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A mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a rail network

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ABSTRACT

This paper includes a mesoscopic simulation modelling methodology developed for analysing and evaluating freight train operations in a rail network. The product of this methodology is a simulation rail network model implemented using an event-based simulation computer package called SIMUL 8. For simulation modelling purposes a decomposition approach is used. This approach allows us to separate the rail network under study into its components such as rail lines, rail yards, rail stations, rail terminals and junctions. The components of the rail network are thought of as interconnected queuing systems that interact and influence one another, so that the global impact of freight train operations in a rail network is captured.

The products presented in this paper are of interest to rail freight tactical management, where global benefits are pursued.

1. Introduction

1.1. Basic production patterns for rail freight transportation

Around the world railway freight operators have traditionally practiced two basic production patterns, namely: *improvised operation* and *structured (scheduled) operation*. In the literature, these two basic production patterns can be met as "*... general philosophies of railroad operation ...*" (e.g., [26,13,34,35]).

Improvised operation, as a matter of principle, is a "*headache for dispatcher*". This pattern is also known as an undisciplined, timetable free, scheduled free operation practice, random schedule, tonnage-based dispatching policy.

Generally speaking, improvised operation means to run freight trains only when they have enough freight/freight cars subject to technical constraints of the rail network. The operating philosophy of the improvised operation is that the dispatcher holds the freight trains until they have enough tonnage to fill them to the capacity limits of the rail line (or rail network). The time factor is not crucial here. There may be operating plans listing a freight train as operating every day, but if the rail freight system cannot fill this train with sufficient number of freight cars, it delays or even cancels the freight train until it is full. In implementing improvised operation the railway freight operators intend to minimize the total number of freight trains that they operate by maximizing their size. This is also known of as "Heavy Haul" and specifies the rail freight operation economics.

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Shortcomings of the improvised operation are:

- The improvised operation is not explicitly focused on customer needs; instead it gives priority to the rail freight operation economics.
- The rail freight systems do not provide services with high customer loyalty.
- The rail freight yards (i.e., the reassembly hubs in the rail network) require a greater storage capacity for freight cars and road locomotive in order to cope with traffic variability and uncertainty.
- Because of daily uncertainty in the movement of freight trains, a greater number of road crews and road locomotives are required to satisfy the customer demands.
- Normally, the rail freight operators that practice improvised operation, experience a significant increase in long run average costs caused by wastage of inputs-factor and higher waiting costs incurred because of idle rolling stock and unassigned train crews.

Improvised operation is a usual practice in US railroads and in some Eastern European Railways. Central and Western European Railways employ a new dispatching policy that is subordinated to strict fixed schedules. The rail freight operators purchