	Railroad unique identification number of the rolling stock. Based on brazilian SIGO.
axles	integer	4	-	Total number of axles in the rolling stock
weight	float	100000.00	[kg]	Total gross weight of the rolling stock
horsepower	float	0.00	HP	Total horsepower of the rolling stock (in case it's self propelled)
length	float	20.00	[m]	Total length of the unit (from the external coupling faces) in meters
operational	boolean	true	-	Flag to check integrity of the rolling stock. If false, the train can't be moved by the controller.

**Source: Own authorship (2021).**

- **TimeDynamics:** responsible for the calculation of the equivalency between the simulation steps and the real-world equivalent period;
- **Train:** this class aims to aggregate the characteristics of a generic train, which consists on a set of *RollingStock* objects with extra identification/specifications used in the presentation layer and dynamic variables/calculations used in the data access layer;
- **TrainEquation:** this class performs the calculation of the dynamics of the train, including its instantaneous velocity, acceleration and the base cost of the train for further processing by the *Dispatcher*;

## 3.2 OPTIMIZATION CONTROLLERS

### 3.2.1 Problem Approach

The process of train planning normally imply on planners drawing up time-tables which are adjusted on-demand as the travel demand forecast changes. However, those plans usually contains several conflicting points where crossings and overtakes should occur in order to allow and optimize the travelling time, the fuel consumption and the company costs.

Optimizing train routes (for timetable planning) on a single-track railroad like (like the ones considered for this project) is known to be NP-hard problem, presenting a high computational cost to obtain a real-life optimal solution, thus raising the need for an appropriate heuristic approach (A. CAPRARA; TOTH, 2002). Evolutionary algorithms were already used by others authors to solve different problems of scheduling, routing and timetabling, presenting good results, such as Al-Hinai and ElMekkawy (2011), Nasiri and Kianfar (2011), C. J. Hinde (0210) and Werner (2011).

For this project, the analyzed variable will be the train cost, computed trough the Equation 33. The cost was considered instead of the fitness because of the closer real-world equivalency and ease of understanding,

$$\begin{aligned}
 t_{COST} = & K_{COST\_NORM} \times \\
 & (K_{METER\_COST} \times t_{ODOMETER} + \\
 & K_{TRAVEL\_COST} \times t_{TRAVEL\_TIME} + \\
 & K_{STOP\_COST} \times t_{STOP\_TIME} + \\
 & K_{DIST\_COST} \times t_{DIST\_GOAL} + \\
 & K_{ACTION\_COST} \times t_{ACTIONS\_LENGTH})
 \end{aligned} \tag{33}$$

where:

- $t_{COST}$ : the instantaneous computed train cost;
- $K_{COST\_NORM}$ : the cost normalizer, used to reduce (or increase) the range of possible values. It was experimentally defined as  $1 \times 10^{-9}$ ;
- $t_{ODOMETER}$ : train odometer, registering the total amount of meters travelled since the beginning of the simulation [ $m$ ];

- $K_{METER\_COST}$ : cost per meter travelled. It was experimentally defined as  $0.2 [m^{-1}]$ ;
- $t_{TRAVEL\_TIME}$ : train travelling time, registering the total amount of seconds the train was moving (velocity greater than zero) since the beginning of the simulation  $[s]$ ;
- $K_{TRAVEL\_COST}$ : cost per second travelling. It was experimentally defined as  $0.4 [m^{-1}]$ ;
- $t_{STOP\_TIME}$ : train stopped time, registering the total amount of seconds the train spent stopped (velocity is zero) since the beginning of the simulation  $[s]$ ;
- $K_{STOP\_COST}$ : cost per second stopped. It was experimentally defined as  $0.3 [s^{-1}]$ ;
- $t_{DIST\_GOAL}$ : train distance to goal, computed by the *SectionMapper* class which retrieves the minimum distance between the train's current head section to its destination  $[m]$ ;
- $K_{DIST\_COST}$ : cost per meter of distance from the destination section. It was experimentally defined as  $0.5 [m^{-1}]$ ;
- $t_{ACTIONS\_LENGTH}$ : register the total amount of actions the train has taken since the beginning of the simulation, in order to encourage simpler solutions despite of complex ones;
- $K_{ACTION\_COST}$ : cost per action taken. It was experimentally defined as 100;

Despite of the computed cost, the *Dispatcher* may also apply penalties for the trains that do not obey the traffic rules, increasing its final computed cost. The implemented penalties are:

- **Simulation aborted:** if for some reason the simulation was aborted (like if a collision happens), the final simulation cost will be multiplied by 100;
- **Reached steps limit:** if the simulation was unable to complete all the trains and was aborted because it reached the steps limit, the final simulation cost will be multiplied by 10;
- **Reached cost limit:** if the simulation was unable to complete all the trains and was aborted because it reached the cost limit (when present), the final simulation cost will be multiplied by 10;
- **Step without movement:** if the simulation was stopped because it reach the maximum amount of consecutive steps without any train moving - indicating a

deadlock condition - the final simulation cost will be multiplied by 10;

From this point on, every simulation will be considered a solution, containing the same set of trains but each one having different sets of actions. The solution will be considered successful if all the trains reaches their respective destinations before the simulation hits a stopping condition (as listed above).

### 3.2.2 Train Actions

The approach considered to solve the problem described earlier is that each train will be able to perform a set of actions managed by the dispatcher, who is constantly checking the route occupancy and implements the basic safety conditions (like avoiding two trains entering the same section). Each of the possible actions are described as:

- **Reverse (REV)**: switches the train direction, toggling between "normal" (when the train is in the same direction as the mileage growth of the route) and "reversed" (when running in the opposite one, meaning that as the train moves the route milestones - relative to the train position - shrinks). The desired velocity is multiplied by  $-1$  in order to reflect the train direction. It's available for a train if it has reached the route end (no further sections) or if all the next sections are blocked. When executed, it also reverses the section occupancy list of the train, flipping the head and tail section. The rolling stock order is preserved, though;
- **Move-Straight (MST)**: implies that the train keeps going on the same track it currently is, even if it's possible to deviate (in a turnout section). It's available for a train if there's another section ahead (not the route end) and if it's not occupied by other train;
- **Move-Deviate (MDV)**: complementing the *Move-Straight* action, this one moves the train to the next deviated section (related to its current one). It's only available if the train is currently on a turnout and if there are two sections immediately ahead of the turnout (considering the train's head direction);
- **Wait-Crossing (WCR)**: performs a stop of the train at the end of its current section and stay at this condition until another train coming in the opposite direction crosses. It's considered executed when the closest train ahead travelling in the opposite direction disappears from the list of trains ahead and

appears in the list of trains behind. It's available if the next section is a turnout, if not all the trains ahead travelling in the opposite direction are also waiting for crossing and if there's another route not occupied between the closest turnouts ahead and behind the current train;

- **Wait-Overtake (WOT):** complementary to the *Wait-Overtake* action, this one also performs a stop of the train at the end of its current section, staying in this condition until a specific state change. In this case, however, it evaluates when a train behind and travelling at the same direction disappears from the list of trains behind and appears in the list of trains ahead, indicating that the overtake was made. It's available if the next section is a turnout, if there's another route not occupied between the closest turnouts ahead and behind the current train and if there's a train with higher priority behind;

### 3.2.3 Controller Design

The controller design was based on the extension of the *BaseController* class, adding the pertinent business logic specific to the strategy implementation. In this project, three controllers were considered: Genetic Algorithm Controller, Particle Swarm Optimization Controller and Random Action Controller. Each of them are described in the following sections.

#### 3.2.3.1 GeneticAlgorithmController

Implemented as the *GeneticAlgorithmController* class, it's responsible for the Genetic Algorithm operators for selection, crossover and mutation.

Each gene is one action that the train takes during the route, which will be an extension of the *BaseAction* class. It can't be defined as either a string-type nor a numeric-type representation, but instead it can be qualified as an object-type representation.

The mutation consists into changing the action randomly choosing over the available ones. The crossover operator works in a similar way by merging the set of actions from the parents, by splitting their set of actions in the middle and combining them to generate a new individual (simulation).

The selection operator order the individuals (simulations) by their cost and



retrieves a subset with  $n$  best solutions, which will proportionally vary to the population size according to a ratio defined in the controller options.

The controller base pseudo-code may be seen in Algorithm 1.

---

**Algorithm 1 – Pseudo-code for the Genetic Algorithm controller.**

---

```

1 variables setup
2 map the positions with values from 0 to 1 corresponding to each of the actions
3 while not reached a stopping condition do
4   if it's the first epoch then
5     create a random set of solutions
6     execute the initial set of solutions
7     skip to next epoch
8   end if
9   for each of the solutions do
10    apply the selection operator
11    apply the crossover operator
12    apply the mutation operator
13  end for
14  execute the unfinished simulations;
15  update the global best solution;
16 end while
17 execute parent BaseController class epoch actions

```

---

**Source: Own authorship (2021).**

The parameters considered for this controller are listed below. They were arbitrary chosen as the development was made and the tests were done. A further optimization of those parameters could be done, however this goes beyond the scope of this project and will be considered as a future improvement.

- **Inertial Parameter:** 0.1;
- **Personal Acceleration Coefficient:** 0.5;
- **Global Acceleration Coefficient:** 0.3;

### 3.2.3.2 ParticleSwarmOptimizationController

Implemented as the *ParticleSwarmOptimizationController* class, it's responsible for the Particle Swarm Optimization Controller operators for selection, crossover and mutation.

Each of its dimensions is defined as one action that the train takes during the route, which will be an extension of the *BaseAction* class, using the same object-type representation as in *GeneticAlgorithmController* class.

It's responsible for the calculation of the velocity of the particles, as well as to

get handle their personal and the global best. It also translates the particles into trains, considering the set actions as the particle position dimensions. The actions are codified into number to allow the mathematical calculation of the velocity. Its base pseudo-code may be seen in Algorithm 2.

---

**Algorithm 2 – Pseudo-code for the Particle Swarm Optimization controller.**

---

```

1 variables setup
2 map the positions with values from 0 to 1 corresponding to each of the actions
3 while not reached a stopping condition do
4   if it's the first epoch then
5     create a random set of solutions
6     execute the initial set of solutions
7     translate the solutions into particles
8     update particles bests
9     skip to next epoch
10  end if
11  delete the current set of solutions
12  for each of the particles do
13    update particle velocities and positions
14    update particle bests
15    parse the new particle position back to train actions;
16  end for
17  execute the new simulations;
18  update the global best solution;
19 end while
20 execute parent BaseController class epoch actions

```

---

**Source: Own authorship (2021).**

The parameters considered for this controller are listed below. They were also arbitrary chosen in the development process, as in the Genetic Algorithm one.

- **Inertial Parameter:** 0.1;
- **Personal Acceleration Coefficient:** 0.5;
- **Global Acceleration Coefficient:** 0.3;

### 3.2.3.3 RandomActionController

Implemented as the *GeneticAlgorithmController* class, it's responsible for the Random Action Controller operators. Its basic consists in a greedy algorithm that regenerates the whole population (of simulations) at the end of every epoch, storing only the best solution in the memory. Its goal is to fast, but not necessarily accurate. It's executed considering the pseudo-code presented in Algorithm 3.

---

**Algorithm 3 – Pseudo-code for the Random Action controller.**


---

```

1 variables setup
2 while not reached a stopping condition do
3   start a new epoch
4   delete all the previous simulations
5   while number of solutions is lower than the population maximum size do
6     Create a new random solution
7   end while
8   run the solutions
9   update the global best
10  update the maximum allowed simulation cost to the value of the current global best
11 end while
12 execute parent BaseController class epoch actions

```

---

**Source: Own authorship (2021).**

### 3.3 SCENARIO IMPLEMENTATIONS

The scenario implementation depends basically on three parameters:

- **Route:** a route will be given to run the scenario. It'll be an object of type *Route* and will define the set of sections (objects of type *Section*) that will be used by the trains (objects of type *Train*) to travel and reach their destinations;
- **Trains:** a set of dictionaries containing the metadata (prefix, length, start section, end section, direction) describing each of the *Train* objects that are going to be spawned on each of the scenario simulations;
- **Controllers:** a set of classes constructor's referencing the available set of controllers to be used in the scenario. Each of them will be tested against the same common configuration (simulation step duration, simulation maximum steps, simulation maximum cost, simulations per controller step, max simulations per controller). The results will then be compared.

The scenario workflow for `__init__` and `run` methods are presented below.

#### 3.3.1 Scenario Workflow

The scenario setup workflow (in `__init__` method) consists in the following ordered steps:

1. Compute an Universally Unique Identifier (UUID);
2. Setup and configure the logger;
3. Invalidate (clear) the cache;

4. Load the route into memory;
5. Check route integrity, asserting that the number of routes in both directions are the same for all the route start/end sections (endpoints);
6. Load the trains into memory;
7. Load the controllers classes constructors list into memory (by default, all the three available: *RandomActionController*, *ParticleSwarmOptimizationController* and *GeneticAlgorithmController*);
8. Reset stop reason, runtime and the instantiated controllers;

The scenario main workflow (in *run* method) consists in the following ordered steps:

1. Reset scenario execution timer, log initialization messages and check cache health;
2. For each of the controllers (by default, all of the available ones):
  - a) Execute method *run()* of the controller;
3. If set to export results (off by default), call inner method to export the graphs, the text results and the synoptic video;
4. Stop scenario execution timer;

Note that the scenario total execution period will also be affected by the time exporting the results. This is intentional as this indicator aims to track the whole duration of the scenario-based experiment, not allowing a controller-based comparison. For this purpose, there are internal controller indicators.

As a future improvement, an integration algorithm to convert Google Earth files (or from other GPS-based drawing tool) into ready-to-use simulation routes could be used to translate real-word data into new scenarios.

Two scenarios will be considered for comparison. They're described in the following sections.

### 3.3.2 Scenario One

The first scenario is used to validate the basic routing capability of the algorithm, having just one siding and two trains moving against each other, so the best global solution is known.

### 3.3.2.1 Real-world equivalency

The section used to represent this scenario was arbitrary chosen as the task goal is to simply perform a crossing of two trains. The railroad that crosses Palmital, in São Paulo State, was picked. The city was settled only five year after the *Estrada de Ferro Sorocabana* started its operations in the fresh new station built in 1914 to attend what was still a village with the same name by the time. A new station (the main one) was built in 1926 and it's still a reference location, being recently repaired. The city development was so connected to the railroad that the residents divide the city into two main zones: north railroad and south railroad - as the city is totally divided by it, referencing places located on either the north or the south side.

### 3.3.2.2 Route

The route consists in the following sections:

- ZIM\_M: Represents the main line inside Ibirarema yard (ZIM), from the inbound turnout (ZIM#1) to the outbound one (ZIM#2), coming from Ourinhos;
- ZIM\_D: Represents the deviated (secondary) line inside Ibirarema-SP yard (ZIM), from the inbound turnout (ZPV#1) to the outbound one (ZPV#2), also coming from Ourinhos;
- ZPV#2: Corresponding to the outbound turnout of Ibirarema yard (ZIM), interconnects ZIM\_M or ZIM\_D (in) to ZIM\_ZPV (out);
- ZIM\_ZPV: Corresponding to the section between the outbound turnout of Ibirarema yard (ZIM#2) up to the inbound turnout of Palmital yard (ZPV), coming from Ourinhos (ZOU);
- ZPV#1: Corresponding to the inbound turnout of Palmital yard (ZPV), interconnects ZIM\_ZPV (in) to ZPV\_M or ZPV\_D (out);
- ZPV\_M: Represents the main line inside Palmital yard (ZPV), from the inbound turnout (ZPV#1) to the outbound one (ZPV#2);
- ZPV\_D: Represents the deviated (secondary) line inside Palmital yard (ZPV), from the inbound turnout (ZPV#1) to the outbound one (ZPV#2);
- ZPV#2: Corresponding to the outbound turnout of Palmital yard (ZPV), interconnects ZPV\_M or ZPV\_P (in) to ZPV\_ZSY (out);

- ZPV\_ZSY: Corresponding to the section between the outbound turnout of Palmital yard (ZPV) up to the main line of Sussuí (ZSY), without turnouts nor sidings;
- ZSY\_P: Corresponding to the section between the outbound turnout of Palmital-SP yard (ZPV) up to the inbound turnout of Cândido Mota-SP (ZCM) yard, towards Assis (ZAS);
- ZSY\_ZCM: Corresponding to the section between the main line of Sussuí-SP (ZSY) up to the inbound turnout of Cândido Mota-SP yard (ZCM#1);
- ZCM#1: Corresponding to the inbound turnout of Palmital yard (ZPV), interconnects ZIM\_ZPM (in) to ZPV\_M or ZPV\_D (out);
- ZCM\_M: Represents the main line inside Cândido Mota yard (ZCM), from the inbound turnout (ZCM#1) to the outbound one (ZCM#2). The route will end up here, although the real railroad once went up to Presidente Epitácio, passing through major cities like Assis and Presidente Prudente, all of them in Sao Paulo state;
- ZCM\_D: Represents the deviated (secondary) line inside Cândido Mota-SP yard (ZCM), from the inbound turnout (ZCM#1) to the outbound one (ZCM#2);

### 3.3.2.3 Rolling stock

The rolling stock for this scenario consists into two trains heading opposite directions, that should safely cross each other:

- Train O41: originated from Ourinhos-SP heading Assis-SP, at the start of the simulation will be at the beginning of the ZIM\_P section (in ZIM yard). It will be 450 meters long and will weight 1,700,000 kilograms (representing a loaded train). It will have a priority of 50;
- Train O14: originated from Assis-SP heading Ourinhos-SP, at the start of the simulation will be at the beginning of the ZCM\_P section (in ZCM yard). It will be the same length as O41 (450 meters long) but will weight 600,000 kilograms instead (representing an empty train). It will have, as equal to O41, a priority of 50;

### 3.3.2.4 Goals and events

The goal of this simulation is that Train O41 reaches the middle of ZCM\_D section, while Train O14 reaches the middle of ZIM\_D one. They should safely perform a crossing in Palmital (ZPV) yard, with one of the trains waiting the other to cross either on the main line (ZPV\_M) or on the deviated one (ZPV\_D). Both trains fits both the main and the deviated line.

There are no speed restrictions and the speed limit is set to  $60.00 \frac{km}{h}$  ( $16.67 \frac{m}{s}$ ).

### 3.3.2.5 Simulation Parameters

The parameters for the individual solutions (simulations) were manually defined considering the maximum expected real time taken to solve the scenario (meaning that all the trains reaches their destinations). This is an empiric limit that must be set and was approximated to three times the expected real-world duration (based on previously known railroad data). This value is used to define both the Maximum Steps and the Maximum Cost, although a manual tuning of these might be required to improve the overall execution time.

The Step Duration was also manually defined as long as possible considering the limitation of discrepancy injection due to the section position calculation: if the time the train takes to cover the distance between its relative position in the section and its ending is bigger then the step duration, this time difference is absorbed as a directly proportional error in the final cost.

The parameters for each of the individual solutions (simulations) created by the controllers are:

- **Step Duration:** fixed in 10 seconds, meaning that each simulation time step will be equivalent to 10 seconds in the real life; this value may be increased to reduce the time the script takes to run;
- **Maximum Steps:** fixed in 1,000 steps, meaning that the simulation will be aborted (and considered to have failed) if have not completed all the trains (meaning that each of them have reached their destinations) in 1,000 time steps (10,000 seconds or nearly 3 hours in real life);
- **Maximum Cost:** fixed in 1,000, meaning that the simulation will be aborted

(and considered to have failed) if the sum of costs for each of the trains in the simulation reaches 1,000;

Considering the parameters definition written previously, the following parameters were considered for each of the controllers, regarding the control of its set of solutions:

- **Solutions Size:** the size of the population (set of solutions) that each of the controllers will run in each of the epochs, fixed in 3 individual. This actually means that each of the controllers will have 3 simulations on its set of solutions by the end of each epoch;
- **Maximum Iterations:** fixed in 30, meaning that the controller execution will be considered completed when 30 unique simulations are run (no matter the result), so each controller will execute at least 10 epochs (as the population size is no greater than 3), but it may be more if an individual (or a group of them) is persisted;

The scenario will be executed 30 times. The Solutions Size was empirically defined based on the available computational environment performance in order not to hang the system execution. It can be adjusted to run less solutions in parallel, thus reducing the computation effort required.

### 3.3.3 Scenario Two

The second scenario is used to validate a more complex routing capability of the algorithm, having a complete route between two major junctions with 5 sidings at different positions. Four trains are added from the start and three others are added at a predetermined amount of steps. The global best solutions is not known.

#### 3.3.3.1 Real-world equivalency

The section used to represent this scenario was chosen due to its importance to the Paraná state railroad network. It starts from Desvio Ribas (LDV), a classification yard that is also a junction of the lines coming from Uvaranas (LUS) in Ponta Grossa and another coming from Guarapuava (LGP). It's the only railroad route in the state that allows the shipment of the inland production. The final point of the route considered for



this scenario is the Eng. Bley yard (LEB), a junction of the lines coming from Desvio Ribas and another one coming from Rio Negro (LRO) - which interconnects Paraná to Santa Catarina and Rio Grande do Sul states - leading to Iguaçu (LIC) in Curitiba and further to the Paranagua (LPG) docks.

The data used to create this scenario - including the route and trains - is based on the network declaration of *Rumo Malha Sul* for the year of 2020, available on ANTT (2020).

### 3.3.3.2 Route

The route consists in the following sections:

- LEB\_M: Represents the main line inside Eng. Bley yard (LEB), from the inbound turnout (LEB#1) to the outbound one (LEB#3), coming from Curitiba;
- LEB\_D: Represents the deviated (secondary) line inside Eng. Bley yard (LEB), from the inbound turnout (LEB#1) to the junction one (LEB#2), also coming from Curitiba;
- LEB#2: Corresponding to the junction turnout of Eng. Bley yard (LEB), interconnects LEB\_D or LEB\_LLA (in) to LEB#3 (out). LEB\_LLA is the section that interconnects Eng. Bley yard (LEB) to Lapa yard (LLA), towards Rio Negro (LRO) and then further into Santa Catarina and Rio Grande do Sul state. This railroad is part of the *TPS - Tronco Principal Sul* (Main South Line);
- LEB#3: Corresponding to the outbound turnout of Eng. Bley yard (LEB), interconnects LEB\_M or LEB#2 (in) to LEB\_LOZ (out);
- LEB\_LOZ: Corresponding to the section between the outbound turnout of Eng. Bley yard (LEB#3) up to the inbound turnout of Ozório de Almeida yard (LOZ#1);
- LOZ#1: Corresponding to the inbound turnout of Ozório de Almeida yard (LOZ), interconnects LEB\_LOZ (in) to LOZ\_M or LOZ\_D (out);
- LOZ\_M: Represents the main line inside Ozório de Almeida yard (LOZ), from the inbound turnout (LOZ#1) to the outbound one (LOZ#2);
- LOZ\_D: Represents the deviated (secondary) line inside Ozório de Almeida yard (LOZ), from the inbound turnout (LOZ#1) to the outbound one (LOZ#2);
- LOZ#2: Corresponding to the outbound turnout of Ozório de Almeida yard

(LOZ), interconnects LOZ\_M or LOZ\_D (in) to LOZ\_LWV (out);

- LOZ\_LWV: Corresponding to the section between the outbound turnout of Ozório de Almeida yard (LOZ#2) up to the inbound turnout of Eng. Walter S. Veloso yard (LWV);
- LWV#1: Corresponding to the inbound turnout of Eng. Walter S. Veloso yard (LWV), interconnects LOZ\_LWV (in) to LWV\_M or LWV\_D (out);
- LWV\_M: Represents the main line inside Eng. Walter S. Veloso yard (LWV), from the inbound turnout (LWV#1) to the outbound one (LWV#2);
- LWV\_D: Represents the deviated (secondary) line inside Eng. Walter S. Veloso yard (LWV), from the inbound turnout (LWV#1) to the outbound one (LWV#2);
- LWV#2: Corresponding to the outbound turnout of Eng. Walter S. Veloso yard (LWV), interconnects LWV\_M or LWV\_D (in) to LWV\_LMO (out);
- LWV\_LMO: Corresponding to the section between the outbound turnout of Eng. Walter S. Veloso yard (LWV#2) up to the inbound turnout of Machado da Costa yard (LMO#1);
- LMO#1: Corresponding to the inbound turnout of Machado da Costa yard (LMO), interconnects LWV\_LMO (in) to LMO\_M or LMO\_D (out);
- LMO\_M: Represents the main line inside Machado da Costa yard (LMO), from the inbound turnout (LMO#1) to the outbound one (LMO#2);
- LMO\_D: Represents the deviated (secondary) line inside Machado da Costa yard (LMO), from the inbound turnout (LMO#1) to the outbound one (LMO#2);
- LMO#2: Corresponding to the outbound turnout of Machado da Costa yard (LMO), interconnects LMO\_M or LMO\_D (in) to LMO\_LLQ (out);
- LMO\_LLQ: Corresponding to the section between the outbound turnout of Machado da Costa yard (LMO#2) up to the inbound turnout of Ângelo Lopes yard (LLQ#1);
- LLQ#1: Corresponding to the inbound turnout of Ângelo Lopes yard (LLQ), interconnects LMO\_LLQ (in) to LLQ\_M or LLQ\_D (out);
- LLQ\_M: Represents the main line inside Ângelo Lopes yard (LLQ), from the inbound turnout (LLQ#1) to the outbound one (LLQ#2);
- LLQ\_D: Represents the deviated (secondary) line inside Ângelo Lopes yard (LLQ), from the inbound turnout (LLQ#1) to the outbound one (LLQ#2);

- LLP#2: Corresponding to the outbound turnout of Ângelo Lopes yard (LLP), interconnects LLP\_M or LLP\_D (in) to LLP\_LLY (out);
- LLP\_LLY: Corresponding to the section between the outbound turnout of Ângelo Lopes yard (LLP#2) up to the inbound turnout of Ângelo Lopes yard (LLY#1);
- LLY#1: Corresponding to the inbound turnout of Lineu do Amaral yard (LLY), interconnects LLP\_LLY (in) to LLY\_M or LLY\_D (out);
- LLY\_M: Represents the main line inside Lineu do Amaral yard (LLY), from the inbound turnout (LLY#1) to the outbound one (LLY#2);
- LLY\_D: Represents the deviated (secondary) line inside Lineu do Amaral yard (LLY), from the inbound turnout (LLY#1) to the outbound one (LLY#2);
- LLY#2: Corresponding to the outbound turnout of Lineu do Amaral yard (LLY), interconnects LLY\_M or LLY\_D (in) to LLY\_LDV (out);
- LLY\_LDV: Corresponding to the section between the outbound turnout of Lineu do Amaral yard (LLP#2) up to the inbound turnout of Desvio Ribas yard (LDV#1);
- LDV#1: Corresponding to the inbound turnout of Desvio Ribas yard (LDV), interconnects LLY\_LDV (in) to LDV\_M or LDV\_D (out);
- LDV\_M: Represents the main line inside Desvio Ribas yard (LDV), from the inbound turnout (LDV#1) to the outbound one (LDV#2);
- LDV\_D: Represents the deviated (secondary) line inside Desvio Ribas yard (LDV), from the inbound turnout (LDV#1) to the outbound one (LDV#2);

### 3.3.3.3 Rolling stock

The rolling stock for this scenario consists into multiple trains heading both directions, with some of them being later added to the simulation, as described below.

- Train K10: originated from Ortigueira (LOR) heading Iguazu (LIC), will spawn from the start of the simulation at the beginning of the LDV\_M section. It will be considered completed (and removed from the route) when reaching the end of LEB\_M section. It will be 1,250 meters long and will weight 6,360,000 kilograms (representing a train with 71 freight cars loaded with cellulose and 2 locomotives). It will have a priority of 90;

- Train D22: originated from Desvio Ribas (LDV) heading Iguaçu (LIC), will spawn from the start of the simulation at the beginning of the LDV\_D section. It will be considered completed (and removed from the route) when reaching the end of LEB\_D section. It will be 1,394 meters long and will weight 6,750,000 kilograms (representing a train with 90 mixed freight cars and 3 locomotives). It will have a priority of 70;
- Train F24: originated from Uvaranas (LUS) heading Rio Negro (LRO), will spawn 300 steps after the start of the simulation at the beginning of the LDV\_D section. It will be considered completed (and removed from the route) when reaching the end of LEB\_D section. It will be 1,848 meters long and will weight 9,800,000 kilograms (representing a train with 120 loaded freight cars and 3 locomotives). It will have a priority of 80;
- Train B21: originated from Iguaçu (LIC) heading Uvaranas (LUS), will spawn 400 steps after the start of the simulation at the beginning of the LEB\_M section. It will be considered completed (and removed from the route) when reaching the end of LDV\_D section. It will be 1,310 meters long and will weight 1,890,000 kilograms (representing a train with 80 empty freight cars and 2 locomotives). It will have a priority of 50;
- Train L09: originated from Iguaçu (LIC) heading Uvaranas (LUS), will from the start of the simulation at the beginning of the LEB\_D section. It will be considered completed (and removed from the route) when reaching the end of LDV\_M section. It will be 1,310 meters long and will weight 1,890,000 kilograms (representing a train with 80 empty freight cars and 2 locomotives). It will have a priority of 60;
- Train M01: originated from Iguaçu (LIC) heading Uvaranas (LUS), will spawn 100 steps after the start of the simulation at the beginning of the LEB\_D section. It will be considered completed (and removed from the route) when reaching the end of LDV\_M section. It will be 650 meters long and will weight 650,000 kilograms (representing a train with 40 empty freight cars and 1 locomotive). It will have a priority of 40;
- Train W01: will represent a maintenance-of-way train with ballast, originated in Eng. Valter S. Veloso (LVW) heading to Lineu do Amaral (LLY), will spawn from the start of the simulation at the beginning of the LVW\_D section. It

will be considered completed (and removed from the route) when reaching the end of LLY\_D section. It will be 150 meters long and will weight 450,000 kilograms (representing a train with 6 freight cars and 1 locomotive). It will have a priority of 20;

#### 3.3.3.4 Goals and events

The goal of this simulation is that all the trains safely reach their respective destinations, performing crossings through the available sidings in the route.

There are no speed restrictions and the speed limit is set to  $60.00 \frac{km}{h}$  ( $16.67 \frac{m}{s}$ ).

#### 3.3.3.5 Simulation Parameters

As on Scenario One, the parameters for the individual solutions were manually defined considering the maximum expected real time taken to solve the scenario and the minimum precision required to have a lower error-prone result. The parameters values are:

- **Step Duration:** fixed in 30 seconds, meaning that each simulation time step will be equivalent to 30 seconds in the real life; this value may be increased to reduce the time the script takes to run;
- **Maximum Steps:** fixed in 2,000 steps, meaning that the simulation will be aborted (and considered to have failed) if have not completed all the trains (meaning that each of them have reached their destinations) in 2,000 time steps (60,000 seconds or nearly 16 hours in real life);
- **Maximum Cost:** fixed in 20,000 meaning that the simulation will be aborted (and considered to have failed) if the sum of costs for each of the trains in the simulation reaches 20,000;

Considering the parameters definition written previously, the following parameters were considered for each of the controllers, regarding the control of its set of solutions:

- **Solutions Size:** the size of the population (set of solutions) that each of the controllers will run in each of the epochs, fixed in 5 individual. This actually means that each of the controllers will have 5 simulations on its set of solutions

by the end of each epoch;

- **Maximum Iterations:** fixed in 50, meaning that the controller execution will be considered completed when 30 unique simulations are run (no matter the result), so each controller will execute at least 10 epochs (as the population size is no greater than 5), but it may be more if an individual (or a group of them) is persisted;

The scenario will also be executed 30 times. The Solutions Size was also empirically defined based on the available computational environment performance in order not to hang the system execution.

### 3.3.4 Data Analysis

The data obtained from the scenarios will be evaluated considering the following variables:

- **BSTC:** being the primary comparison criteria, the Best Simulation Total Cost (BSTC) is the lowest simulation accumulated cost found by the controller. It is affected by several minor variables as described in Equation 33;
- **Runtime:** used as an auxiliary comparison criteria, the runtime represents the total period used by the controller to run the pre-determined number of simulations and compute the solutions;
- **Successful Simulations:** also used as an auxiliary comparison criteria, represents the total amount of successful (not early aborted due to a stop criteria) simulations, which can indicate a higher amount of different solutions to the same proposed scenario;

A graphical dispersion representation of the BSTC evolution along the steps for each of the simulations, for every step and epoch, will be presented for all the controllers. There will be also graphical dispersion representation of the controllers' runtime, and a graphical grouped representation of the amount of successful and failed simulations.

A statistical comparison will be made between pairs of controllers' scenario results (thus comparing RND against PSO, RND against AG, and PSO against AG).

The comparison method chosen for this project is the Wilcoxon Signed-Rank Test, a non-parametric statistical hypothesis test, determining whether two samples are

paired (or related) (CORDER; FOREMAN, 2011).

The null hypothesis is the default assumption for the test, meaning that both samples have the same distribution. It is based on two values: the p-value and the significance level. The result will be either:

- **Fail to Reject H0**: if the p-value is above the significance level, it's not possible to say that H0 is false - that is - it is not possible to affirm that the data-sets are different;
- **Reject H0**: if the p-value is lower the significance level, it can be assumed that there are statistically significant evidences to reject the null hypothesis, and thus to accept that the data-sets are statistically different (from different data-sets);

For this project, a significance level of 0.05 was assumed, representing a confidence level of 95% on the hypothesis test result.

The result will be supported by the average (mean value) of the data, considering a comparison where H0 was rejected, thus allowing to qualify two different data-sets by their performance (indicated by the average).

## 4 RESULTS AND DISCUSSION

Each of the scenarios defined in chapter 3 was evaluated using all the three optimization controllers. Their respective results are presented on this chapter.

### 4.1 SCENARIO ONE

The raw data results, a summary of the performance variables, and the discussion for Scenario One are presented in this section.

The data points obtained for the controllers executed on Scenario One are presented on Table 4, in which:

- **No.:** an incremental counter to be used as further reference;
- **Comparison ID:** a Universally Unique Identifier (UUID) assigned for each of the 30 comparisons that were run;
- **Step:** the step counter inside the comparison scenario. Note that when one of the controllers' values is "-", it means that this step was not required (stop criteria reached earlier);
- **RND BSTC:** the Random Action Controller Best Simulation Total Cost, representing the lowest (best) cost that the controller has ever reached up to that step. A "-" value indicates that this step was not executed as the controller due to a stop criteria already achieved. A "NaN" value indicates that no successful simulation has ever been found by the controller, thus the best cost is infinite;
- **PSO BSTC:** the Particle Swarm Optimization Controller Best Simulation Total Cost, representing the lowest (best) cost that the controller has ever reached up to that step. As in the other controllers' values, a "-" indicates that this step was not executed due to a stop criteria already achieved. Also, a "NaN" value indicates that no successful simulation has been found by the controller and the best cost is infinite;
- **GA BSTC:** the Genetic Algorithm Controller Best Simulation Total Cost, representing the lowest (best) cost that the controller has ever reached up to that step. As in the other controllers' values, a "-" indicates that this step was not executed due to a stop criteria already achieved. Also, a "NaN" value indicates that no successful simulation has ever been found by the controller



and the best cost is infinite;

**Table 4 – Scenario 1 Results Per Step**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
1	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	1	105.56	NaN	105.56
2	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	2	105.56	NaN	105.56
3	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	3	105.56	105.56	105.56
4	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	4	105.56	105.56	105.56
5	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	5	105.56	105.56	105.56
6	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	6	105.56	105.56	105.56
7	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	7	105.56	105.56	105.56
8	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	8	105.56	105.56	105.56
9	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	9	105.56	105.56	105.56
10	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	10	105.56	105.56	105.56
11	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	11	-	-	105.56
12	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	12	-	-	105.56
13	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	13	-	-	105.56
14	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	14	-	-	105.56
15	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	15	-	-	105.56
16	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	16	-	-	105.56
17	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	17	-	-	105.56
18	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	18	-	-	105.56
19	8bd47c0c-f6b1-40e3-a0d4-83f751840f26	19	-	-	105.56
20	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	1	NaN	105.56	105.56
21	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	2	105.56	105.56	105.56
22	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	3	105.56	105.56	105.56
23	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	4	105.56	105.56	105.56
24	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	5	105.56	105.56	105.56
25	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	6	105.56	105.56	105.56
26	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	7	105.56	105.56	105.56
27	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	8	105.56	105.56	105.56
28	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	9	105.56	105.56	105.56
29	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	10	105.56	105.56	105.56
30	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	11	-	-	105.56
31	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	12	-	-	105.56
32	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	13	-	-	105.56
33	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	14	-	-	105.56
34	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	15	-	-	105.56
35	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	16	-	-	105.56
36	cf5fd5b1-f027-4eb3-b856-f1ec4e2ed17a	17	-	-	105.56
37	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	1	NaN	NaN	105.56
38	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	2	105.56	NaN	105.56
39	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	3	105.56	105.56	105.56
40	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	4	105.56	105.56	105.56
41	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	5	105.56	105.56	105.56
42	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	6	105.56	105.56	105.56
43	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	7	105.56	105.56	105.56
44	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	8	105.56	105.56	105.56
45	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	9	105.56	105.56	105.56
46	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	10	105.56	105.56	105.56
47	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	11	-	-	105.56
48	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	12	-	-	105.56

(continue)

Table 4 – Scenario 1 Results Per Step (continuation)

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
49	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	13	-	-	105.56
50	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	14	-	-	105.56
51	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	15	-	-	105.56
52	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	16	-	-	105.56
53	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	17	-	-	105.56
54	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	18	-	-	105.56
55	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	19	-	-	105.56
56	48059c63-fdd5-4011-8cf5-5b9fd4df9c69	20	-	-	105.56
57	e1165dc0-2478-41c5-9576-1c9fd486ab24	1	105.56	NaN	105.56
58	e1165dc0-2478-41c5-9576-1c9fd486ab24	2	105.56	NaN	105.56
59	e1165dc0-2478-41c5-9576-1c9fd486ab24	3	105.56	NaN	105.56
60	e1165dc0-2478-41c5-9576-1c9fd486ab24	4	105.56	105.56	105.56
61	e1165dc0-2478-41c5-9576-1c9fd486ab24	5	105.56	105.56	105.56
62	e1165dc0-2478-41c5-9576-1c9fd486ab24	6	105.56	105.56	105.56
63	e1165dc0-2478-41c5-9576-1c9fd486ab24	7	105.56	105.56	105.56
64	e1165dc0-2478-41c5-9576-1c9fd486ab24	8	105.56	105.56	105.56
65	e1165dc0-2478-41c5-9576-1c9fd486ab24	9	105.56	105.56	105.56
66	e1165dc0-2478-41c5-9576-1c9fd486ab24	10	105.56	105.56	105.56
67	e1165dc0-2478-41c5-9576-1c9fd486ab24	11	-	-	105.56
68	e1165dc0-2478-41c5-9576-1c9fd486ab24	12	-	-	105.56
69	e1165dc0-2478-41c5-9576-1c9fd486ab24	13	-	-	105.56
70	e1165dc0-2478-41c5-9576-1c9fd486ab24	14	-	-	105.56
71	e1165dc0-2478-41c5-9576-1c9fd486ab24	15	-	-	105.56
72	e1165dc0-2478-41c5-9576-1c9fd486ab24	16	-	-	105.56
73	e1165dc0-2478-41c5-9576-1c9fd486ab24	17	-	-	105.56
74	e1165dc0-2478-41c5-9576-1c9fd486ab24	18	-	-	105.56
75	e1165dc0-2478-41c5-9576-1c9fd486ab24	19	-	-	105.56
76	e1165dc0-2478-41c5-9576-1c9fd486ab24	20	-	-	105.56
77	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	1	105.56	105.56	105.56
78	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	2	105.56	105.56	105.56
79	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	3	105.56	105.56	105.56
80	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	4	105.56	105.56	105.56
81	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	5	105.56	105.56	105.56
82	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	6	105.56	105.56	105.56
83	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	7	105.56	105.56	105.56
84	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	8	105.56	105.56	105.56
85	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	9	105.56	105.56	105.56
86	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	10	105.56	105.56	105.56
87	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	11	-	-	105.56
88	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	12	-	-	105.56
89	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	13	-	-	105.56
90	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	14	-	-	105.56
91	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	15	-	-	105.56
92	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	16	-	-	105.56
93	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	17	-	-	105.56
94	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	18	-	-	105.56
95	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	19	-	-	105.56
96	2b0c6ab2-2321-4e1b-b80b-6f15ab4c9dd7	20	-	-	105.56
97	6203d209-d7fa-43fb-84e6-f04aaa23f744	1	105.56	105.56	105.56
98	6203d209-d7fa-43fb-84e6-f04aaa23f744	2	105.56	105.56	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
99	6203d209-d7fa-43fb-84e6-f04aaa23f744	3	105.56	105.56	105.56
100	6203d209-d7fa-43fb-84e6-f04aaa23f744	4	105.56	105.56	105.56
101	6203d209-d7fa-43fb-84e6-f04aaa23f744	5	105.56	105.56	105.56
102	6203d209-d7fa-43fb-84e6-f04aaa23f744	6	105.56	105.56	105.56
103	6203d209-d7fa-43fb-84e6-f04aaa23f744	7	105.56	105.56	105.56
104	6203d209-d7fa-43fb-84e6-f04aaa23f744	8	105.56	105.56	105.56
105	6203d209-d7fa-43fb-84e6-f04aaa23f744	9	105.56	105.56	105.56
106	6203d209-d7fa-43fb-84e6-f04aaa23f744	10	105.56	105.56	105.56
107	6203d209-d7fa-43fb-84e6-f04aaa23f744	11	-	-	105.56
108	6203d209-d7fa-43fb-84e6-f04aaa23f744	12	-	-	105.56
109	6203d209-d7fa-43fb-84e6-f04aaa23f744	13	-	-	105.56
110	6203d209-d7fa-43fb-84e6-f04aaa23f744	14	-	-	105.56
111	6203d209-d7fa-43fb-84e6-f04aaa23f744	15	-	-	105.56
112	6203d209-d7fa-43fb-84e6-f04aaa23f744	16	-	-	105.56
113	1c925a8e-ff16-445e-881a-859a508e8037	1	NaN	NaN	105.56
114	1c925a8e-ff16-445e-881a-859a508e8037	2	105.56	NaN	105.56
115	1c925a8e-ff16-445e-881a-859a508e8037	3	105.56	105.56	105.56
116	1c925a8e-ff16-445e-881a-859a508e8037	4	105.56	105.56	105.56
117	1c925a8e-ff16-445e-881a-859a508e8037	5	105.56	105.56	105.56
118	1c925a8e-ff16-445e-881a-859a508e8037	6	105.56	105.56	105.56
119	1c925a8e-ff16-445e-881a-859a508e8037	7	105.56	105.56	105.56
120	1c925a8e-ff16-445e-881a-859a508e8037	8	105.56	105.56	105.56
121	1c925a8e-ff16-445e-881a-859a508e8037	9	105.56	105.56	105.56
122	1c925a8e-ff16-445e-881a-859a508e8037	10	105.56	105.56	105.56
123	1c925a8e-ff16-445e-881a-859a508e8037	11	-	-	105.56
124	1c925a8e-ff16-445e-881a-859a508e8037	12	-	-	105.56
125	1c925a8e-ff16-445e-881a-859a508e8037	13	-	-	105.56
126	1c925a8e-ff16-445e-881a-859a508e8037	14	-	-	105.56
127	1c925a8e-ff16-445e-881a-859a508e8037	15	-	-	105.56
128	1c925a8e-ff16-445e-881a-859a508e8037	16	-	-	105.56
129	1c925a8e-ff16-445e-881a-859a508e8037	17	-	-	105.56
130	1c925a8e-ff16-445e-881a-859a508e8037	18	-	-	105.56
131	1c925a8e-ff16-445e-881a-859a508e8037	19	-	-	105.56
132	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	1	NaN	NaN	105.56
133	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	2	105.56	NaN	105.56
134	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	3	105.56	NaN	105.56
135	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	4	105.56	NaN	105.56
136	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	5	105.56	NaN	105.56
137	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	6	105.56	105.56	105.56
138	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	7	105.56	105.56	105.56
139	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	8	105.56	105.56	105.56
140	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	9	105.56	105.56	105.56
141	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	10	105.56	105.56	105.56
142	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	11	-	-	105.56
143	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	12	-	-	105.56
144	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	13	-	-	105.56
145	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	14	-	-	105.56
146	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	15	-	-	105.56
147	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	16	-	-	105.56
148	1e3f4582-a131-4a3c-9c3b-9bb7b4c02099	17	-	-	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
149	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	1	105.56	NaN	NaN
150	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	2	105.56	NaN	NaN
151	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	3	105.56	NaN	NaN
152	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	4	105.56	NaN	NaN
153	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	5	105.56	NaN	NaN
154	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	6	105.56	NaN	NaN
155	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	7	105.56	NaN	105.56
156	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	8	105.56	105.56	105.56
157	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	9	105.56	105.56	105.56
158	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	10	105.56	105.56	105.56
159	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	11	-	-	105.56
160	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	12	-	-	105.56
161	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	13	-	-	105.56
162	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	14	-	-	105.56
163	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	15	-	-	105.56
164	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	16	-	-	105.56
165	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	17	-	-	105.56
166	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	18	-	-	105.56
167	eebfc08a-c2d5-4d73-9966-5fc8799bee6e	19	-	-	105.56
168	f527c3ba-f803-47d0-bfb2-ea8f13149a22	1	NaN	105.56	105.56
169	f527c3ba-f803-47d0-bfb2-ea8f13149a22	2	NaN	105.56	105.56
170	f527c3ba-f803-47d0-bfb2-ea8f13149a22	3	105.56	105.56	105.56
171	f527c3ba-f803-47d0-bfb2-ea8f13149a22	4	105.56	105.56	105.56
172	f527c3ba-f803-47d0-bfb2-ea8f13149a22	5	105.56	105.56	105.56
173	f527c3ba-f803-47d0-bfb2-ea8f13149a22	6	105.56	105.56	105.56
174	f527c3ba-f803-47d0-bfb2-ea8f13149a22	7	105.56	105.56	105.56
175	f527c3ba-f803-47d0-bfb2-ea8f13149a22	8	105.56	105.56	105.56
176	f527c3ba-f803-47d0-bfb2-ea8f13149a22	9	105.56	105.56	105.56
177	f527c3ba-f803-47d0-bfb2-ea8f13149a22	10	105.56	105.56	105.56
178	f527c3ba-f803-47d0-bfb2-ea8f13149a22	11	-	-	105.56
179	f527c3ba-f803-47d0-bfb2-ea8f13149a22	12	-	-	105.56
180	f527c3ba-f803-47d0-bfb2-ea8f13149a22	13	-	-	105.56
181	f527c3ba-f803-47d0-bfb2-ea8f13149a22	14	-	-	105.56
182	f527c3ba-f803-47d0-bfb2-ea8f13149a22	15	-	-	105.56
183	f527c3ba-f803-47d0-bfb2-ea8f13149a22	16	-	-	105.56
184	f527c3ba-f803-47d0-bfb2-ea8f13149a22	17	-	-	105.56
185	f527c3ba-f803-47d0-bfb2-ea8f13149a22	18	-	-	105.56
186	4f8aceb8-5cac-42d6-81b7-0be5166069b3	1	105.56	105.56	NaN
187	4f8aceb8-5cac-42d6-81b7-0be5166069b3	2	105.56	105.56	NaN
188	4f8aceb8-5cac-42d6-81b7-0be5166069b3	3	105.56	105.56	NaN
189	4f8aceb8-5cac-42d6-81b7-0be5166069b3	4	105.56	105.56	NaN
190	4f8aceb8-5cac-42d6-81b7-0be5166069b3	5	105.56	105.56	NaN
191	4f8aceb8-5cac-42d6-81b7-0be5166069b3	6	105.56	105.56	NaN
192	4f8aceb8-5cac-42d6-81b7-0be5166069b3	7	105.56	105.56	NaN
193	4f8aceb8-5cac-42d6-81b7-0be5166069b3	8	105.56	105.56	NaN
194	4f8aceb8-5cac-42d6-81b7-0be5166069b3	9	105.56	105.56	NaN
195	4f8aceb8-5cac-42d6-81b7-0be5166069b3	10	105.56	105.56	NaN
196	4f8aceb8-5cac-42d6-81b7-0be5166069b3	11	-	-	105.56
197	4f8aceb8-5cac-42d6-81b7-0be5166069b3	12	-	-	105.56
198	4f8aceb8-5cac-42d6-81b7-0be5166069b3	13	-	-	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
199	4f8aceb8-5cac-42d6-81b7-0be5166069b3	14	-	-	105.56
200	4f8aceb8-5cac-42d6-81b7-0be5166069b3	15	-	-	105.56
201	4f8aceb8-5cac-42d6-81b7-0be5166069b3	16	-	-	105.56
202	4f8aceb8-5cac-42d6-81b7-0be5166069b3	17	-	-	105.56
203	4f8aceb8-5cac-42d6-81b7-0be5166069b3	18	-	-	105.56
204	68fbd0fe-14ae-419e-9532-4febdb0a851d	1	NaN	NaN	105.56
205	68fbd0fe-14ae-419e-9532-4febdb0a851d	2	NaN	NaN	105.56
206	68fbd0fe-14ae-419e-9532-4febdb0a851d	3	NaN	105.56	105.56
207	68fbd0fe-14ae-419e-9532-4febdb0a851d	4	NaN	105.56	105.56
208	68fbd0fe-14ae-419e-9532-4febdb0a851d	5	NaN	105.56	105.56
209	68fbd0fe-14ae-419e-9532-4febdb0a851d	6	105.56	105.56	105.56
210	68fbd0fe-14ae-419e-9532-4febdb0a851d	7	105.56	105.56	105.56
211	68fbd0fe-14ae-419e-9532-4febdb0a851d	8	105.56	105.56	105.56
212	68fbd0fe-14ae-419e-9532-4febdb0a851d	9	105.56	105.56	105.56
213	68fbd0fe-14ae-419e-9532-4febdb0a851d	10	105.56	105.56	105.56
214	68fbd0fe-14ae-419e-9532-4febdb0a851d	11	-	-	105.56
215	68fbd0fe-14ae-419e-9532-4febdb0a851d	12	-	-	105.56
216	68fbd0fe-14ae-419e-9532-4febdb0a851d	13	-	-	105.56
217	68fbd0fe-14ae-419e-9532-4febdb0a851d	14	-	-	105.56
218	68fbd0fe-14ae-419e-9532-4febdb0a851d	15	-	-	105.56
219	68fbd0fe-14ae-419e-9532-4febdb0a851d	16	-	-	105.56
220	68fbd0fe-14ae-419e-9532-4febdb0a851d	17	-	-	105.56
221	4da392a8-d792-4bf5-a3e9-30d47def86b6	1	105.56	105.56	105.56
222	4da392a8-d792-4bf5-a3e9-30d47def86b6	2	105.56	105.56	105.56
223	4da392a8-d792-4bf5-a3e9-30d47def86b6	3	105.56	105.56	105.56
224	4da392a8-d792-4bf5-a3e9-30d47def86b6	4	105.56	105.56	105.56
225	4da392a8-d792-4bf5-a3e9-30d47def86b6	5	105.56	105.56	105.56
226	4da392a8-d792-4bf5-a3e9-30d47def86b6	6	105.56	105.56	105.56
227	4da392a8-d792-4bf5-a3e9-30d47def86b6	7	105.56	105.56	105.56
228	4da392a8-d792-4bf5-a3e9-30d47def86b6	8	105.56	105.56	105.56
229	4da392a8-d792-4bf5-a3e9-30d47def86b6	9	105.56	105.56	105.56
230	4da392a8-d792-4bf5-a3e9-30d47def86b6	10	105.56	105.56	105.56
231	4da392a8-d792-4bf5-a3e9-30d47def86b6	11	-	-	105.56
232	4da392a8-d792-4bf5-a3e9-30d47def86b6	12	-	-	105.56
233	4da392a8-d792-4bf5-a3e9-30d47def86b6	13	-	-	105.56
234	4da392a8-d792-4bf5-a3e9-30d47def86b6	14	-	-	105.56
235	4da392a8-d792-4bf5-a3e9-30d47def86b6	15	-	-	105.56
236	4da392a8-d792-4bf5-a3e9-30d47def86b6	16	-	-	105.56
237	e7b99daa-79e1-4907-823d-faf763ad9d95	1	105.56	105.56	105.56
238	e7b99daa-79e1-4907-823d-faf763ad9d95	2	105.56	105.56	105.56
239	e7b99daa-79e1-4907-823d-faf763ad9d95	3	105.56	105.56	105.56
240	e7b99daa-79e1-4907-823d-faf763ad9d95	4	105.56	105.56	105.56
241	e7b99daa-79e1-4907-823d-faf763ad9d95	5	105.56	105.56	105.56
242	e7b99daa-79e1-4907-823d-faf763ad9d95	6	105.56	105.56	105.56
243	e7b99daa-79e1-4907-823d-faf763ad9d95	7	105.56	105.56	105.56
244	e7b99daa-79e1-4907-823d-faf763ad9d95	8	105.56	105.56	105.56
245	e7b99daa-79e1-4907-823d-faf763ad9d95	9	105.56	105.56	105.56
246	e7b99daa-79e1-4907-823d-faf763ad9d95	10	105.56	105.56	105.56
247	e7b99daa-79e1-4907-823d-faf763ad9d95	11	-	-	105.56
248	e7b99daa-79e1-4907-823d-faf763ad9d95	12	-	-	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
249	e7b99daa-79e1-4907-823d-faf763ad9d95	13	-	-	105.56
250	e7b99daa-79e1-4907-823d-faf763ad9d95	14	-	-	105.56
251	e7b99daa-79e1-4907-823d-faf763ad9d95	15	-	-	105.56
252	e7b99daa-79e1-4907-823d-faf763ad9d95	16	-	-	105.56
253	e7b99daa-79e1-4907-823d-faf763ad9d95	17	-	-	105.56
254	e7b99daa-79e1-4907-823d-faf763ad9d95	18	-	-	105.56
255	e7b99daa-79e1-4907-823d-faf763ad9d95	19	-	-	105.56
256	0d24927b-a454-4042-90fb-58ee48b2855b	1	105.56	105.56	105.56
257	0d24927b-a454-4042-90fb-58ee48b2855b	2	105.56	105.56	105.56
258	0d24927b-a454-4042-90fb-58ee48b2855b	3	105.56	105.56	105.56
259	0d24927b-a454-4042-90fb-58ee48b2855b	4	105.56	105.56	105.56
260	0d24927b-a454-4042-90fb-58ee48b2855b	5	105.56	105.56	105.56
261	0d24927b-a454-4042-90fb-58ee48b2855b	6	105.56	105.56	105.56
262	0d24927b-a454-4042-90fb-58ee48b2855b	7	105.56	105.56	105.56
263	0d24927b-a454-4042-90fb-58ee48b2855b	8	105.56	105.56	105.56
264	0d24927b-a454-4042-90fb-58ee48b2855b	9	105.56	105.56	105.56
265	0d24927b-a454-4042-90fb-58ee48b2855b	10	105.56	105.56	105.56
266	0d24927b-a454-4042-90fb-58ee48b2855b	11	-	-	105.56
267	0d24927b-a454-4042-90fb-58ee48b2855b	12	-	-	105.56
268	0d24927b-a454-4042-90fb-58ee48b2855b	13	-	-	105.56
269	0d24927b-a454-4042-90fb-58ee48b2855b	14	-	-	105.56
270	0d24927b-a454-4042-90fb-58ee48b2855b	15	-	-	105.56
271	0d24927b-a454-4042-90fb-58ee48b2855b	16	-	-	105.56
272	0d24927b-a454-4042-90fb-58ee48b2855b	17	-	-	105.56
273	0d24927b-a454-4042-90fb-58ee48b2855b	18	-	-	105.56
274	e16bf23e-2889-4e78-8561-0ff3399f3837	1	105.56	NaN	105.56
275	e16bf23e-2889-4e78-8561-0ff3399f3837	2	105.56	NaN	105.56
276	e16bf23e-2889-4e78-8561-0ff3399f3837	3	105.56	NaN	105.56
277	e16bf23e-2889-4e78-8561-0ff3399f3837	4	105.56	NaN	105.56
278	e16bf23e-2889-4e78-8561-0ff3399f3837	5	105.56	NaN	105.56
279	e16bf23e-2889-4e78-8561-0ff3399f3837	6	105.56	NaN	105.56
280	e16bf23e-2889-4e78-8561-0ff3399f3837	7	105.56	105.56	105.56
281	e16bf23e-2889-4e78-8561-0ff3399f3837	8	105.56	105.56	105.56
282	e16bf23e-2889-4e78-8561-0ff3399f3837	9	105.56	105.56	105.56
283	e16bf23e-2889-4e78-8561-0ff3399f3837	10	105.56	105.56	105.56
284	e16bf23e-2889-4e78-8561-0ff3399f3837	11	-	-	105.56
285	e16bf23e-2889-4e78-8561-0ff3399f3837	12	-	-	105.56
286	e16bf23e-2889-4e78-8561-0ff3399f3837	13	-	-	105.56
287	e16bf23e-2889-4e78-8561-0ff3399f3837	14	-	-	105.56
288	e16bf23e-2889-4e78-8561-0ff3399f3837	15	-	-	105.56
289	e16bf23e-2889-4e78-8561-0ff3399f3837	16	-	-	105.56
290	e16bf23e-2889-4e78-8561-0ff3399f3837	17	-	-	105.56
291	e16bf23e-2889-4e78-8561-0ff3399f3837	18	-	-	105.56
292	e16bf23e-2889-4e78-8561-0ff3399f3837	19	-	-	105.56
293	e16bf23e-2889-4e78-8561-0ff3399f3837	20	-	-	105.56
294	e16bf23e-2889-4e78-8561-0ff3399f3837	21	-	-	105.56
295	e16bf23e-2889-4e78-8561-0ff3399f3837	22	-	-	105.56
296	fc1173ab-3f58-4343-b187-80ae77b1e2a3	1	NaN	NaN	105.56
297	fc1173ab-3f58-4343-b187-80ae77b1e2a3	2	105.56	NaN	105.56
298	fc1173ab-3f58-4343-b187-80ae77b1e2a3	3	105.56	NaN	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
299	fc1173ab-3f58-4343-b187-80ae77b1e2a3	4	105.56	105.56	105.56
300	fc1173ab-3f58-4343-b187-80ae77b1e2a3	5	105.56	105.56	105.56
301	fc1173ab-3f58-4343-b187-80ae77b1e2a3	6	105.56	105.56	105.56
302	fc1173ab-3f58-4343-b187-80ae77b1e2a3	7	105.56	105.56	105.56
303	fc1173ab-3f58-4343-b187-80ae77b1e2a3	8	105.56	105.56	105.56
304	fc1173ab-3f58-4343-b187-80ae77b1e2a3	9	105.56	105.56	105.56
305	fc1173ab-3f58-4343-b187-80ae77b1e2a3	10	105.56	105.56	105.56
306	fc1173ab-3f58-4343-b187-80ae77b1e2a3	11	-	-	105.56
307	fc1173ab-3f58-4343-b187-80ae77b1e2a3	12	-	-	105.56
308	fc1173ab-3f58-4343-b187-80ae77b1e2a3	13	-	-	105.56
309	fc1173ab-3f58-4343-b187-80ae77b1e2a3	14	-	-	105.56
310	fc1173ab-3f58-4343-b187-80ae77b1e2a3	15	-	-	105.56
311	fc1173ab-3f58-4343-b187-80ae77b1e2a3	16	-	-	105.56
312	fc1173ab-3f58-4343-b187-80ae77b1e2a3	17	-	-	105.56
313	fc1173ab-3f58-4343-b187-80ae77b1e2a3	18	-	-	105.56
314	6707185a-635c-4654-993d-d3425d9cf271	1	105.56	105.56	NaN
315	6707185a-635c-4654-993d-d3425d9cf271	2	105.56	105.56	NaN
316	6707185a-635c-4654-993d-d3425d9cf271	3	105.56	105.56	NaN
317	6707185a-635c-4654-993d-d3425d9cf271	4	105.56	105.56	105.56
318	6707185a-635c-4654-993d-d3425d9cf271	5	105.56	105.56	105.56
319	6707185a-635c-4654-993d-d3425d9cf271	6	105.56	105.56	105.56
320	6707185a-635c-4654-993d-d3425d9cf271	7	105.56	105.56	105.56
321	6707185a-635c-4654-993d-d3425d9cf271	8	105.56	105.56	105.56
322	6707185a-635c-4654-993d-d3425d9cf271	9	105.56	105.56	105.56
323	6707185a-635c-4654-993d-d3425d9cf271	10	105.56	105.56	105.56
324	6707185a-635c-4654-993d-d3425d9cf271	11	-	-	105.56
325	6707185a-635c-4654-993d-d3425d9cf271	12	-	-	105.56
326	6707185a-635c-4654-993d-d3425d9cf271	13	-	-	105.56
327	6707185a-635c-4654-993d-d3425d9cf271	14	-	-	105.56
328	6707185a-635c-4654-993d-d3425d9cf271	15	-	-	105.56
329	6707185a-635c-4654-993d-d3425d9cf271	16	-	-	105.56
330	6707185a-635c-4654-993d-d3425d9cf271	17	-	-	105.56
331	6707185a-635c-4654-993d-d3425d9cf271	18	-	-	105.56
332	6707185a-635c-4654-993d-d3425d9cf271	19	-	-	105.56
333	6707185a-635c-4654-993d-d3425d9cf271	20	-	-	105.56
334	fdabfc73-a63d-4852-a94e-32af7a7a85ad	1	105.56	105.56	105.56
335	fdabfc73-a63d-4852-a94e-32af7a7a85ad	2	105.56	105.56	105.56
336	fdabfc73-a63d-4852-a94e-32af7a7a85ad	3	105.56	105.56	105.56
337	fdabfc73-a63d-4852-a94e-32af7a7a85ad	4	105.56	105.56	105.56
338	fdabfc73-a63d-4852-a94e-32af7a7a85ad	5	105.56	105.56	105.56
339	fdabfc73-a63d-4852-a94e-32af7a7a85ad	6	105.56	105.56	105.56
340	fdabfc73-a63d-4852-a94e-32af7a7a85ad	7	105.56	105.56	105.56
341	fdabfc73-a63d-4852-a94e-32af7a7a85ad	8	105.56	105.56	105.56
342	fdabfc73-a63d-4852-a94e-32af7a7a85ad	9	105.56	105.56	105.56
343	fdabfc73-a63d-4852-a94e-32af7a7a85ad	10	105.56	105.56	105.56
344	fdabfc73-a63d-4852-a94e-32af7a7a85ad	11	-	-	105.56
345	fdabfc73-a63d-4852-a94e-32af7a7a85ad	12	-	-	105.56
346	fdabfc73-a63d-4852-a94e-32af7a7a85ad	13	-	-	105.56
347	fdabfc73-a63d-4852-a94e-32af7a7a85ad	14	-	-	105.56
348	fdabfc73-a63d-4852-a94e-32af7a7a85ad	15	-	-	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
349	fdabfc73-a63d-4852-a94e-32af7a7a85ad	16	-	-	105.56
350	fdabfc73-a63d-4852-a94e-32af7a7a85ad	17	-	-	105.56
351	fdabfc73-a63d-4852-a94e-32af7a7a85ad	18	-	-	105.56
352	fdabfc73-a63d-4852-a94e-32af7a7a85ad	19	-	-	105.56
353	fdabfc73-a63d-4852-a94e-32af7a7a85ad	20	-	-	105.56
354	fdabfc73-a63d-4852-a94e-32af7a7a85ad	21	-	-	105.56
355	fdabfc73-a63d-4852-a94e-32af7a7a85ad	22	-	-	105.56
356	e6afafba-9644-46c4-a853-50d2ad646a2f	1	105.56	NaN	NaN
357	e6afafba-9644-46c4-a853-50d2ad646a2f	2	105.56	NaN	NaN
358	e6afafba-9644-46c4-a853-50d2ad646a2f	3	105.56	NaN	105.56
359	e6afafba-9644-46c4-a853-50d2ad646a2f	4	105.56	105.56	105.56
360	e6afafba-9644-46c4-a853-50d2ad646a2f	5	105.56	105.56	105.56
361	e6afafba-9644-46c4-a853-50d2ad646a2f	6	105.56	105.56	105.56
362	e6afafba-9644-46c4-a853-50d2ad646a2f	7	105.56	105.56	105.56
363	e6afafba-9644-46c4-a853-50d2ad646a2f	8	105.56	105.56	105.56
364	e6afafba-9644-46c4-a853-50d2ad646a2f	9	105.56	105.56	105.56
365	e6afafba-9644-46c4-a853-50d2ad646a2f	10	105.56	105.56	105.56
366	e6afafba-9644-46c4-a853-50d2ad646a2f	11	-	-	105.56
367	e6afafba-9644-46c4-a853-50d2ad646a2f	12	-	-	105.56
368	e6afafba-9644-46c4-a853-50d2ad646a2f	13	-	-	105.56
369	e6afafba-9644-46c4-a853-50d2ad646a2f	14	-	-	105.56
370	e6afafba-9644-46c4-a853-50d2ad646a2f	15	-	-	105.56
371	e6afafba-9644-46c4-a853-50d2ad646a2f	16	-	-	105.56
372	e6afafba-9644-46c4-a853-50d2ad646a2f	17	-	-	105.56
373	c30909dd-2b4b-440b-a1b2-21bc5e857b81	1	NaN	NaN	105.56
374	c30909dd-2b4b-440b-a1b2-21bc5e857b81	2	105.56	NaN	105.56
375	c30909dd-2b4b-440b-a1b2-21bc5e857b81	3	105.56	105.56	105.56
376	c30909dd-2b4b-440b-a1b2-21bc5e857b81	4	105.56	105.56	105.56
377	c30909dd-2b4b-440b-a1b2-21bc5e857b81	5	105.56	105.56	105.56
378	c30909dd-2b4b-440b-a1b2-21bc5e857b81	6	105.56	105.56	105.56
379	c30909dd-2b4b-440b-a1b2-21bc5e857b81	7	105.56	105.56	105.56
380	c30909dd-2b4b-440b-a1b2-21bc5e857b81	8	105.56	105.56	105.56
381	c30909dd-2b4b-440b-a1b2-21bc5e857b81	9	105.56	105.56	105.56
382	c30909dd-2b4b-440b-a1b2-21bc5e857b81	10	105.56	105.56	105.56
383	c30909dd-2b4b-440b-a1b2-21bc5e857b81	11	-	-	105.56
384	c30909dd-2b4b-440b-a1b2-21bc5e857b81	12	-	-	105.56
385	c30909dd-2b4b-440b-a1b2-21bc5e857b81	13	-	-	105.56
386	c30909dd-2b4b-440b-a1b2-21bc5e857b81	14	-	-	105.56
387	c30909dd-2b4b-440b-a1b2-21bc5e857b81	15	-	-	105.56
388	c30909dd-2b4b-440b-a1b2-21bc5e857b81	16	-	-	105.56
389	c30909dd-2b4b-440b-a1b2-21bc5e857b81	17	-	-	105.56
390	c30909dd-2b4b-440b-a1b2-21bc5e857b81	18	-	-	105.56
391	c30909dd-2b4b-440b-a1b2-21bc5e857b81	19	-	-	105.56
392	62688411-17b6-460d-a6b5-12714c96d9ab	1	105.56	NaN	NaN
393	62688411-17b6-460d-a6b5-12714c96d9ab	2	105.56	NaN	NaN
394	62688411-17b6-460d-a6b5-12714c96d9ab	3	105.56	NaN	NaN
395	62688411-17b6-460d-a6b5-12714c96d9ab	4	105.56	105.56	NaN
396	62688411-17b6-460d-a6b5-12714c96d9ab	5	105.56	105.56	NaN
397	62688411-17b6-460d-a6b5-12714c96d9ab	6	105.56	105.56	NaN
398	62688411-17b6-460d-a6b5-12714c96d9ab	7	105.56	105.56	NaN

(continue)



**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
399	62688411-17b6-460d-a6b5-12714c96d9ab	8	105.56	105.56	NaN
400	62688411-17b6-460d-a6b5-12714c96d9ab	9	105.56	105.56	NaN
401	62688411-17b6-460d-a6b5-12714c96d9ab	10	105.56	105.56	NaN
402	62688411-17b6-460d-a6b5-12714c96d9ab	11	-	-	NaN
403	62688411-17b6-460d-a6b5-12714c96d9ab	12	-	-	NaN
404	62688411-17b6-460d-a6b5-12714c96d9ab	13	-	-	NaN
405	62688411-17b6-460d-a6b5-12714c96d9ab	14	-	-	NaN
406	62688411-17b6-460d-a6b5-12714c96d9ab	15	-	-	NaN
407	62688411-17b6-460d-a6b5-12714c96d9ab	16	-	-	NaN
408	62688411-17b6-460d-a6b5-12714c96d9ab	17	-	-	NaN
409	62688411-17b6-460d-a6b5-12714c96d9ab	18	-	-	NaN
410	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	1	NaN	NaN	105.56
411	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	2	105.56	NaN	105.56
412	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	3	105.56	NaN	105.56
413	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	4	105.56	NaN	105.56
414	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	5	105.56	NaN	105.56
415	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	6	105.56	105.56	105.56
416	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	7	105.56	105.56	105.56
417	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	8	105.56	105.56	105.56
418	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	9	105.56	105.56	105.56
419	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	10	105.56	105.56	105.56
420	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	11	-	-	105.56
421	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	12	-	-	105.56
422	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	13	-	-	105.56
423	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	14	-	-	105.56
424	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	15	-	-	105.56
425	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	16	-	-	105.56
426	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	17	-	-	105.56
427	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	18	-	-	105.56
428	ff7508f6-a55f-4d08-8f61-3dee4b6d14ce	19	-	-	105.56
429	173dd531-24fe-4f19-9bdc-9548cb9dc213	1	105.56	105.56	NaN
430	173dd531-24fe-4f19-9bdc-9548cb9dc213	2	105.56	105.56	NaN
431	173dd531-24fe-4f19-9bdc-9548cb9dc213	3	105.56	105.56	NaN
432	173dd531-24fe-4f19-9bdc-9548cb9dc213	4	105.56	105.56	NaN
433	173dd531-24fe-4f19-9bdc-9548cb9dc213	5	105.56	105.56	NaN
434	173dd531-24fe-4f19-9bdc-9548cb9dc213	6	105.56	105.56	NaN
435	173dd531-24fe-4f19-9bdc-9548cb9dc213	7	105.56	105.56	NaN
436	173dd531-24fe-4f19-9bdc-9548cb9dc213	8	105.56	105.56	NaN
437	173dd531-24fe-4f19-9bdc-9548cb9dc213	9	105.56	105.56	NaN
438	173dd531-24fe-4f19-9bdc-9548cb9dc213	10	105.56	105.56	NaN
439	173dd531-24fe-4f19-9bdc-9548cb9dc213	11	-	-	NaN
440	173dd531-24fe-4f19-9bdc-9548cb9dc213	12	-	-	NaN
441	173dd531-24fe-4f19-9bdc-9548cb9dc213	13	-	-	105.56
442	173dd531-24fe-4f19-9bdc-9548cb9dc213	14	-	-	105.56
443	173dd531-24fe-4f19-9bdc-9548cb9dc213	15	-	-	105.56
444	173dd531-24fe-4f19-9bdc-9548cb9dc213	16	-	-	105.56
445	173dd531-24fe-4f19-9bdc-9548cb9dc213	17	-	-	105.56
446	173dd531-24fe-4f19-9bdc-9548cb9dc213	18	-	-	105.56
447	173dd531-24fe-4f19-9bdc-9548cb9dc213	19	-	-	105.56
448	173dd531-24fe-4f19-9bdc-9548cb9dc213	20	-	-	105.56

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
449	58f9c680-404a-415a-aa86-e6f9d5feac1f	1	NaN	105.56	NaN
450	58f9c680-404a-415a-aa86-e6f9d5feac1f	2	NaN	105.56	NaN
451	58f9c680-404a-415a-aa86-e6f9d5feac1f	3	105.56	105.56	NaN
452	58f9c680-404a-415a-aa86-e6f9d5feac1f	4	105.56	105.56	NaN
453	58f9c680-404a-415a-aa86-e6f9d5feac1f	5	105.56	105.56	NaN
454	58f9c680-404a-415a-aa86-e6f9d5feac1f	6	105.56	105.56	105.56
455	58f9c680-404a-415a-aa86-e6f9d5feac1f	7	105.56	105.56	105.56
456	58f9c680-404a-415a-aa86-e6f9d5feac1f	8	105.56	105.56	105.56
457	58f9c680-404a-415a-aa86-e6f9d5feac1f	9	105.56	105.56	105.56
458	58f9c680-404a-415a-aa86-e6f9d5feac1f	10	105.56	105.56	105.56
459	58f9c680-404a-415a-aa86-e6f9d5feac1f	11	-	-	105.56
460	58f9c680-404a-415a-aa86-e6f9d5feac1f	12	-	-	105.56
461	58f9c680-404a-415a-aa86-e6f9d5feac1f	13	-	-	105.56
462	58f9c680-404a-415a-aa86-e6f9d5feac1f	14	-	-	105.56
463	58f9c680-404a-415a-aa86-e6f9d5feac1f	15	-	-	105.56
464	58f9c680-404a-415a-aa86-e6f9d5feac1f	16	-	-	105.56
465	58f9c680-404a-415a-aa86-e6f9d5feac1f	17	-	-	105.56
466	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	1	105.56	105.56	105.56
467	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	2	105.56	105.56	105.56
468	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	3	105.56	105.56	105.56
469	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	4	105.56	105.56	105.56
470	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	5	105.56	105.56	105.56
471	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	6	105.56	105.56	105.56
472	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	7	105.56	105.56	105.56
473	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	8	105.56	105.56	105.56
474	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	9	105.56	105.56	105.56
475	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	10	105.56	105.56	105.56
476	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	11	-	-	105.56
477	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	12	-	-	105.56
478	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	13	-	-	105.56
479	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	14	-	-	105.56
480	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	15	-	-	105.56
481	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	16	-	-	105.56
482	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	17	-	-	105.56
483	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	18	-	-	105.56
484	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	19	-	-	105.56
485	ca07c7ee-6911-44a6-a170-2c7a7f5a403d	20	-	-	105.56
486	5b262cdb-8675-48ad-893f-1be594348194	1	105.56	NaN	NaN
487	5b262cdb-8675-48ad-893f-1be594348194	2	105.56	NaN	NaN
488	5b262cdb-8675-48ad-893f-1be594348194	3	105.56	105.56	NaN
489	5b262cdb-8675-48ad-893f-1be594348194	4	105.56	105.56	NaN
490	5b262cdb-8675-48ad-893f-1be594348194	5	105.56	105.56	NaN
491	5b262cdb-8675-48ad-893f-1be594348194	6	105.56	105.56	NaN
492	5b262cdb-8675-48ad-893f-1be594348194	7	105.56	105.56	NaN
493	5b262cdb-8675-48ad-893f-1be594348194	8	105.56	105.56	NaN
494	5b262cdb-8675-48ad-893f-1be594348194	9	105.56	105.56	NaN
495	5b262cdb-8675-48ad-893f-1be594348194	10	105.56	105.56	NaN
496	5b262cdb-8675-48ad-893f-1be594348194	11	-	-	NaN
497	5b262cdb-8675-48ad-893f-1be594348194	12	-	-	NaN
498	5b262cdb-8675-48ad-893f-1be594348194	13	-	-	NaN

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
499	5b262cdb-8675-48ad-893f-1be594348194	14	-	-	NaN
500	5b262cdb-8675-48ad-893f-1be594348194	15	-	-	NaN
501	5b262cdb-8675-48ad-893f-1be594348194	16	-	-	NaN
502	5b262cdb-8675-48ad-893f-1be594348194	17	-	-	NaN
503	5b262cdb-8675-48ad-893f-1be594348194	18	-	-	NaN
504	5b262cdb-8675-48ad-893f-1be594348194	19	-	-	NaN
505	5b262cdb-8675-48ad-893f-1be594348194	20	-	-	NaN
506	f76b2046-648c-45ef-b345-6454544e0eba	1	105.56	105.56	NaN
507	f76b2046-648c-45ef-b345-6454544e0eba	2	105.56	105.56	NaN
508	f76b2046-648c-45ef-b345-6454544e0eba	3	105.56	105.56	NaN
509	f76b2046-648c-45ef-b345-6454544e0eba	4	105.56	105.56	NaN
510	f76b2046-648c-45ef-b345-6454544e0eba	5	105.56	105.56	NaN
511	f76b2046-648c-45ef-b345-6454544e0eba	6	105.56	105.56	NaN
512	f76b2046-648c-45ef-b345-6454544e0eba	7	105.56	105.56	105.56
513	f76b2046-648c-45ef-b345-6454544e0eba	8	105.56	105.56	105.56
514	f76b2046-648c-45ef-b345-6454544e0eba	9	105.56	105.56	105.56
515	f76b2046-648c-45ef-b345-6454544e0eba	10	105.56	105.56	105.56
516	f76b2046-648c-45ef-b345-6454544e0eba	11	-	-	105.56
517	f76b2046-648c-45ef-b345-6454544e0eba	12	-	-	105.56
518	f76b2046-648c-45ef-b345-6454544e0eba	13	-	-	105.56
519	f76b2046-648c-45ef-b345-6454544e0eba	14	-	-	105.56
520	f76b2046-648c-45ef-b345-6454544e0eba	15	-	-	105.56
521	f76b2046-648c-45ef-b345-6454544e0eba	16	-	-	105.56
522	f76b2046-648c-45ef-b345-6454544e0eba	17	-	-	105.56
523	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	1	105.56	105.56	105.56
524	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	2	105.56	105.56	105.56
525	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	3	105.56	105.56	105.56
526	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	4	105.56	105.56	105.56
527	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	5	105.56	105.56	105.56
528	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	6	105.56	105.56	105.56
529	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	7	105.56	105.56	105.56
530	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	8	105.56	105.56	105.56
531	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	9	105.56	105.56	105.56
532	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	10	105.56	105.56	105.56
533	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	11	-	-	105.56
534	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	12	-	-	105.56
535	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	13	-	-	105.56
536	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	14	-	-	105.56
537	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	15	-	-	105.56
538	f1ae2601-0246-4762-bc7b-2e8e15e5e23f	16	-	-	105.56
539	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	1	105.56	105.56	NaN
540	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	2	105.56	105.56	NaN
541	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	3	105.56	105.56	NaN
542	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	4	105.56	105.56	NaN
543	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	5	105.56	105.56	NaN
544	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	6	105.56	105.56	NaN
545	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	7	105.56	105.56	NaN
546	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	8	105.56	105.56	NaN
547	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	9	105.56	105.56	NaN
548	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	10	105.56	105.56	NaN

(continue)

**Table 4 – Scenario 1 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
549	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	11	-	-	NaN
550	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	12	-	-	NaN
551	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	13	-	-	NaN
552	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	14	-	-	NaN
553	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	15	-	-	NaN
554	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	16	-	-	NaN
555	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	17	-	-	NaN
556	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	18	-	-	NaN
557	b66e388c-e13e-49d4-b4f9-2fcf0487de6e	19	-	-	NaN

**Source: Own authorship (2021).**

By analysing Table 4, the persistence of individuals from the Genetic Algorithm Controller (GA) is reflected in the amount of epochs required to achieve the same number of unique individuals, which is greater in comparison with other controllers. Both the Random Action Controller (RND) and the Particle Swarm Optimization Controller (PSO) generated a fresh new set of individuals on every epoch, resulting in 10 epochs with 3 individuals each to reach the desired amount of 30 unique simulations (on each run). The GA controller, instead, took up to 20 epochs to execute the required amount of unique simulations.

Another general observation of the GA data is the presence of comparisons where it hasn't achieved any successful solution, like the ones presented on lines 392 to 409, 486 to 505, and 539 to 557, indicating that more randomization might be required. This behavior was not observed on the other controllers.

A data representation for the performance variables of the controllers is shown in Table 5, in which:

- **RND CTR:** Controller Total Runtime (CTR) of the Random Action Controller (total execution time to reach the stop criteria);
- **RND BSTC:** Best Simulation Total Cost (BSTC) of the Random Action Controller (the lowest simulation accumulated cost that the controller has found);
- **PSO CTR:** Controller Total Runtime (CTR) of the Particle Swarm Optimization Controller (total execution time to reach the stop criteria);
- **PSO BSTC:** Best Simulation Total Cost (BSTC) of the Particle Swarm Optimization Controller (the lowest simulation accumulated cost that the controller has found);
- **GA CTR:** Controller Total Runtime (CTR) of the Genetic Algorithm Controller

(total execution time to reach the stop criteria);

- **GA BSTC:** Best Simulation Total Cost (BSTC) of the Genetic Algorithm Controller (the lowest simulation accumulated cost that the controller has found);

**Table 5 – Scenario 1 Performance Results**

No.	RND CTR	RND BSTC	PSO CTR	PSO BSTC	GA CTR	GA BSTC
1	00:00:15	105.56	00:00:30	105.56	00:00:26	105.56
2	00:00:16	105.56	00:00:26	105.56	00:00:35	105.56
3	00:00:19	105.56	00:00:27	105.56	00:00:30	105.56
4	00:00:17	105.56	00:00:35	105.56	00:00:32	105.56
5	00:00:16	105.56	00:00:31	105.56	00:00:38	105.56
6	00:00:15	105.56	00:00:31	105.56	00:00:34	105.56
7	00:00:18	105.56	00:00:25	105.56	00:00:33	105.56
8	00:00:18	105.56	00:00:33	105.56	00:00:28	105.56
9	00:00:17	105.56	00:00:39	105.56	00:00:36	105.56
10	00:00:19	105.56	00:00:30	105.56	00:00:28	105.56
11	00:00:17	105.56	00:00:30	105.56	00:00:35	105.56
12	00:00:24	105.56	00:00:26	105.56	00:00:23	105.56
13	00:00:17	105.56	00:00:28	105.56	00:00:26	105.56
14	00:00:16	105.56	00:00:25	105.56	00:00:28	105.56
15	00:00:17	105.56	00:00:23	105.56	00:00:31	105.56
16	00:00:17	105.56	00:00:35	105.56	00:00:25	105.56
17	00:00:18	105.56	00:00:36	105.56	00:00:29	105.56
18	00:00:17	105.56	00:00:32	105.56	00:00:29	105.56
19	00:00:17	105.56	00:00:29	105.56	00:00:32	105.56
20	00:00:15	105.56	00:00:32	105.56	00:00:29	105.56
21	00:00:18	105.56	00:00:31	105.56	00:00:30	105.56
22	00:00:16	105.56	00:00:28	105.56	00:00:39	NaN
23	00:00:19	105.56	00:00:33	105.56	00:00:33	105.56
24	00:00:16	105.56	00:00:28	105.56	00:00:37	105.56
25	00:00:19	105.56	00:00:32	105.56	00:00:37	105.56
26	00:00:16	105.56	00:00:32	105.56	00:00:35	105.56
27	00:00:17	105.56	00:00:31	105.56	00:00:40	NaN
28	00:00:17	105.56	00:00:31	105.56	00:00:37	105.56
29	00:00:14	105.56	00:00:27	105.56	00:00:32	105.56
30	00:00:16	105.56	00:00:30	105.56	00:00:42	NaN
<b>SUM</b>	<b>00:08:33</b>	<b>3166.88</b>	<b>00:15:06</b>	<b>3166.88</b>	<b>00:16:09</b>	<b>5535.41</b>
<b>AVG</b>	<b>00:00:17</b>	<b>105.00</b>	<b>00:00:30</b>	<b>105.00</b>	<b>00:00:32</b>	<b>184.00</b>

Source: Own authorship (2021).

The statistical Wilcoxon Signed-Rank Test results for the controllers' BSTC on Scenario One is presented on Table 6.

Considering the hypothesis results presented on Table 6, it can be affirmed that the Genetic Algorithm Controller results are statistically different from both the Random Action Controller and the Particle Swarm Optimization Controller ones. This difference, however, cannot be affirmed between the Random Action Controller and the Particle Swarm Optimization Controller.

**Table 6 – Scenario 1 Wilcoxon Rank-sum Statistic Results**

Pair A Data	Pair B Data	Statistics	p-Value	Result
RND BSTC	PSO BSTC	0.00	0.16	Fail to reject H0
RND BSTC	AG BSTC	0.00	0.02	Reject H0
PSO BSTC	AG BSTC	2.50	0.05	Reject H0
RND CTR	PSO CTR	0.00	0.00	Reject H0
RND CTR	AG CTR	1.00	0.00	Reject H0
PSO CTR	AG CTR	126.50	0.05	Reject H0

**Source: Own authorship (2021).**

The rejection of the CTR (Controller Total Runtime) hypothesis for all the three comparisons shows that each controllers performs statistically different regarding the total execution time. It will be used as an auxiliary variable in the performance comparison.

Taking in consideration the average indicator presented on Table 5 and the hypothesis mentioned previously, it can be assumed that the Random Action Controller performed best, as it is not statistically different from the Particle Swarm Optimization Controller but it had a faster CTR while achieving the same solutions data-set. The average BSTC for the Genetic Algorithm showed to be higher (due to uncompleted solutions) and the Wilcoxon tests indicated that this difference exists, thus ranking this controller in last position considering the performance variables.

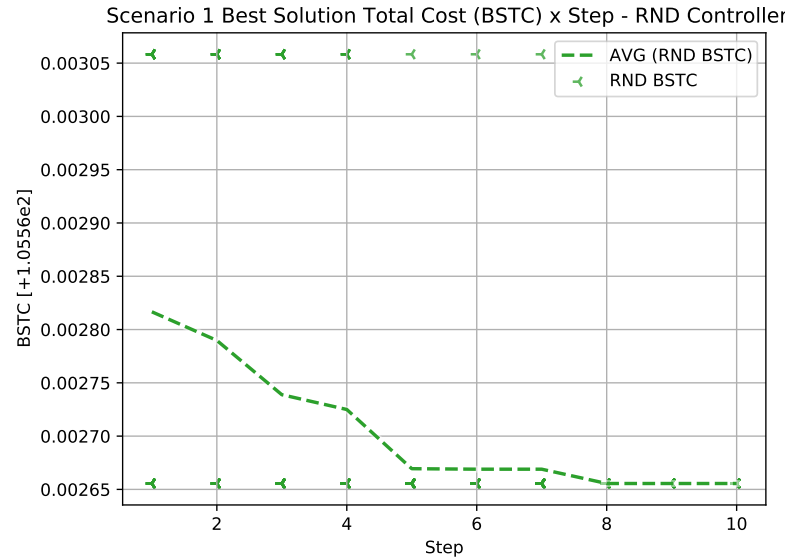
The main analysis variable is the Best Solution Total Cost (BSTC) per step, for each of the controllers. The raw data for this scenario is presented in Graph 1, Graph 2, and Graph 3. The graphs also presents the average indicator to be used as comparison criteria.

Note on Graph 1 that there are clearly two possible solutions, as expected: one considering train O41 waiting on ZPV\_D while O14 crosses through ZPV\_P and the other where train O41 waits on ZPV\_P while O14 crosses through ZPV\_D. The first option is slightly better as there's no speed restriction for the train crossing (O14) while train O41 (that would come to stop and wait soon) entered the turnout with a deviate position, having to slow down.

A combined view of all the three graphs may be seen in Graph 4, showing the Best Solution Total Cost (BSTC) per step for all the three controllers during the 30 runs of Scenario One with the parameters described in the previous section.

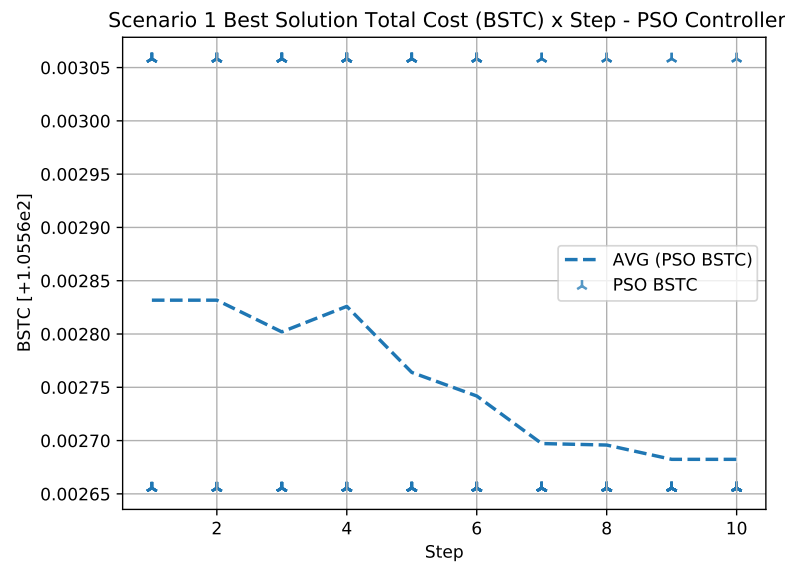
From the results presented on Graph 4 we may see that the Random Action Controller had the fastest optimal solution convergence, hitting the lowest BSTC fastest than the other controllers. The Genetic Algorithm Controller had the slowest one, mostly

**Graph 1 – Best Solution Total Cost (BSTC) per step for the Random Action Controller on Scenario One.**



Source: Own authorship (2021).

**Graph 2 – Best Solution Total Cost (BSTC) per step for the Particle Swarm Optimization Controller on Scenario One.**



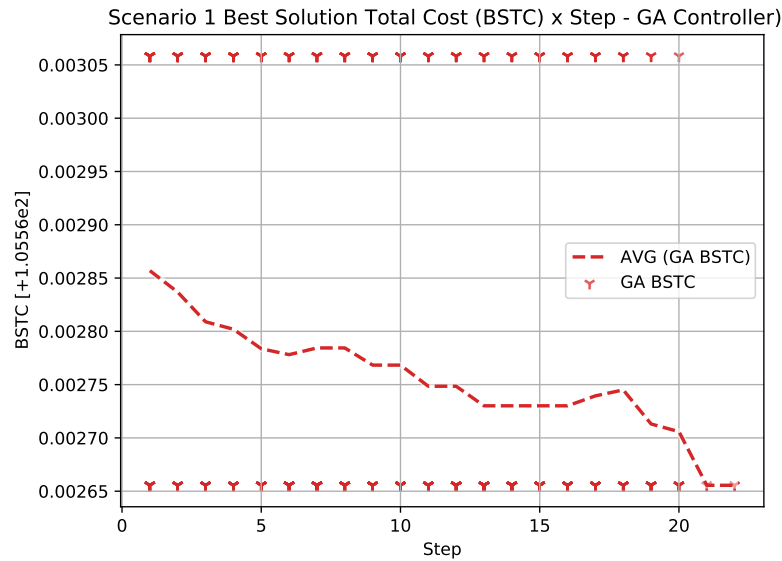
Source: Own authorship (2021).

due to its slower convergence nature by persisting some of the individuals from the population. Even so, all the three controllers achieved the known pair of solutions.

The graph presented on Graph 5 shows the total execution time of each of the 30 runs for all the tested controllers in Scenario 1, considering the parameters described in the previous section.

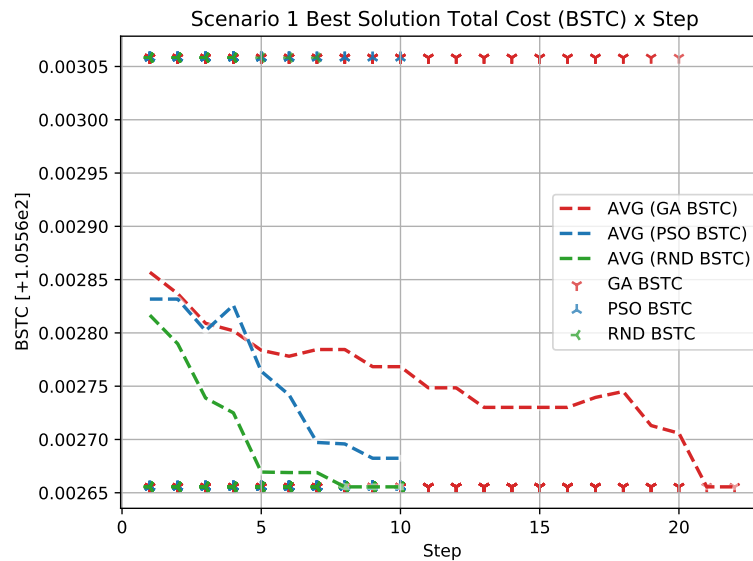
Observing Graph 5, the Random Action Controller (RND) is the fastest one,

**Graph 3 – Best Solution Total Cost (BSTC) per step for the Genetic Algorithm Controller on Scenario One.**



Source: Own authorship (2021).

**Graph 4 – Best Solution Total Cost (BSTC) per step for all the tested controllers on Scenario One.**



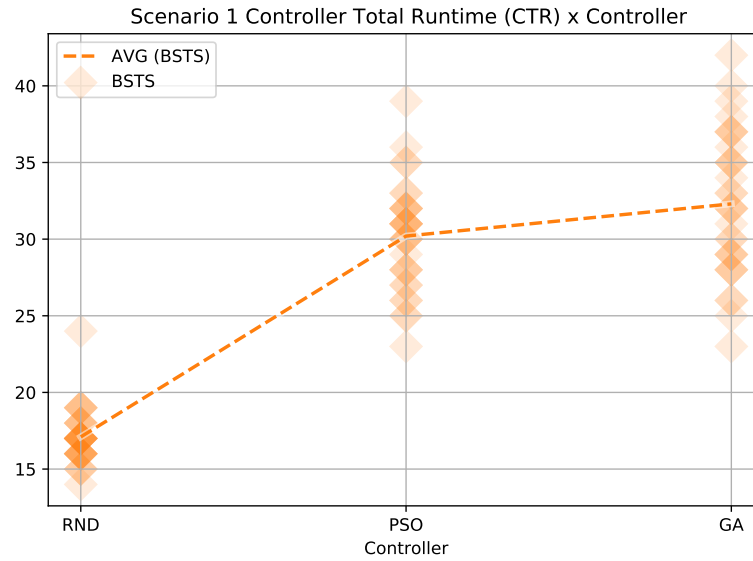
Source: Own authorship (2021).

requiring a lower computational effort than the others as there’s no logic behind generating new possible solutions: it’s just randomness. The Particle Swarm Optimization Controller (PSO) stands in the second place requiring a shorter period to execute (along a lower amount of epochs) but similar to the GA one, which stands in last on this criteria.

The graph presented on Graph 6 presents the total amount of unique simulations run on each of the controllers, as well as groups them by their final status. A failed simulation means that it was halted due to a stop criteria (steps limit or cost



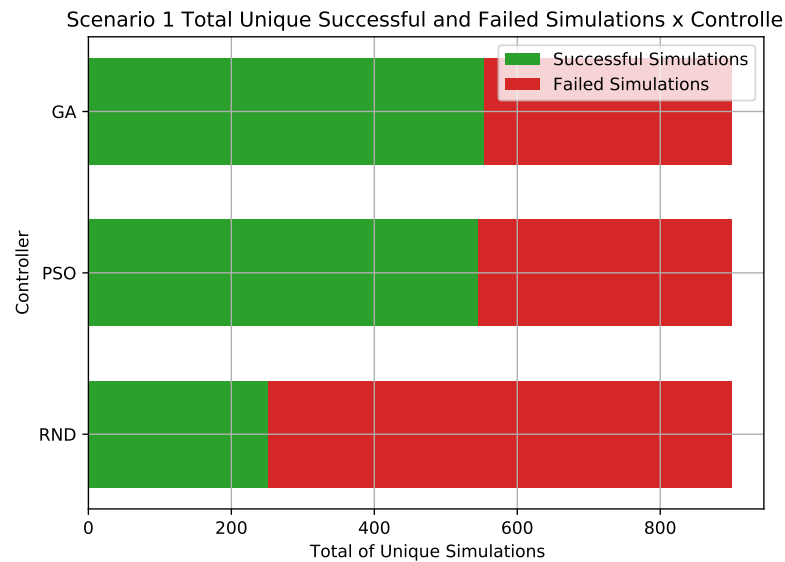
**Graph 5 – Total execution time for each of the controllers.**



**Source: Own authorship (2021).**

limit, whichever comes first). On the other hand, a successful one means that all the trains in the scenario reached their destinations before the simulation halted due to a predetermined stop criteria.

**Graph 6 – Total unique simulations (successful and failed ones) for each of the controllers.**



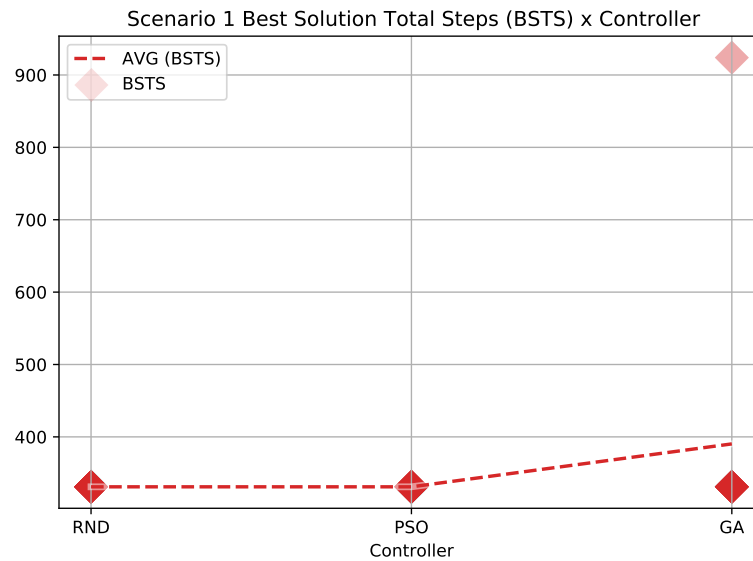
**Source: Own authorship (2021).**

Graph 6 presents the number of unique simulations for each of the controllers (the total amount is the same for all the three), grouping them by successful and failed ones. The Random Action Controller (RND) had the highest amount of failed simulations achieving a success rate of only 28% - an expected behavior as there's no logic behind

creating a new possible solution (simulation). Both the Particle Swarm Optimization Controller (PSO) and the Genetic Algorithm Controller (AG) had a similar performance within this indicator, achieving a success rate of nearly 61%.

The data presented on Graph 7 show the total amount of steps for the best solution found on each of the 30 runs for all the tested controllers. The markers have a transparency (15%) so regions with higher frequency may be identified.

**Graph 7 – Best Solution Total Steps (BSTS) for each of the controllers.**



Source: Own authorship (2021).

A data summarizing from Scenario One is presented in Table 7.

**Table 7 – Scenario 1 Results Summary**

Indicator	RND	PSO	GA
Total epochs	300	300	557
Total simulations	900	900	900
Total successful simulations	252	546	554
Best solution cost	105	105	105
Best solution total steps	331	331	331
Best solution calculated real time elapsed	00:55:10	00:55:10	00:55:10
Controller total runtime	00:08:33	00:15:06	00:16:09

Source: Own authorship (2021).

The five frames presented in Figure 23 highlight the crossing action needed to solve the problem proposed on this scenario. The first, when the trains are approaching and clearly waiting on the siding while the other train crosses is the solution for this scenario. The next shows the approach moment of O41 when it has the decision of either going straight to ZPV\_P or deviate to ZPV\_D. The third frame shows train

O41 already waiting for crossing at ZPV\_D, while train O14 is still approaching in the opposite direction. The fourth shows the exact moment when the crossing is successfully happening. The final one shows both trains successfully travelling to their destinations after the crossing has taken place.

**Figure 23 – Synoptic Video partial frames from a simulation successfully executed on Scenario One.**



Source: Own authorship (2021).

An improvement point for this project could be to provide a timetable graph for the best solution, providing a static graphical representation of the solution. The synoptic video was chosen, instead, due to the greater amount of data present (step-per-step instant velocity, route occupancy, available actions, executing action, relative position, among others).

## 4.2 SCENARIO TWO

The raw data results, a summary of the performance variables, and the discussion for Scenario Two are presented in this section.

The data points obtained for the controllers executed on Scenario One are presented on Table 8, in which:

- **No.:** an incremental counter to be used as further reference;
- **Comparison ID:** a Universally Unique Identifier (UUID) assigned for each of the 30 comparisons that were run;
- **Step:** the step counter inside the comparison scenario. Note that when one of the controllers' values is "-", it means that this step was not required (stop criteria reached earlier);
- **RND BSTC:** the Random Action Controller Best Simulation Total Cost, representing the lowest (best) cost that the controller has ever reached up to that step. A "-" value indicates that this step was not executed as the controller due to a stop criteria already achieved. A "NaN" value indicates that no successful simulation has ever been found by the controller, thus the best cost is infinite;
- **PSO BSTC:** the Particle Swarm Optimization Controller Best Simulation Total Cost, representing the lowest (best) cost that the controller has ever reached up to that step. As in the other controllers' values, a "-" indicates that this step was not executed due to a stop criteria already achieved. Also, a "NaN" value indicates that no successful simulation has been found by the controller and the best cost is infinite;
- **GA BSTC:** the Genetic Algorithm Controller Best Simulation Total Cost, representing the lowest (best) cost that the controller has ever reached up to that step. As in the other controllers' values, a "-" indicates that this step was not executed due to a stop criteria already achieved. Also, a "NaN" value indicates that no successful simulation has ever been found by the controller and the best cost is infinite;

**Table 8 – Scenario 2 Results Per Step**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
1	397facce-d6ce-4c08-b24c-f21720f3e342	1	5695.54	NaN	404.27
2	397facce-d6ce-4c08-b24c-f21720f3e342	2	3680.36	NaN	404.27
3	397facce-d6ce-4c08-b24c-f21720f3e342	3	3680.36	10828.57	404.27

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
4	397facce-d6ce-4c08-b24c-f21720f3e342	4	2747.84	10828.57	404.27
5	397facce-d6ce-4c08-b24c-f21720f3e342	5	2747.84	7871.20	404.27
6	397facce-d6ce-4c08-b24c-f21720f3e342	6	2747.84	7871.20	404.27
7	397facce-d6ce-4c08-b24c-f21720f3e342	7	2747.84	7871.20	404.27
8	397facce-d6ce-4c08-b24c-f21720f3e342	8	1508.70	7871.20	404.27
9	397facce-d6ce-4c08-b24c-f21720f3e342	9	1508.70	2022.34	404.27
10	397facce-d6ce-4c08-b24c-f21720f3e342	10	1288.50	1392.15	404.27
11	397facce-d6ce-4c08-b24c-f21720f3e342	11	-	-	404.27
12	397facce-d6ce-4c08-b24c-f21720f3e342	12	-	-	404.27
13	397facce-d6ce-4c08-b24c-f21720f3e342	13	-	-	404.27
14	397facce-d6ce-4c08-b24c-f21720f3e342	14	-	-	404.27
15	397facce-d6ce-4c08-b24c-f21720f3e342	15	-	-	404.27
16	397facce-d6ce-4c08-b24c-f21720f3e342	16	-	-	404.27
17	6db2f781-deb3-427d-a57a-4a0d0486a24d	1	NaN	1920.46	NaN
18	6db2f781-deb3-427d-a57a-4a0d0486a24d	2	NaN	1920.46	NaN
19	6db2f781-deb3-427d-a57a-4a0d0486a24d	3	NaN	1920.46	NaN
20	6db2f781-deb3-427d-a57a-4a0d0486a24d	4	4677.84	1920.46	2602.33
21	6db2f781-deb3-427d-a57a-4a0d0486a24d	5	3941.63	1920.46	2602.33
22	6db2f781-deb3-427d-a57a-4a0d0486a24d	6	3941.63	1920.46	2602.33
23	6db2f781-deb3-427d-a57a-4a0d0486a24d	7	3007.25	1920.46	2602.33
24	6db2f781-deb3-427d-a57a-4a0d0486a24d	8	2897.42	1920.46	2602.33
25	6db2f781-deb3-427d-a57a-4a0d0486a24d	9	1256.91	1920.46	2602.33
26	6db2f781-deb3-427d-a57a-4a0d0486a24d	10	1256.91	1920.46	2602.33
27	6db2f781-deb3-427d-a57a-4a0d0486a24d	11	-	-	2602.33
28	6db2f781-deb3-427d-a57a-4a0d0486a24d	12	-	-	2602.33
29	6db2f781-deb3-427d-a57a-4a0d0486a24d	13	-	-	2602.33
30	6db2f781-deb3-427d-a57a-4a0d0486a24d	14	-	-	2602.33
31	6db2f781-deb3-427d-a57a-4a0d0486a24d	15	-	-	2602.33
32	6db2f781-deb3-427d-a57a-4a0d0486a24d	16	-	-	2602.33
33	6db2f781-deb3-427d-a57a-4a0d0486a24d	17	-	-	2602.33
34	b93daf9f-d69c-4d66-b28d-0a42a6004602	1	3826.93	3803.27	3236.81
35	b93daf9f-d69c-4d66-b28d-0a42a6004602	2	738.17	3803.27	921.29
36	b93daf9f-d69c-4d66-b28d-0a42a6004602	3	738.17	3803.27	921.29
37	b93daf9f-d69c-4d66-b28d-0a42a6004602	4	496.03	3803.27	921.29
38	b93daf9f-d69c-4d66-b28d-0a42a6004602	5	496.03	434.80	921.29
39	b93daf9f-d69c-4d66-b28d-0a42a6004602	6	496.03	434.80	921.29
40	b93daf9f-d69c-4d66-b28d-0a42a6004602	7	496.03	434.80	921.29
41	b93daf9f-d69c-4d66-b28d-0a42a6004602	8	496.03	434.80	921.29
42	b93daf9f-d69c-4d66-b28d-0a42a6004602	9	496.03	434.80	921.29
43	b93daf9f-d69c-4d66-b28d-0a42a6004602	10	496.03	434.80	921.29
44	b93daf9f-d69c-4d66-b28d-0a42a6004602	11	-	-	921.29
45	b93daf9f-d69c-4d66-b28d-0a42a6004602	12	-	-	921.29
46	b93daf9f-d69c-4d66-b28d-0a42a6004602	13	-	-	921.29
47	b93daf9f-d69c-4d66-b28d-0a42a6004602	14	-	-	921.29
48	b93daf9f-d69c-4d66-b28d-0a42a6004602	15	-	-	921.29
49	b93daf9f-d69c-4d66-b28d-0a42a6004602	16	-	-	921.29
50	b93daf9f-d69c-4d66-b28d-0a42a6004602	17	-	-	921.29
51	1b01b184-821f-4e5e-ad04-f3f9af0f254d	1	NaN	NaN	1670.63
52	1b01b184-821f-4e5e-ad04-f3f9af0f254d	2	2734.24	8927.10	1670.63
53	1b01b184-821f-4e5e-ad04-f3f9af0f254d	3	2734.24	1508.70	1670.63

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
54	1b01b184-821f-4e5e-ad04-f3f9af0f254d	4	1320.40	1508.70	1670.63
55	1b01b184-821f-4e5e-ad04-f3f9af0f254d	5	1320.40	1508.70	1670.63
56	1b01b184-821f-4e5e-ad04-f3f9af0f254d	6	1320.40	1508.70	1670.63
57	1b01b184-821f-4e5e-ad04-f3f9af0f254d	7	1320.40	1508.70	1670.63
58	1b01b184-821f-4e5e-ad04-f3f9af0f254d	8	1320.40	1508.70	1670.63
59	1b01b184-821f-4e5e-ad04-f3f9af0f254d	9	1320.40	1508.70	1670.63
60	1b01b184-821f-4e5e-ad04-f3f9af0f254d	10	1320.40	1508.70	1670.63
61	1b01b184-821f-4e5e-ad04-f3f9af0f254d	11	-	-	1670.63
62	1b01b184-821f-4e5e-ad04-f3f9af0f254d	12	-	-	1670.63
63	1b01b184-821f-4e5e-ad04-f3f9af0f254d	13	-	-	1670.63
64	1b01b184-821f-4e5e-ad04-f3f9af0f254d	14	-	-	1255.35
65	1b01b184-821f-4e5e-ad04-f3f9af0f254d	15	-	-	1255.35
66	1b01b184-821f-4e5e-ad04-f3f9af0f254d	16	-	-	1255.35
67	d9a57590-bf00-4ed7-845e-073413fc0ab8	1	1241.48	2210.18	NaN
68	d9a57590-bf00-4ed7-845e-073413fc0ab8	2	1241.48	2210.18	6587.77
69	d9a57590-bf00-4ed7-845e-073413fc0ab8	3	1241.48	2210.18	6587.77
70	d9a57590-bf00-4ed7-845e-073413fc0ab8	4	1241.48	2210.18	3866.12
71	d9a57590-bf00-4ed7-845e-073413fc0ab8	5	1241.48	2210.18	3866.12
72	d9a57590-bf00-4ed7-845e-073413fc0ab8	6	1241.48	2210.18	3866.12
73	d9a57590-bf00-4ed7-845e-073413fc0ab8	7	1241.48	2210.18	1284.09
74	d9a57590-bf00-4ed7-845e-073413fc0ab8	8	1241.48	2210.18	1284.09
75	d9a57590-bf00-4ed7-845e-073413fc0ab8	9	1241.48	2210.18	1284.09
76	d9a57590-bf00-4ed7-845e-073413fc0ab8	10	1241.48	2210.18	1284.09
77	d9a57590-bf00-4ed7-845e-073413fc0ab8	11	-	-	1284.09
78	d9a57590-bf00-4ed7-845e-073413fc0ab8	12	-	-	1284.09
79	d9a57590-bf00-4ed7-845e-073413fc0ab8	13	-	-	1284.09
80	d9a57590-bf00-4ed7-845e-073413fc0ab8	14	-	-	1284.09
81	d9a57590-bf00-4ed7-845e-073413fc0ab8	15	-	-	1284.09
82	d9a57590-bf00-4ed7-845e-073413fc0ab8	16	-	-	1284.09
83	d9a57590-bf00-4ed7-845e-073413fc0ab8	17	-	-	1284.09
84	c43219c2-0183-4353-8341-a81a297645dc	1	NaN	NaN	NaN
85	c43219c2-0183-4353-8341-a81a297645dc	2	5018.43	NaN	NaN
86	c43219c2-0183-4353-8341-a81a297645dc	3	5018.43	NaN	NaN
87	c43219c2-0183-4353-8341-a81a297645dc	4	5018.43	NaN	4242.31
88	c43219c2-0183-4353-8341-a81a297645dc	5	2022.32	404.27	4242.31
89	c43219c2-0183-4353-8341-a81a297645dc	6	2022.32	404.27	4242.31
90	c43219c2-0183-4353-8341-a81a297645dc	7	741.75	404.27	4242.31
91	c43219c2-0183-4353-8341-a81a297645dc	8	741.75	404.27	4242.31
92	c43219c2-0183-4353-8341-a81a297645dc	9	741.75	404.27	4242.31
93	c43219c2-0183-4353-8341-a81a297645dc	10	741.75	404.27	4242.31
94	c43219c2-0183-4353-8341-a81a297645dc	11	-	-	4242.31
95	c43219c2-0183-4353-8341-a81a297645dc	12	-	-	1639.01
96	c43219c2-0183-4353-8341-a81a297645dc	13	-	-	1639.01
97	c43219c2-0183-4353-8341-a81a297645dc	14	-	-	1589.94
98	c43219c2-0183-4353-8341-a81a297645dc	15	-	-	1589.94
99	c43219c2-0183-4353-8341-a81a297645dc	16	-	-	1589.94
100	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	1	1253.22	2595.28	NaN
101	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	2	1253.22	2595.28	NaN
102	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	3	1253.22	2595.28	4938.60
103	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	4	1253.22	2595.28	4938.60

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
104	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	5	1253.22	2064.81	4938.60
105	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	6	1253.22	929.69	4938.60
106	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	7	1253.22	929.69	3710.18
107	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	8	1253.22	929.69	3710.18
108	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	9	1253.22	929.69	3710.18
109	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	10	1253.22	929.69	3710.18
110	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	11	-	-	3710.18
111	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	12	-	-	3710.18
112	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	13	-	-	3710.18
113	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	14	-	-	3710.18
114	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	15	-	-	1404.34
115	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	16	-	-	1404.34
116	7bbfcfb2-5dae-4922-90ef-3a611c3c1d63	17	-	-	1404.34
117	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	1	3234.11	NaN	3123.45
118	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	2	3234.11	2788.07	3123.45
119	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	3	3234.11	2788.07	3123.45
120	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	4	3234.11	710.81	3123.45
121	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	5	3052.57	710.81	3123.45
122	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	6	3052.57	710.81	3123.45
123	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	7	3052.57	710.81	3123.45
124	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	8	3052.57	710.81	3123.45
125	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	9	404.27	710.81	3123.45
126	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	10	404.27	710.81	1198.50
127	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	11	-	-	1198.50
128	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	12	-	-	1198.50
129	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	13	-	-	1198.50
130	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	14	-	-	1198.50
131	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	15	-	-	1198.50
132	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	16	-	-	404.27
133	a3159e80-9ae2-46ea-87ad-a53d8ba6920e	17	-	-	404.27
134	9cf3fa76-67a4-4b1f-95ed-1078105b106d	1	1404.35	NaN	1483.89
135	9cf3fa76-67a4-4b1f-95ed-1078105b106d	2	1404.35	NaN	710.82
136	9cf3fa76-67a4-4b1f-95ed-1078105b106d	3	1404.35	5850.95	710.82
137	9cf3fa76-67a4-4b1f-95ed-1078105b106d	4	1404.35	5850.95	710.82
138	9cf3fa76-67a4-4b1f-95ed-1078105b106d	5	1404.35	5850.95	710.82
139	9cf3fa76-67a4-4b1f-95ed-1078105b106d	6	1404.35	5850.95	710.82
140	9cf3fa76-67a4-4b1f-95ed-1078105b106d	7	1404.35	5850.95	710.82
141	9cf3fa76-67a4-4b1f-95ed-1078105b106d	8	1404.35	802.58	710.82
142	9cf3fa76-67a4-4b1f-95ed-1078105b106d	9	1404.35	802.58	710.82
143	9cf3fa76-67a4-4b1f-95ed-1078105b106d	10	806.16	802.58	710.82
144	9cf3fa76-67a4-4b1f-95ed-1078105b106d	11	-	-	710.82
145	9cf3fa76-67a4-4b1f-95ed-1078105b106d	12	-	-	710.82
146	9cf3fa76-67a4-4b1f-95ed-1078105b106d	13	-	-	710.82
147	9cf3fa76-67a4-4b1f-95ed-1078105b106d	14	-	-	710.82
148	9cf3fa76-67a4-4b1f-95ed-1078105b106d	15	-	-	710.82
149	9cf3fa76-67a4-4b1f-95ed-1078105b106d	16	-	-	710.82
150	80e74062-af8e-47d9-83b6-1b5dbf979170	1	5543.75	NaN	1892.23
151	80e74062-af8e-47d9-83b6-1b5dbf979170	2	5543.75	NaN	1892.23
152	80e74062-af8e-47d9-83b6-1b5dbf979170	3	2591.89	NaN	1892.23
153	80e74062-af8e-47d9-83b6-1b5dbf979170	4	2591.89	713.99	1892.23

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
154	80e74062-af8e-47d9-83b6-1b5dbf979170	5	2591.89	713.99	1892.23
155	80e74062-af8e-47d9-83b6-1b5dbf979170	6	431.62	713.99	1670.63
156	80e74062-af8e-47d9-83b6-1b5dbf979170	7	431.62	713.99	1670.63
157	80e74062-af8e-47d9-83b6-1b5dbf979170	8	431.62	713.99	1670.63
158	80e74062-af8e-47d9-83b6-1b5dbf979170	9	431.62	713.99	1670.63
159	80e74062-af8e-47d9-83b6-1b5dbf979170	10	431.62	713.99	1670.63
160	80e74062-af8e-47d9-83b6-1b5dbf979170	11	-	-	1670.63
161	80e74062-af8e-47d9-83b6-1b5dbf979170	12	-	-	1670.63
162	80e74062-af8e-47d9-83b6-1b5dbf979170	13	-	-	1670.63
163	80e74062-af8e-47d9-83b6-1b5dbf979170	14	-	-	1670.63
164	80e74062-af8e-47d9-83b6-1b5dbf979170	15	-	-	1670.63
165	80e74062-af8e-47d9-83b6-1b5dbf979170	16	-	-	1670.63
166	fb36bc3c-dc0f-4e40-8edd-6fc433937624	1	NaN	NaN	NaN
167	fb36bc3c-dc0f-4e40-8edd-6fc433937624	2	1966.58	NaN	NaN
168	fb36bc3c-dc0f-4e40-8edd-6fc433937624	3	1966.58	6110.01	NaN
169	fb36bc3c-dc0f-4e40-8edd-6fc433937624	4	1966.58	6110.01	NaN
170	fb36bc3c-dc0f-4e40-8edd-6fc433937624	5	1966.58	6110.01	2221.04
171	fb36bc3c-dc0f-4e40-8edd-6fc433937624	6	1966.58	1255.35	2221.04
172	fb36bc3c-dc0f-4e40-8edd-6fc433937624	7	1966.58	1255.35	2221.04
173	fb36bc3c-dc0f-4e40-8edd-6fc433937624	8	1966.58	1255.35	1611.48
174	fb36bc3c-dc0f-4e40-8edd-6fc433937624	9	1966.58	1255.35	1611.48
175	fb36bc3c-dc0f-4e40-8edd-6fc433937624	10	1966.58	1255.35	1611.48
176	fb36bc3c-dc0f-4e40-8edd-6fc433937624	11	-	-	1611.48
177	fb36bc3c-dc0f-4e40-8edd-6fc433937624	12	-	-	1611.48
178	fb36bc3c-dc0f-4e40-8edd-6fc433937624	13	-	-	1611.48
179	fb36bc3c-dc0f-4e40-8edd-6fc433937624	14	-	-	1611.48
180	fb36bc3c-dc0f-4e40-8edd-6fc433937624	15	-	-	1611.48
181	fb36bc3c-dc0f-4e40-8edd-6fc433937624	16	-	-	1611.48
182	fb36bc3c-dc0f-4e40-8edd-6fc433937624	17	-	-	1611.48
183	951f1941-a6bc-4375-9118-5ead019985f6	1	404.27	9676.97	3007.22
184	951f1941-a6bc-4375-9118-5ead019985f6	2	404.27	6418.08	3007.22
185	951f1941-a6bc-4375-9118-5ead019985f6	3	404.27	1258.52	3007.22
186	951f1941-a6bc-4375-9118-5ead019985f6	4	404.27	1258.52	3007.22
187	951f1941-a6bc-4375-9118-5ead019985f6	5	404.27	1258.52	3007.22
188	951f1941-a6bc-4375-9118-5ead019985f6	6	404.27	1258.52	3007.22
189	951f1941-a6bc-4375-9118-5ead019985f6	7	404.27	1258.52	3007.22
190	951f1941-a6bc-4375-9118-5ead019985f6	8	404.27	1258.52	3007.22
191	951f1941-a6bc-4375-9118-5ead019985f6	9	404.27	1246.01	3007.22
192	951f1941-a6bc-4375-9118-5ead019985f6	10	404.27	1246.01	3007.22
193	951f1941-a6bc-4375-9118-5ead019985f6	11	-	-	3007.22
194	951f1941-a6bc-4375-9118-5ead019985f6	12	-	-	3007.22
195	951f1941-a6bc-4375-9118-5ead019985f6	13	-	-	3007.22
196	951f1941-a6bc-4375-9118-5ead019985f6	14	-	-	3007.22
197	951f1941-a6bc-4375-9118-5ead019985f6	15	-	-	1832.28
198	951f1941-a6bc-4375-9118-5ead019985f6	16	-	-	1832.28
199	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	1	NaN	1054.78	NaN
200	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	2	3083.40	1054.78	NaN
201	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	3	2473.38	1054.78	4824.42
202	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	4	2473.38	1054.78	3048.10
203	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	5	404.27	1054.78	3048.10

(continue)



**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
204	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	6	404.27	1054.78	3048.10
205	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	7	404.27	1054.78	3048.10
206	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	8	404.27	1054.78	3048.10
207	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	9	404.27	1054.78	3048.10
208	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	10	404.27	1054.78	3048.10
209	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	11	-	-	3048.10
210	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	12	-	-	3048.10
211	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	13	-	-	3048.10
212	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	14	-	-	3048.10
213	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	15	-	-	3048.10
214	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	16	-	-	3048.10
215	8e5fe7a6-dddb-4b35-9e64-40af4d49af99	17	-	-	3048.10
216	02c45751-b25f-4daa-8d5d-4a7242ee6b35	1	NaN	NaN	NaN
217	02c45751-b25f-4daa-8d5d-4a7242ee6b35	2	4091.37	3515.71	NaN
218	02c45751-b25f-4daa-8d5d-4a7242ee6b35	3	4091.37	3515.71	3385.81
219	02c45751-b25f-4daa-8d5d-4a7242ee6b35	4	4091.37	3515.71	1201.68
220	02c45751-b25f-4daa-8d5d-4a7242ee6b35	5	1027.43	3515.71	1201.68
221	02c45751-b25f-4daa-8d5d-4a7242ee6b35	6	1027.43	3037.01	1201.68
222	02c45751-b25f-4daa-8d5d-4a7242ee6b35	7	1027.43	3037.01	1201.68
223	02c45751-b25f-4daa-8d5d-4a7242ee6b35	8	1027.43	3037.01	1201.68
224	02c45751-b25f-4daa-8d5d-4a7242ee6b35	9	1027.43	3037.01	1201.68
225	02c45751-b25f-4daa-8d5d-4a7242ee6b35	10	1027.43	3037.01	1201.68
226	02c45751-b25f-4daa-8d5d-4a7242ee6b35	11	-	-	1201.68
227	02c45751-b25f-4daa-8d5d-4a7242ee6b35	12	-	-	1201.68
228	02c45751-b25f-4daa-8d5d-4a7242ee6b35	13	-	-	1201.68
229	02c45751-b25f-4daa-8d5d-4a7242ee6b35	14	-	-	1201.68
230	02c45751-b25f-4daa-8d5d-4a7242ee6b35	15	-	-	1201.68
231	02c45751-b25f-4daa-8d5d-4a7242ee6b35	16	-	-	1198.50
232	02c45751-b25f-4daa-8d5d-4a7242ee6b35	17	-	-	1198.50
233	9def2a84-67d6-496f-a1c5-b5097ecf3a78	1	1230.95	431.62	3734.72
234	9def2a84-67d6-496f-a1c5-b5097ecf3a78	2	1230.95	431.62	3734.72
235	9def2a84-67d6-496f-a1c5-b5097ecf3a78	3	1230.95	431.62	3734.72
236	9def2a84-67d6-496f-a1c5-b5097ecf3a78	4	1230.95	431.62	3734.72
237	9def2a84-67d6-496f-a1c5-b5097ecf3a78	5	1230.95	431.62	3734.72
238	9def2a84-67d6-496f-a1c5-b5097ecf3a78	6	1230.95	431.62	3734.72
239	9def2a84-67d6-496f-a1c5-b5097ecf3a78	7	1230.95	431.62	3734.72
240	9def2a84-67d6-496f-a1c5-b5097ecf3a78	8	710.82	431.62	3734.72
241	9def2a84-67d6-496f-a1c5-b5097ecf3a78	9	710.82	431.62	3734.72
242	9def2a84-67d6-496f-a1c5-b5097ecf3a78	10	710.82	431.62	3734.72
243	9def2a84-67d6-496f-a1c5-b5097ecf3a78	11	-	-	2761.00
244	9def2a84-67d6-496f-a1c5-b5097ecf3a78	12	-	-	2761.00
245	9def2a84-67d6-496f-a1c5-b5097ecf3a78	13	-	-	2761.00
246	9def2a84-67d6-496f-a1c5-b5097ecf3a78	14	-	-	2761.00
247	9def2a84-67d6-496f-a1c5-b5097ecf3a78	15	-	-	2761.00
248	9def2a84-67d6-496f-a1c5-b5097ecf3a78	16	-	-	2761.00
249	9def2a84-67d6-496f-a1c5-b5097ecf3a78	17	-	-	2761.00
250	92039b6b-ee5f-4a36-889e-3d7daa03b72c	1	3912.86	1964.60	7722.17
251	92039b6b-ee5f-4a36-889e-3d7daa03b72c	2	828.97	1964.60	7722.17
252	92039b6b-ee5f-4a36-889e-3d7daa03b72c	3	828.97	1964.60	404.27
253	92039b6b-ee5f-4a36-889e-3d7daa03b72c	4	828.97	1964.60	404.27

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
254	92039b6b-ee5f-4a36-889e-3d7daa03b72c	5	828.97	1964.60	404.27
255	92039b6b-ee5f-4a36-889e-3d7daa03b72c	6	828.97	1964.60	404.27
256	92039b6b-ee5f-4a36-889e-3d7daa03b72c	7	828.97	1964.60	404.27
257	92039b6b-ee5f-4a36-889e-3d7daa03b72c	8	828.97	1597.29	404.27
258	92039b6b-ee5f-4a36-889e-3d7daa03b72c	9	828.97	1597.29	404.27
259	92039b6b-ee5f-4a36-889e-3d7daa03b72c	10	828.97	1597.29	404.27
260	92039b6b-ee5f-4a36-889e-3d7daa03b72c	11	-	-	404.27
261	92039b6b-ee5f-4a36-889e-3d7daa03b72c	12	-	-	404.27
262	92039b6b-ee5f-4a36-889e-3d7daa03b72c	13	-	-	404.27
263	92039b6b-ee5f-4a36-889e-3d7daa03b72c	14	-	-	404.27
264	92039b6b-ee5f-4a36-889e-3d7daa03b72c	15	-	-	404.27
265	92039b6b-ee5f-4a36-889e-3d7daa03b72c	16	-	-	404.27
266	92039b6b-ee5f-4a36-889e-3d7daa03b72c	17	-	-	404.27
267	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	1	NaN	1418.74	NaN
268	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	2	5404.26	1418.74	1255.35
269	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	3	5404.26	1418.74	1255.35
270	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	4	1567.08	1418.74	1255.35
271	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	5	404.27	434.80	1255.35
272	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	6	404.27	434.80	1255.35
273	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	7	404.27	434.80	1255.35
274	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	8	404.27	434.80	1255.35
275	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	9	404.27	434.80	1255.35
276	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	10	404.27	434.80	1255.35
277	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	11	-	-	1255.35
278	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	12	-	-	1255.35
279	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	13	-	-	1255.35
280	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	14	-	-	1255.35
281	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	15	-	-	1255.35
282	4aae428a-e7d0-4c5d-ad26-ca7f6d667cf9	16	-	-	1255.35
283	219c0129-b856-4779-854b-de2be1099adf	1	NaN	NaN	10612.08
284	219c0129-b856-4779-854b-de2be1099adf	2	2323.70	NaN	10612.08
285	219c0129-b856-4779-854b-de2be1099adf	3	1159.67	3091.63	10612.08
286	219c0129-b856-4779-854b-de2be1099adf	4	434.79	3091.63	10612.08
287	219c0129-b856-4779-854b-de2be1099adf	5	434.79	3091.63	10612.08
288	219c0129-b856-4779-854b-de2be1099adf	6	434.79	3091.63	10612.08
289	219c0129-b856-4779-854b-de2be1099adf	7	434.79	3091.63	10612.08
290	219c0129-b856-4779-854b-de2be1099adf	8	434.79	3091.63	3549.94
291	219c0129-b856-4779-854b-de2be1099adf	9	434.79	3091.63	3549.94
292	219c0129-b856-4779-854b-de2be1099adf	10	434.79	3091.63	3165.78
293	219c0129-b856-4779-854b-de2be1099adf	11	-	-	3165.78
294	219c0129-b856-4779-854b-de2be1099adf	12	-	-	2557.66
295	219c0129-b856-4779-854b-de2be1099adf	13	-	-	2557.66
296	219c0129-b856-4779-854b-de2be1099adf	14	-	-	2557.66
297	219c0129-b856-4779-854b-de2be1099adf	15	-	-	2557.66
298	219c0129-b856-4779-854b-de2be1099adf	16	-	-	2557.66
299	219c0129-b856-4779-854b-de2be1099adf	17	-	-	2557.66
300	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	1	NaN	NaN	2437.01
301	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	2	7306.49	NaN	2437.01
302	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	3	7306.49	NaN	1999.10
303	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	4	2758.29	NaN	1999.10

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
304	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	5	2758.29	NaN	1999.10
305	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	6	2063.79	4727.06	1999.10
306	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	7	2063.79	4727.06	1999.10
307	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	8	2063.79	3441.75	1999.10
308	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	9	2063.79	3441.75	1999.10
309	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	10	2063.79	3441.75	1999.10
310	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	11	-	-	1999.10
311	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	12	-	-	1148.80
312	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	13	-	-	1148.80
313	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	14	-	-	1148.80
314	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	15	-	-	1148.80
315	0acd3ce1-b6d2-4ea1-8c20-d0c6e51d740d	16	-	-	1148.80
316	4acbb35c-3944-4017-ab54-93e8c77c963e	1	NaN	NaN	NaN
317	4acbb35c-3944-4017-ab54-93e8c77c963e	2	NaN	NaN	NaN
318	4acbb35c-3944-4017-ab54-93e8c77c963e	3	NaN	NaN	NaN
319	4acbb35c-3944-4017-ab54-93e8c77c963e	4	1198.50	NaN	2352.98
320	4acbb35c-3944-4017-ab54-93e8c77c963e	5	1198.50	NaN	2352.98
321	4acbb35c-3944-4017-ab54-93e8c77c963e	6	1198.50	NaN	828.96
322	4acbb35c-3944-4017-ab54-93e8c77c963e	7	1027.89	NaN	828.96
323	4acbb35c-3944-4017-ab54-93e8c77c963e	8	1027.89	828.96	828.96
324	4acbb35c-3944-4017-ab54-93e8c77c963e	9	1027.89	434.80	828.96
325	4acbb35c-3944-4017-ab54-93e8c77c963e	10	1027.89	434.80	828.96
326	4acbb35c-3944-4017-ab54-93e8c77c963e	11	-	-	828.96
327	4acbb35c-3944-4017-ab54-93e8c77c963e	12	-	-	828.96
328	4acbb35c-3944-4017-ab54-93e8c77c963e	13	-	-	828.96
329	4acbb35c-3944-4017-ab54-93e8c77c963e	14	-	-	828.96
330	4acbb35c-3944-4017-ab54-93e8c77c963e	15	-	-	828.96
331	4acbb35c-3944-4017-ab54-93e8c77c963e	16	-	-	828.96
332	d771ba91-8eab-43a1-af3c-b611b4651d32	1	1030.61	NaN	7148.55
333	d771ba91-8eab-43a1-af3c-b611b4651d32	2	1030.61	NaN	7148.55
334	d771ba91-8eab-43a1-af3c-b611b4651d32	3	404.27	NaN	7148.55
335	d771ba91-8eab-43a1-af3c-b611b4651d32	4	404.27	NaN	7148.55
336	d771ba91-8eab-43a1-af3c-b611b4651d32	5	404.27	NaN	7148.55
337	d771ba91-8eab-43a1-af3c-b611b4651d32	6	404.27	NaN	1198.50
338	d771ba91-8eab-43a1-af3c-b611b4651d32	7	404.27	NaN	1198.50
339	d771ba91-8eab-43a1-af3c-b611b4651d32	8	404.27	NaN	1198.50
340	d771ba91-8eab-43a1-af3c-b611b4651d32	9	404.27	11899.42	1198.50
341	d771ba91-8eab-43a1-af3c-b611b4651d32	10	404.27	1253.21	1198.50
342	d771ba91-8eab-43a1-af3c-b611b4651d32	11	-	-	1198.50
343	d771ba91-8eab-43a1-af3c-b611b4651d32	12	-	-	431.62
344	d771ba91-8eab-43a1-af3c-b611b4651d32	13	-	-	431.62
345	d771ba91-8eab-43a1-af3c-b611b4651d32	14	-	-	431.62
346	d771ba91-8eab-43a1-af3c-b611b4651d32	15	-	-	431.62
347	d771ba91-8eab-43a1-af3c-b611b4651d32	16	-	-	431.62
348	d771ba91-8eab-43a1-af3c-b611b4651d32	17	-	-	431.62
349	e611b071-1145-4930-af78-2a02b4729910	1	1984.09	7566.54	NaN
350	e611b071-1145-4930-af78-2a02b4729910	2	1984.09	7566.54	7378.42
351	e611b071-1145-4930-af78-2a02b4729910	3	1984.09	7566.54	7175.44
352	e611b071-1145-4930-af78-2a02b4729910	4	1984.09	6103.34	1551.68
353	e611b071-1145-4930-af78-2a02b4729910	5	1984.09	2515.21	1551.68

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
354	e611b071-1145-4930-af78-2a02b4729910	6	1984.09	2515.21	1551.68
355	e611b071-1145-4930-af78-2a02b4729910	7	1984.09	2515.21	1551.68
356	e611b071-1145-4930-af78-2a02b4729910	8	1984.09	2515.21	1551.68
357	e611b071-1145-4930-af78-2a02b4729910	9	714.40	2515.21	1551.68
358	e611b071-1145-4930-af78-2a02b4729910	10	714.40	2515.21	1551.68
359	e611b071-1145-4930-af78-2a02b4729910	11	-	-	1551.68
360	e611b071-1145-4930-af78-2a02b4729910	12	-	-	1551.68
361	e611b071-1145-4930-af78-2a02b4729910	13	-	-	1551.68
362	e611b071-1145-4930-af78-2a02b4729910	14	-	-	1551.68
363	e611b071-1145-4930-af78-2a02b4729910	15	-	-	1551.68
364	e611b071-1145-4930-af78-2a02b4729910	16	-	-	1551.68
365	e611b071-1145-4930-af78-2a02b4729910	17	-	-	1551.68
366	8d999873-5f73-43fd-91fd-c0c72e51fa42	1	NaN	5706.81	1501.37
367	8d999873-5f73-43fd-91fd-c0c72e51fa42	2	5473.69	5706.81	1501.37
368	8d999873-5f73-43fd-91fd-c0c72e51fa42	3	5473.69	5706.81	1501.37
369	8d999873-5f73-43fd-91fd-c0c72e51fa42	4	5473.69	5706.81	1501.37
370	8d999873-5f73-43fd-91fd-c0c72e51fa42	5	5473.69	5706.81	1501.37
371	8d999873-5f73-43fd-91fd-c0c72e51fa42	6	5473.69	5706.81	1501.37
372	8d999873-5f73-43fd-91fd-c0c72e51fa42	7	5473.69	5706.81	1501.37
373	8d999873-5f73-43fd-91fd-c0c72e51fa42	8	1610.27	5706.81	1501.37
374	8d999873-5f73-43fd-91fd-c0c72e51fa42	9	1159.67	5016.25	1055.23
375	8d999873-5f73-43fd-91fd-c0c72e51fa42	10	1159.67	5016.25	1055.23
376	8d999873-5f73-43fd-91fd-c0c72e51fa42	11	-	-	1055.23
377	8d999873-5f73-43fd-91fd-c0c72e51fa42	12	-	-	1055.23
378	8d999873-5f73-43fd-91fd-c0c72e51fa42	13	-	-	1027.89
379	8d999873-5f73-43fd-91fd-c0c72e51fa42	14	-	-	1027.89
380	bb2542ef-9cb5-4e68-ad34-07f0c882332e	1	1198.50	NaN	NaN
381	bb2542ef-9cb5-4e68-ad34-07f0c882332e	2	1198.50	NaN	NaN
382	bb2542ef-9cb5-4e68-ad34-07f0c882332e	3	834.22	11252.80	NaN
383	bb2542ef-9cb5-4e68-ad34-07f0c882332e	4	834.22	2605.52	NaN
384	bb2542ef-9cb5-4e68-ad34-07f0c882332e	5	834.22	2605.52	NaN
385	bb2542ef-9cb5-4e68-ad34-07f0c882332e	6	834.22	2605.52	NaN
386	bb2542ef-9cb5-4e68-ad34-07f0c882332e	7	834.22	2605.52	7967.48
387	bb2542ef-9cb5-4e68-ad34-07f0c882332e	8	834.22	2605.52	3178.39
388	bb2542ef-9cb5-4e68-ad34-07f0c882332e	9	834.22	2605.52	3178.39
389	bb2542ef-9cb5-4e68-ad34-07f0c882332e	10	738.17	2605.52	3178.39
390	bb2542ef-9cb5-4e68-ad34-07f0c882332e	11	-	-	3178.39
391	bb2542ef-9cb5-4e68-ad34-07f0c882332e	12	-	-	3178.39
392	bb2542ef-9cb5-4e68-ad34-07f0c882332e	13	-	-	3178.39
393	bb2542ef-9cb5-4e68-ad34-07f0c882332e	14	-	-	3178.39
394	bb2542ef-9cb5-4e68-ad34-07f0c882332e	15	-	-	3178.39
395	bb2542ef-9cb5-4e68-ad34-07f0c882332e	16	-	-	2522.74
396	bb2542ef-9cb5-4e68-ad34-07f0c882332e	17	-	-	2522.74
397	264a8d64-f97e-4425-b859-f21ab7b4aa1f	1	496.03	NaN	4349.93
398	264a8d64-f97e-4425-b859-f21ab7b4aa1f	2	496.03	1691.77	4349.93
399	264a8d64-f97e-4425-b859-f21ab7b4aa1f	3	496.03	1691.77	4349.93
400	264a8d64-f97e-4425-b859-f21ab7b4aa1f	4	496.03	1691.77	4349.93
401	264a8d64-f97e-4425-b859-f21ab7b4aa1f	5	496.03	1691.77	4349.93
402	264a8d64-f97e-4425-b859-f21ab7b4aa1f	6	496.03	921.29	4349.93
403	264a8d64-f97e-4425-b859-f21ab7b4aa1f	7	496.03	921.29	4349.93

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
404	264a8d64-f97e-4425-b859-f21ab7b4aa1f	8	496.03	921.29	4349.93
405	264a8d64-f97e-4425-b859-f21ab7b4aa1f	9	496.03	921.29	4349.93
406	264a8d64-f97e-4425-b859-f21ab7b4aa1f	10	496.03	921.29	4349.93
407	264a8d64-f97e-4425-b859-f21ab7b4aa1f	11	-	-	4349.93
408	264a8d64-f97e-4425-b859-f21ab7b4aa1f	12	-	-	4349.93
409	264a8d64-f97e-4425-b859-f21ab7b4aa1f	13	-	-	4349.93
410	264a8d64-f97e-4425-b859-f21ab7b4aa1f	14	-	-	4349.93
411	264a8d64-f97e-4425-b859-f21ab7b4aa1f	15	-	-	4349.93
412	264a8d64-f97e-4425-b859-f21ab7b4aa1f	16	-	-	4349.93
413	264a8d64-f97e-4425-b859-f21ab7b4aa1f	17	-	-	4349.93
414	d132a6e7-6ef3-4c05-b391-d48682ad097d	1	NaN	2216.74	NaN
415	d132a6e7-6ef3-4c05-b391-d48682ad097d	2	4654.82	2216.74	NaN
416	d132a6e7-6ef3-4c05-b391-d48682ad097d	3	1993.59	2216.74	2022.32
417	d132a6e7-6ef3-4c05-b391-d48682ad097d	4	1201.68	2216.74	2022.32
418	d132a6e7-6ef3-4c05-b391-d48682ad097d	5	1201.68	2216.74	2022.32
419	d132a6e7-6ef3-4c05-b391-d48682ad097d	6	1201.68	2216.74	2022.32
420	d132a6e7-6ef3-4c05-b391-d48682ad097d	7	1201.68	2216.74	2022.32
421	d132a6e7-6ef3-4c05-b391-d48682ad097d	8	1201.68	2216.74	2022.32
422	d132a6e7-6ef3-4c05-b391-d48682ad097d	9	1201.68	2216.74	2022.32
423	d132a6e7-6ef3-4c05-b391-d48682ad097d	10	1201.68	2216.74	2022.32
424	d132a6e7-6ef3-4c05-b391-d48682ad097d	11	-	-	2022.32
425	d132a6e7-6ef3-4c05-b391-d48682ad097d	12	-	-	2022.32
426	d132a6e7-6ef3-4c05-b391-d48682ad097d	13	-	-	2022.32
427	d132a6e7-6ef3-4c05-b391-d48682ad097d	14	-	-	2022.32
428	d132a6e7-6ef3-4c05-b391-d48682ad097d	15	-	-	2022.32
429	d132a6e7-6ef3-4c05-b391-d48682ad097d	16	-	-	2022.32
430	d132a6e7-6ef3-4c05-b391-d48682ad097d	17	-	-	2022.32
431	d132a6e7-6ef3-4c05-b391-d48682ad097d	18	-	-	2022.32
432	d132a6e7-6ef3-4c05-b391-d48682ad097d	19	-	-	2022.32
433	89aced1e-1782-4d95-b641-3ce725dfc5b5	1	3048.63	NaN	3048.08
434	89aced1e-1782-4d95-b641-3ce725dfc5b5	2	3048.63	4234.31	3048.08
435	89aced1e-1782-4d95-b641-3ce725dfc5b5	3	3048.63	1320.40	3048.08
436	89aced1e-1782-4d95-b641-3ce725dfc5b5	4	3048.63	1320.40	3048.08
437	89aced1e-1782-4d95-b641-3ce725dfc5b5	5	3048.63	1320.40	3048.08
438	89aced1e-1782-4d95-b641-3ce725dfc5b5	6	3048.63	1320.40	3048.08
439	89aced1e-1782-4d95-b641-3ce725dfc5b5	7	3048.63	1198.50	3048.08
440	89aced1e-1782-4d95-b641-3ce725dfc5b5	8	3048.63	1198.50	3048.08
441	89aced1e-1782-4d95-b641-3ce725dfc5b5	9	3048.63	1198.50	2912.07
442	89aced1e-1782-4d95-b641-3ce725dfc5b5	10	3048.63	1198.50	2912.07
443	89aced1e-1782-4d95-b641-3ce725dfc5b5	11	-	-	2912.07
444	89aced1e-1782-4d95-b641-3ce725dfc5b5	12	-	-	2912.07
445	89aced1e-1782-4d95-b641-3ce725dfc5b5	13	-	-	2912.07
446	89aced1e-1782-4d95-b641-3ce725dfc5b5	14	-	-	2912.07
447	89aced1e-1782-4d95-b641-3ce725dfc5b5	15	-	-	2912.07
448	89aced1e-1782-4d95-b641-3ce725dfc5b5	16	-	-	2912.07
449	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	1	431.63	2540.42	NaN
450	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	2	431.63	2540.42	9183.13
451	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	3	431.63	2363.08	1469.49
452	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	4	431.63	2363.08	1469.49
453	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	5	431.63	2363.08	1469.49

(continue)

**Table 8 – Scenario 2 Results Per Step (continuation)**

No.	Comparison ID	Step	RND BSTC	PSO BSTC	GA BSTC
454	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	6	431.63	2363.08	1469.49
455	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	7	431.63	2363.08	1469.49
456	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	8	431.63	2363.08	1469.49
457	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	9	431.63	2363.08	1469.49
458	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	10	431.63	2363.08	1469.49
459	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	11	-	-	1469.49
460	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	12	-	-	1469.49
461	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	13	-	-	1469.49
462	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	14	-	-	1469.49
463	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	15	-	-	1469.49
464	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	16	-	-	1469.49
465	ec2cd49c-5f6e-46c2-af5c-1076c5d78da9	17	-	-	1469.49
466	74d590b8-5c95-4b7b-9467-42bfe209dde9	1	NaN	3898.31	NaN
467	74d590b8-5c95-4b7b-9467-42bfe209dde9	2	NaN	3898.31	NaN
468	74d590b8-5c95-4b7b-9467-42bfe209dde9	3	1726.92	3898.31	5904.01
469	74d590b8-5c95-4b7b-9467-42bfe209dde9	4	1726.92	3898.31	5904.01
470	74d590b8-5c95-4b7b-9467-42bfe209dde9	5	1726.92	2063.79	5904.01
471	74d590b8-5c95-4b7b-9467-42bfe209dde9	6	1030.60	2063.79	5904.01
472	74d590b8-5c95-4b7b-9467-42bfe209dde9	7	1030.60	2063.79	1608.29
473	74d590b8-5c95-4b7b-9467-42bfe209dde9	8	1030.60	2063.79	1608.29
474	74d590b8-5c95-4b7b-9467-42bfe209dde9	9	1030.60	2063.79	1608.29
475	74d590b8-5c95-4b7b-9467-42bfe209dde9	10	741.35	2063.79	1608.29
476	74d590b8-5c95-4b7b-9467-42bfe209dde9	11	-	-	1608.29
477	74d590b8-5c95-4b7b-9467-42bfe209dde9	12	-	-	1608.29
478	74d590b8-5c95-4b7b-9467-42bfe209dde9	13	-	-	1608.29
479	74d590b8-5c95-4b7b-9467-42bfe209dde9	14	-	-	1608.29
480	74d590b8-5c95-4b7b-9467-42bfe209dde9	15	-	-	710.82
481	c3540585-a6fc-410f-a65d-3343e192f0d6	1	404.27	3236.79	3243.14
482	c3540585-a6fc-410f-a65d-3343e192f0d6	2	404.27	3236.79	3243.14
483	c3540585-a6fc-410f-a65d-3343e192f0d6	3	404.27	3236.79	3243.14
484	c3540585-a6fc-410f-a65d-3343e192f0d6	4	404.27	3236.79	3243.14
485	c3540585-a6fc-410f-a65d-3343e192f0d6	5	404.27	3236.79	3243.14
486	c3540585-a6fc-410f-a65d-3343e192f0d6	6	404.27	3236.79	2731.01
487	c3540585-a6fc-410f-a65d-3343e192f0d6	7	404.27	2591.04	2731.01
488	c3540585-a6fc-410f-a65d-3343e192f0d6	8	404.27	2591.04	2731.01
489	c3540585-a6fc-410f-a65d-3343e192f0d6	9	404.27	2591.04	2731.01
490	c3540585-a6fc-410f-a65d-3343e192f0d6	10	404.27	2591.04	2731.01
491	c3540585-a6fc-410f-a65d-3343e192f0d6	11	-	-	2731.01
492	c3540585-a6fc-410f-a65d-3343e192f0d6	12	-	-	2731.01
493	c3540585-a6fc-410f-a65d-3343e192f0d6	13	-	-	2731.01
494	c3540585-a6fc-410f-a65d-3343e192f0d6	14	-	-	2731.01
495	c3540585-a6fc-410f-a65d-3343e192f0d6	15	-	-	2731.01
496	c3540585-a6fc-410f-a65d-3343e192f0d6	16	-	-	2731.01

Source: Own authorship (2021).

The analysis of Table 8 shows again the persistence of individuals from the Genetic Algorithm Controller (GA), increasing the amount of epochs required to achieve the same number of unique individuals. Both the Random Action Controller (RND)

and the Particle Swarm Optimization Controller (PSO) generated a fresh new set of individuals on every epoch, resulting in 10 epochs with 5 individuals each to reach the desired amount of 50 unique simulations (on each run). The GA controller, again, took up to 20 epochs to execute the required amount of unique simulations.

In this scenario, however, the GA controller could successfully complete all the steps with at least one valid solution. This might suggest that it's performing better under complex situations. The BSTC didn't converge to a single value, generating a set of different possible solutions.

A data representation for the performance variables of the controllers is shown in Table 9, in which:

- **RND CTR**: Controller Total Runtime (CTR) of the Random Action Controller (total execution time to reach the stop criteria);
- **RND BSTC**: Best Simulation Total Cost (BSTC) of the Random Action Controller (the lowest simulation accumulated cost that the controller has found);
- **PSO CTR**: Controller Total Runtime (CTR) of the Particle Swarm Optimization Controller (total execution time to reach the stop criteria);
- **PSO BSTC**: Best Simulation Total Cost (BSTC) of the Particle Swarm Optimization Controller (the lowest simulation accumulated cost that the controller has found);
- **GA CTR**: Controller Total Runtime (CTR) of the Genetic Algorithm Controller (total execution time to reach the stop criteria);
- **GA BSTC**: Best Simulation Total Cost (BSTC) of the Genetic Algorithm Controller (the lowest simulation accumulated cost that the controller has found);

The statistical Wilcoxon Signed-Rank Test results for the controllers' BSTC on Scenario Two is presented on Table 6.

Considering the hypothesis results presented on Table 10, it can be affirmed that the Random Action Controller results are statistically different from both the Genetic Algorithm Controller and the Particle Swarm Optimization Controller ones. This difference, however, cannot be affirmed between the Genetic Algorithm Controller and the Particle Swarm Optimization Controller.

The hypothesis regarding the CTRs (Controller Total Runtime) achieved the same conclusions as in the BSTC one. The total execution time of the Random Action Controller is statistically different from both the Genetic Algorithm Controller and the

**Table 9 – Scenario 2 Performance Results**

<b>No.</b>	<b>RND CTR</b>	<b>RND BSTC</b>	<b>PSO CTR</b>	<b>PSO BSTC</b>	<b>GA CTR</b>	<b>GA BSTC</b>
1	00:13:05	1288.50	00:24:23	1392.15	00:23:06	404.27
2	00:15:49	1256.91	00:24:57	1920.46	00:24:59	2602.33
3	00:07:06	496.03	00:22:36	434.80	00:24:06	921.29
4	00:12:05	1320.40	00:27:04	1508.70	00:26:45	1255.35
5	00:08:35	1241.48	00:26:21	2210.18	00:25:08	1284.09
6	00:12:31	741.75	00:22:20	404.27	00:24:09	1589.94
7	00:08:22	1253.22	00:19:55	929.69	00:20:47	1404.34
8	00:10:44	404.27	00:21:53	710.81	00:22:31	404.27
9	00:08:35	806.16	00:24:30	802.58	00:20:21	710.82
10	00:09:23	431.62	00:24:04	713.99	00:24:15	1670.63
11	00:10:10	1966.58	00:21:05	1255.35	00:21:48	1611.48
12	00:05:34	404.27	00:23:53	1246.01	00:22:42	1832.28
13	00:08:41	404.27	00:25:37	1054.78	00:24:19	3048.10
14	00:10:02	1027.43	00:24:12	3037.01	00:22:31	1198.50
15	00:07:46	710.82	00:22:41	431.62	00:23:35	2761.00
16	00:07:58	828.97	00:24:37	1597.29	00:22:17	404.27
17	00:09:56	404.27	00:19:31	434.80	00:22:22	1255.35
18	00:07:51	434.79	00:21:41	3091.63	00:19:54	2557.66
19	00:13:51	2063.79	00:23:46	3441.75	00:22:05	1148.80
20	00:13:11	1027.89	00:23:05	434.80	00:22:19	828.96
21	00:05:42	404.27	00:23:27	1253.21	00:22:58	431.62
22	00:09:46	714.40	00:24:06	2515.21	00:23:34	1551.68
23	00:17:46	1159.67	00:31:55	5016.25	00:30:01	1027.89
24	00:07:36	738.17	00:26:50	2605.52	00:41:38	2522.74
25	00:05:28	496.03	00:23:47	921.29	00:21:29	4349.93
26	00:10:40	1201.68	00:26:15	2216.74	00:24:31	2022.32
27	00:11:22	3048.63	00:24:34	1198.50	00:24:17	2912.07
28	00:05:12	431.63	00:22:42	2363.08	00:20:51	1469.49
29	00:16:36	741.35	00:27:26	2063.79	00:27:09	710.82
30	00:04:35	404.27	00:22:48	2591.04	00:20:49	2731.01
<b>SUM</b>	<b>04:55:58</b>	<b>27853.54</b>	<b>12:02:01</b>	<b>49797.31</b>	<b>11:57:16</b>	<b>48623.32</b>
<b>AVG</b>	<b>00:09:51</b>	<b>928.00</b>	<b>00:24:04</b>	<b>1659.00</b>	<b>00:23:54</b>	<b>1620.00</b>

Source: Own authorship (2021).

Particle Swarm Optimization Controller, although these later two are not statistically different from each other.

Taking in consideration the average indicator presented on Table 9 and the hypothesis mentioned previously, it can be assumed that the Random Action Controller performed best, as its BSTC values are statistically different from both the Particle Swarm Optimization Controller and the Genetic Algorithm Controller and its average BSTC value is lower than the others.

Both the Particle Swarm Optimization Controller and the Genetic Algorithm Controller achieved statistically the same results on both the BSTC and CTR values.

The main analysis variable is the Best Solution Total Cost (BSTC) per step, for



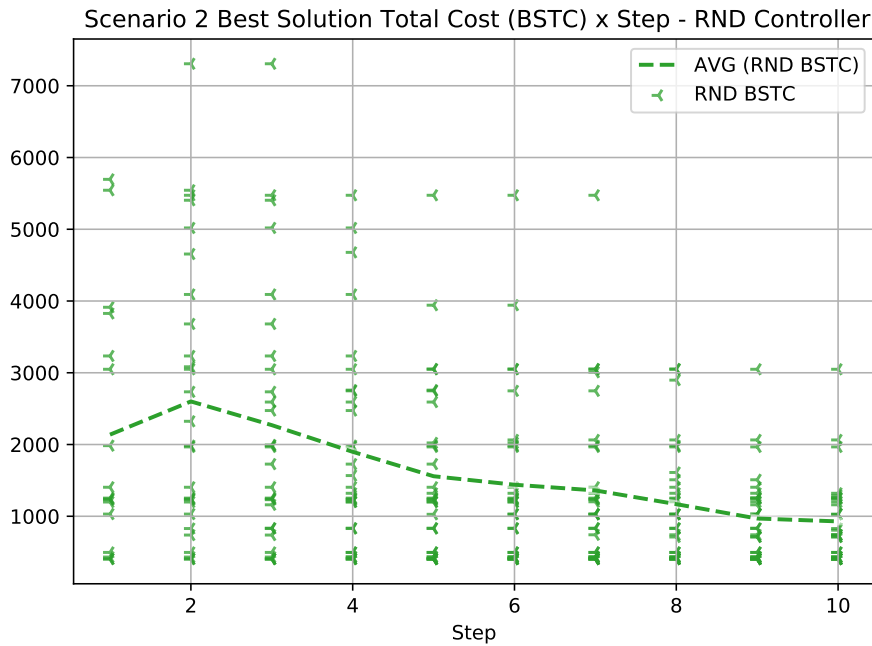
**Table 10 – Scenario 2 Wilcoxon Rank-sum Statistic Results**

Pair A Data	Pair B Data	Statistics	p-Value	Result
RND BSTC	PSO BSTC	80.00	0.00	Reject H0
RND BSTC	AG BSTC	104.00	0.01	Reject H0
PSO BSTC	AG BSTC	222.00	0.83	Fail to reject H0
RND CTR	PSO CTR	0.00	0.00	Reject H0
RND CTR	AG CTR	0.00	0.00	Reject H0
PSO CTR	AG CTR	140.00	0.06	Fail to reject H0

**Source: Own authorship (2021).**

each of the controllers. The raw data for this scenario is presented in Graph 8, Graph 9, and Graph 10. The graphs also presents the average indicator to be used as comparison criteria.

**Graph 8 – Best Solution Total Cost (BSTC) per step for the Random Action Controller.**



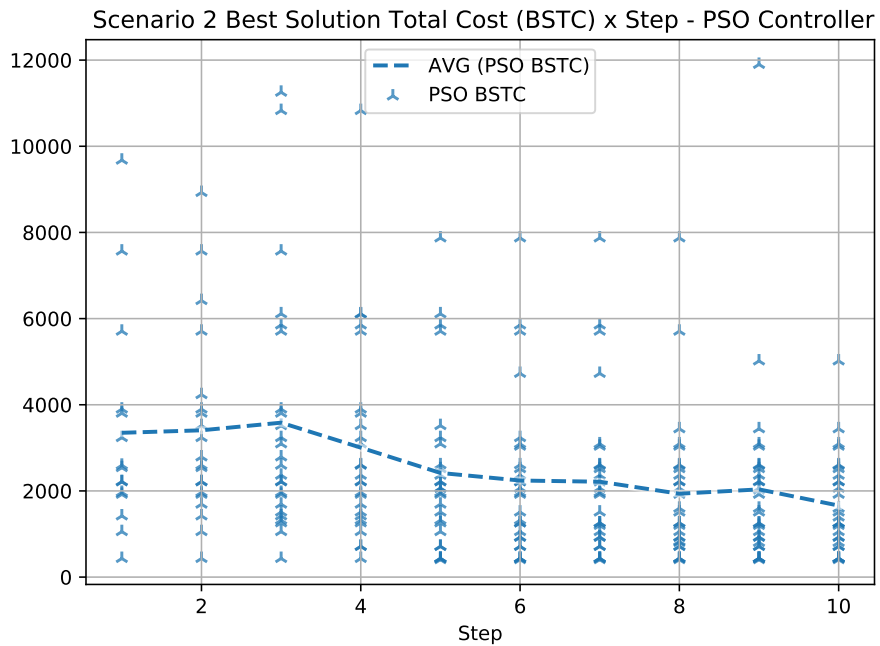
**Source: Own authorship (2021).**

Note on Graph 1 that there is a convergence of the average BSTC indicator to the solutions with lower cost, validating the optimization purpose and the greedy behaviour of the Random Action Controller.

On Graph 9 this convergence can also be perceived, but with a wider range of valid solutions (note the BSTC y-axis scale).

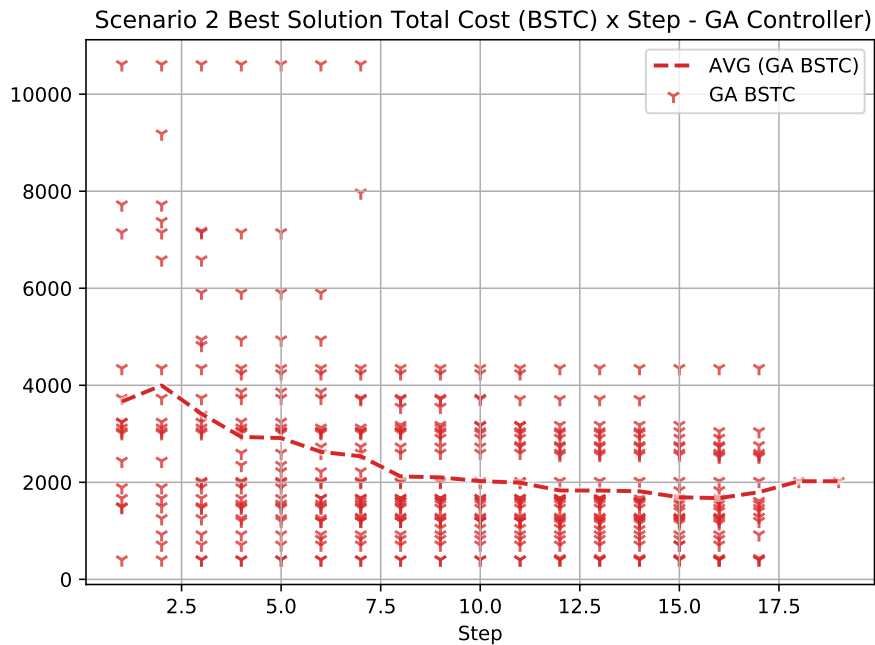
As stated previously, the GA controller might need more entropy. This can also be supported by the repeated sequences (same BSTC for several steps) on Graph 10. A fine-tuning of the mutation operator parameters could solve this.

**Graph 9 – Best Solution Total Cost (BSTC) per step for the Particle Swarm Optimization Controller.**



Source: Own authorship (2021).

**Graph 10 – Best Solution Total Cost (BSTC) per step for the Genetic Algorithm Controller.**



Source: Own authorship (2021).

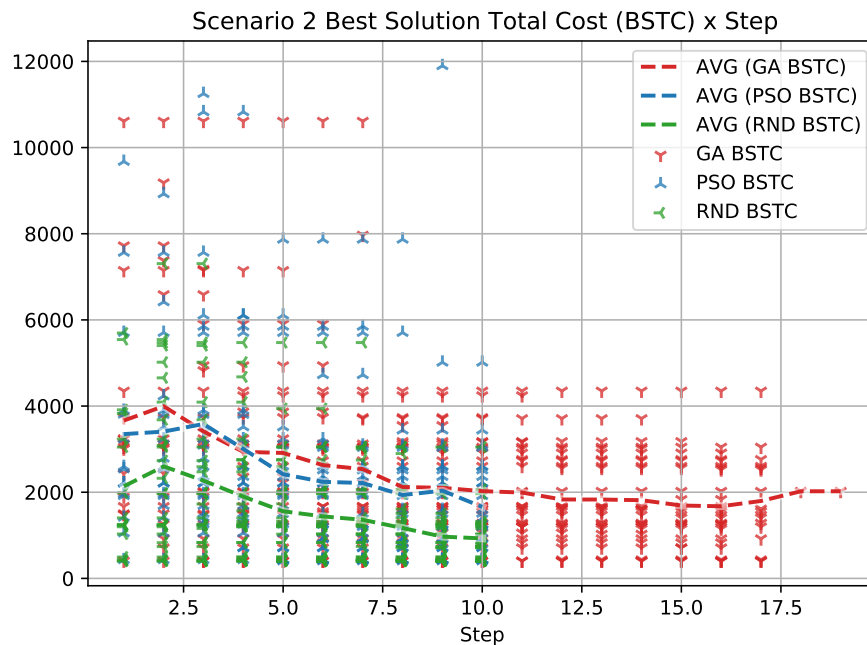
Another point of improvement of this project could be adding more controllers for comparison. The Artificial Bee Colony (ABC) algorithm and the Differential Evolution (DE) algorithm were considered as candidates to the tests, although there wasn't enough

time to develop them.

The addition of other scenarios could also indicate more improvement points, as well as provide more results for comparison among the controllers.

A combined view of all the three graphs may be seen in Graph 11, showing the Best Solution Total Cost (BSTC) for each of the three controllers during the 30 runs of Scenario 2 with the parameters described in the previous section.

**Graph 11 – Best Solution Total Cost (BSTC) per step for all the tested controllers.**



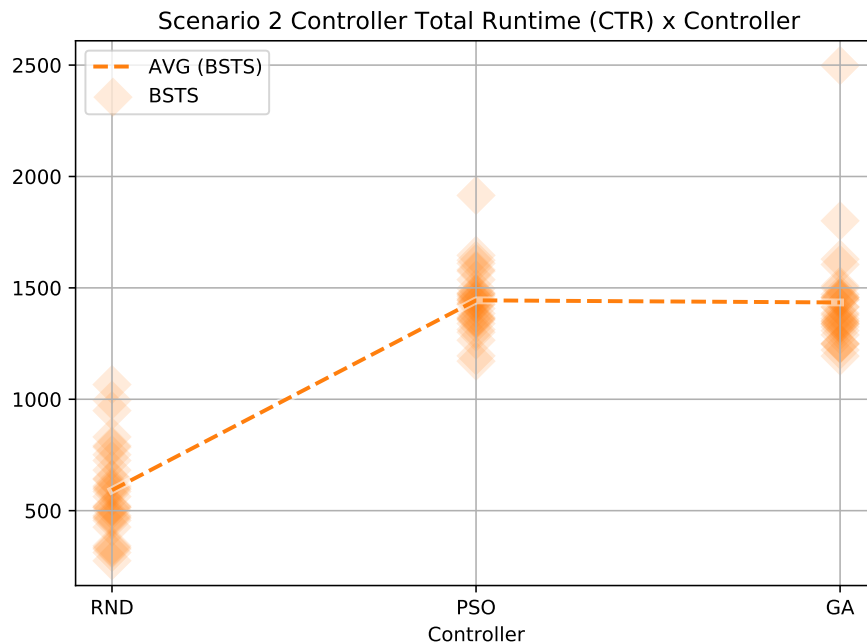
**Source: Own authorship (2021).**

From the results presented on Graph 11 we may see that the Random Action Controller had again the fastest optimal solution convergence, hitting the lowest BSTC fastest than the other controllers. It also reached the lowest BSTC average.

The Genetic Algorithm Controller took again the highest amount of steps to complete. All the three controllers achieved an optimal solution.

The graph presented on Graph 12 shows the total execution time of each of the 30 runs for all the tested controllers in Scenario 2, considering the parameters described in the previous section.

Observing Graph 12, the Random Action Controller (RND) is again the fastest one (due to its lower computational effort). Both the Particle Swarm Optimization Controller (PSO) and the Genetic Algorithm (GA) had the same execution time considering the average indicator.

**Graph 12 – Total execution time for each of the controllers.**

**Source: Own authorship (2021).**

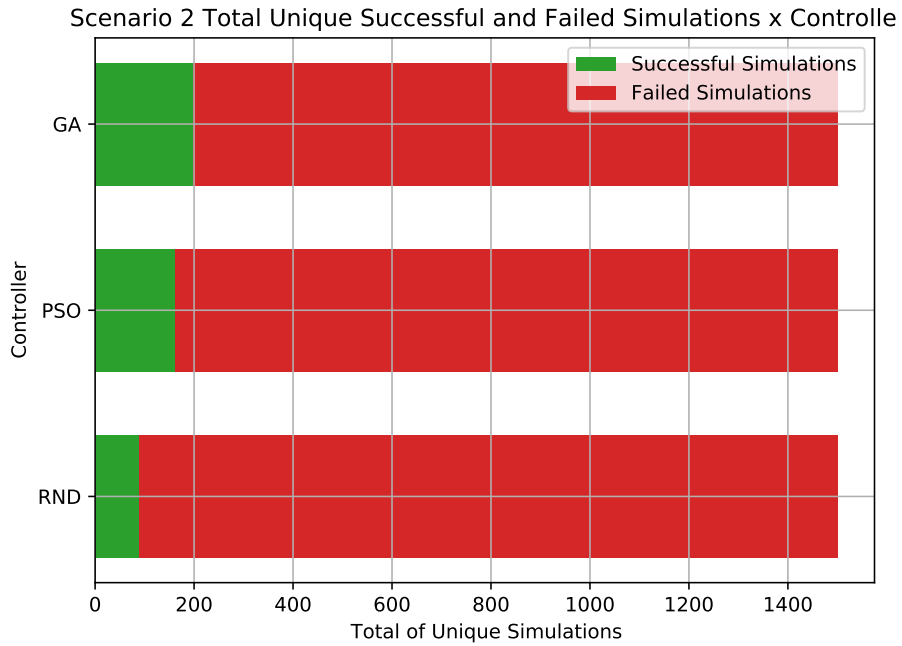
The graph presented on Graph 13 presents the total amount of unique simulations run on each of the controllers, as well as groups them by their final status. A failed simulation means that it was halted due to a stop criteria (steps limit or cost limit, whichever comes first). On the other hand, a successful one means that all the trains in the scenario reached their destinations before the simulation halted due to a predetermined stop criteria.

The Genetic Algorithm (GA) controller had the highest number of unique successful simulations (success rate: 13%) compared to the others, but still closer to the value from the Particle Swarm Optimization (PSO) controller (success rate: 11%) than to the Random Action (RND) controller (success rate: 6%). The complexity of this scenario is clearly higher than the previous one.

The graph presented on Graph 14 show the total amount of steps for the best solution found on each of the 30 runs for all the tested controllers. The markers have a transparency (25%) so regions with higher frequency may be identified.

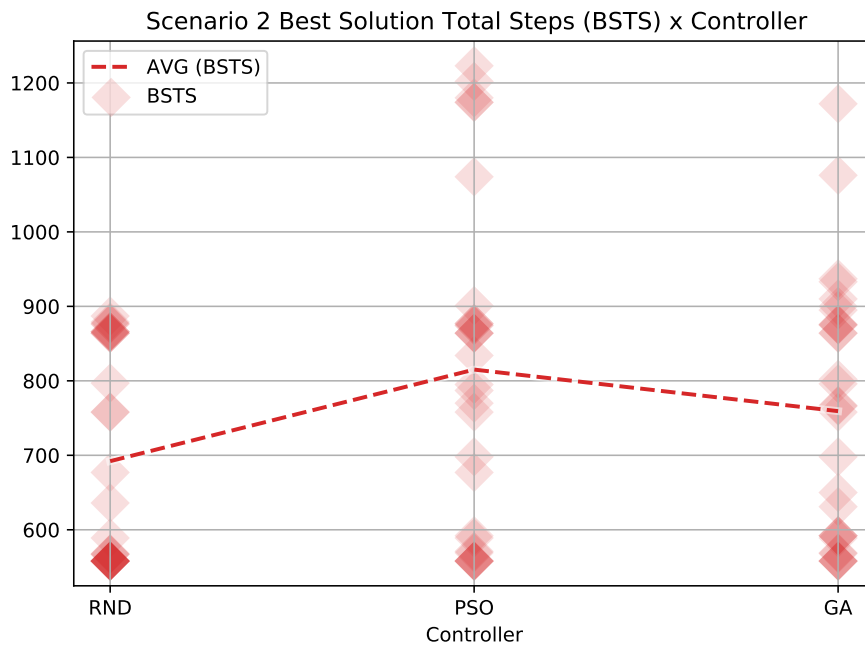
The data presented in Graph 14 shows the greater diversity of valid solutions found by both the PSO and the GA controller, compared to the greedy approach used on the RND one. This might be a decisive indicator if the scenario objective is to provide different solutions to a major problem - not necessarily the lowest cost - during a disaster

**Graph 13 – Total unique simulations (successful and failed ones) for each of the controllers.**



Source: Own authorship (2021).

**Graph 14 – Best Solution Total Steps (BSTS) for each of the controllers.**



Source: Own authorship (2021).

response, for example.

A data summarizing from Scenario 2 is presented in Table 11.

Observing Table 11 it's noted that all the three controllers reached the same optimal solution, indicating a global solution for the purposed scenario. The 30 runs for

**Table 11 – Scenario 2 Results Summary**

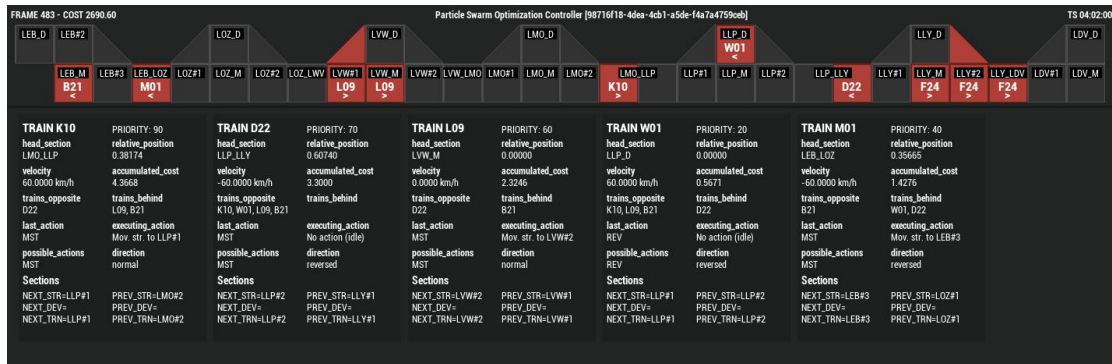
Indicator	RND	PSO	GA
Total epochs	300	300	496
Total simulations	1500	1500	1500
Total successful simulations	88	161	198
Best solution cost	404	404	404
Best solution total steps	558	558	558
Best solution calculated real time elapsed	04:39:00	04:39:00	04:39:00
Controller total runtime	04:55:58	12:02:01	11:57:16

Source: Own authorship (2021).

both the PSO and GA controllers took approximately 12 hours, indicating that a refactor with a lighter approach should be made in the simulation core code.

The frame presented in Figure 24 displays a moment when the trains B21, M01, L09, K10, W01, D22 and F24 are moving through the route.

**Figure 24 – Synoptic Video frame from the results of Scenario Two.**



Source: Own authorship (2021).

Note that this frame is not cropped only to the occupancy map (as the one presented in Figure 23), but instead shows the whole image of a frame in the synoptic video resulted from a successful simulation of the PSO controller on Scenario Two. The lower section (with the text) contains the information of trains (one block for each) running in the route, refreshing every step. It's useful to debug the behavior of the simulation core, the actions execution and the trains' dynamics.

## 5 CONCLUSION AND PERSPECTIVES

The main objective for this project is to provide an open-source tool for railroad traffic management and perform an optimization based on bio-inspired metaheuristics. The goal behind this objective is to help in the decision-making process of the railroad dispatchers. By considering the results obtained from the data presented in the previous chapter - and also the output video which supported the validation of the simulation dynamics - the open-source simulation tool proved itself to be functional, thus achieving the main objective.

All the tested controllers provided valid solutions to the proposed scenarios. In the harder one - based on the real-life data from an active railroad in Paraná state - they also provided a set of different possible solutions for the same preconditions, reinforcing the concept that the tool could be used to help in the decision-making process of the railroad dispatchers.

Regarding the specific objectives proposed at the beginning of this project, all the concepts used in this project were described in chapter 2, giving the proper context for people from both the academic and professional areas to understand, reproduce and contribute to this project.

The code was written in a well-known programming language that owns almost one third of the development market share, while still using an open-source license and versioning, thus allowing community contributions and a further research from every interested public, including - but not restricted to - students, developers, teachers and enthusiasts.

The project is also accessible from multiple platforms - not only because of the programming language, but also because of the usage of Docker containers, allowing the basic kernel required to run the simulation tool to be ported and executed on different devices and operating systems.

Two heuristic controllers - Genetic Algorithm (GA), and Particle Swarm Optimization (PSO) - were successfully implemented through a base interface class, allowing their code to focus only in their respective operators. Another third controller - the Random Action (RND) one - was created to compare the convergence of the heuristic strategy with a simple greedy random guessing of the solution (similar to a brute-force approach).

The comparison among the results from the three implemented controllers was

made, resulting in the RND performing best on both scenarios. Despite of achieving statistically the same BSTC as the PSO one, the RND controller achieved the fastest total execution time to complete both the scenarios. The GA and PSO controllers, on the other hand, provided a greater amount of valid solutions (success rate) on both scenarios, providing also a higher number of unique valid solutions the harder scenario. This may come handy on the decision-making process purposed by this work.

One point that could be changed is the composition of the individuals (simulations). Instead of choosing between some defined set of solutions with several business rules attached to it, a more generic approach could consider only the acceleration point, reverse position and breaking intensity as commands, thus allowing the algorithm to learn how to control the train itself. The *Dispatcher* could still apply penalties with a reinforcement learning approach.

Another approach could be using the sections as of the route as the individuals' composition, translating that into an action at every step. The distance to goal in the Equation 33 showed to be computationally expensive, as the *SectionMapper* must compute all the possible routes from the train's head section up to its destination, retrieving the shortest one. This could be remove for a better performance.

The reverse action introduced a lot of complexity in the trains' decisions. A great simplification and speed up could be achieved by making the assumption that the trains do not reverse - which would still allow such operation to be made in a higher level through the exclusion and creation of a new train. This also happens in the real life, as trains going loaded and coming back unloaded have different prefixes, even being exactly the same set of rolling stock.

Despite the simulation results, railroads and programming are two long-time subjects very much appreciated by the author. Both the oldest memories as a young child watching the locomotives doing their duties in the station yard to the first *hello world* written in Visual Basic 6.0 almost two decades ago, the desire for understanding more of those two worlds guided the author into multiple remarkable virtual and physical journeys, leading up to this project. You may check the happiness of the author in his shinning eyes while in the driver's seat of a SD40-2 locomotive in Photograph 7, on a photograph taken in the Christmas Day of 2012.

The development of this project was a great opportunity to gather topics from both areas and contribute to the academic one by providing an open-source tool with



**Photograph 7 – The author in a SD40-2 locomotive.**



**Source: Own authorship (2012).**

public access to the whole source-code, as well as having this document and the code comments as guidelines.

The completion of the work, however, proved to be harder than expected. Problems and decisions were raised during both the planning and the execution, requiring an extra research that compromised the time to develop new features, scenarios and controllers.

Actually working as a Software Development Engineer, this project also helped the author to apply his professional knowledge into the academic area, which he believes is a great skill to have as a future teacher. Furthermore, it was a great opportunity to expand the connections and to gain experience in both areas.

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**APPENDIX A — REPORT OF RESULTS FOR SCENARIO ONE**

===== SCENARIO REPORT =====

Route: ComparisonRouteOne

Trains:

Prefix: 041  
 Start Section: ZIM\_P  
 End Section: ZCM\_D  
 Is Reversed: NO  
 Priority: 50

Prefix: 014  
 Start Section: ZCM\_P  
 End Section: ZIM\_D  
 Is Reversed: NO  
 Priority: 50

== Random Action Controller Report ==

Options used:

CONTROLLER - max\_thread\_workers: 8  
 CONTROLLER - max\_iterations: 30  
 CONTROLLER - max\_consecutive\_steps\_with\_same\_best: 0  
 SIMULATION - step\_duration: 10  
 SIMULATION - max\_steps: 1000  
 SIMULATION - max\_steps\_without\_train\_movement: 0  
 SIMULATION - max\_cost: 109.76987536799997

Total steps: 10  
 Total iterations: 30  
 Total successful iterations: 7  
 Stop reason: Reached maximum iterations count  
 Best solution UUID: dd3ea5ac-ac20-4b9f-b5d4-9561a7af4669  
 Best solution cost: 109.76987536799997  
 Best solution status: SUCCESS  
 Best solution total steps: 336  
 Best solution calculated real time elapsed: 00:56:00  
 Controller total runtime: 00:00:17

== Particle Swarm Optimization Controller Report ==

Options used:

CONTROLLER - max\_thread\_workers: 8  
 CONTROLLER - max\_iterations: 30  
 CONTROLLER - max\_consecutive\_steps\_with\_same\_best: 0  
 SIMULATION - step\_duration: 10  
 SIMULATION - max\_steps: 1000  
 SIMULATION - max\_steps\_without\_train\_movement: 0  
 SIMULATION - max\_cost: 1000.0

Total steps: 10  
 Total iterations: 30  
 Total successful iterations: 15  
 Stop reason: Reached maximum iterations count  
 Best solution UUID: 9edac568-50a5-4277-8d08-e22984b8f565  
 Best solution cost: 109.76987536799997  
 Best solution status: SUCCESS  
 Best solution total steps: 336  
 Best solution calculated real time elapsed: 00:56:00  
 Controller total runtime: 00:00:27

## == Genetic Algorithm Controller Report ==

## Options used:

CONTROLLER - max\_thread\_workers: 8  
CONTROLLER - max\_iterations: 30  
CONTROLLER - max\_consecutive\_steps\_with\_same\_best: 0  
SIMULATION - step\_duration: 10  
SIMULATION - max\_steps: 1000  
SIMULATION - max\_steps\_without\_train\_movement: 0  
SIMULATION - max\_cost: 1000.0

Total steps: 16

Total iterations: 30

Total successful iterations: 8

Stop reason: Reached maximum iterations count

Best solution UUID: ab07f0f2-d64a-4789-84f5-10c2fb1c528f

Best solution cost: 109.76987536799997

Best solution status: SUCCESS

Best solution total steps: 336

Best solution calculated real time elapsed: 00:56:00

Controller total runtime: 00:00:29

**APPENDIX B — REPORT OF RESULTS FOR SCENARIO TWO**

===== SCENARIO REPORT =====

Route: ComparisonRouteTwo

Trains:

Prefix: K10

Start Section: LDV\_M

End Section: LEB\_M

Is Reversed: NO

Priority: 100

Prefix: K90

Start Section: LDV\_D

End Section: LEB\_D

Is Reversed: NO

Priority: 70

Prefix: F30

Start Section: LDV\_D

End Section: LEB\_D

Is Reversed: NO

Priority: 50

Prefix: D52

Start Section: LEB\_M

End Section: LDV\_D

Is Reversed: NO

Priority: 50

Prefix: U27

Start Section: LEB\_D

End Section: LDV\_M

Is Reversed: NO

Priority: 60

Prefix: U23

Start Section: LEB\_D

End Section: LDV\_M

Is Reversed: NO

Priority: 60

Prefix: W01

Start Section: LVW\_D

End Section: LLY\_D

Is Reversed: NO

Priority: 1

== Random Action Controller Report ==

Options used:

CONTROLLER - max\_thread\_workers: 8

CONTROLLER - max\_iterations: 50

CONTROLLER - max\_consecutive\_steps\_with\_same\_best: 0

SIMULATION - step\_duration: 30

SIMULATION - max\_steps: 5000

SIMULATION - max\_steps\_without\_train\_movement: 0

SIMULATION - max\_cost: 7919.094680998307

Total steps: 10

Total iterations: 50

Total successful iterations: 2

Stop reason: Reached maximum iterations count  
 Best solution UUID: f405da2c-f5b5-4bbe-ab2b-c8294e2c4ace  
 Best solution cost: 7919.094680998307  
 Best solution status: SUCCESS  
 Best solution total steps: 1450  
 Best solution calculated real time elapsed: 12:05:00  
 Controller total runtime: 00:21:20

== Particle Swarm Optimization Controller Report ==

Options used:

CONTROLLER - max\_thread\_workers: 8  
 CONTROLLER - max\_iterations: 50  
 CONTROLLER - max\_consecutive\_steps\_with\_same\_best: 0  
 SIMULATION - step\_duration: 30  
 SIMULATION - max\_steps: 5000  
 SIMULATION - max\_steps\_without\_train\_movement: 0  
 SIMULATION - max\_cost: 5000000.0

Total steps: 10  
 Total iterations: 50  
 Total successful iterations: 11  
 Stop reason: Reached maximum iterations count  
 Best solution UUID: cdb7a1eb-0beb-4fab-8234-0bf145d38b46  
 Best solution cost: 1518.3983491795998  
 Best solution status: SUCCESS  
 Best solution total steps: 676  
 Best solution calculated real time elapsed: 05:38:00  
 Controller total runtime: 01:00:45

== Genetic Algorithm Controller Report ==

Options used:

CONTROLLER - max\_thread\_workers: 8  
 CONTROLLER - max\_iterations: 50  
 CONTROLLER - max\_consecutive\_steps\_with\_same\_best: 0  
 SIMULATION - step\_duration: 30  
 SIMULATION - max\_steps: 5000  
 SIMULATION - max\_steps\_without\_train\_movement: 0  
 SIMULATION - max\_cost: 5000000.0

Total steps: 16  
 Total iterations: 50  
 Total successful iterations: 10  
 Stop reason: Reached maximum iterations count  
 Best solution UUID: 84e19d41-8da3-4a84-b68a-a688a33f854b  
 Best solution cost: 11295.1046592632  
 Best solution status: SUCCESS  
 Best solution total steps: 1590  
 Best solution calculated real time elapsed: 13:15:00  
 Controller total runtime: 00:59:34

**ANNEX A — COUPAL-GARVER-SMITH ALGORITHM FLOWCHART**



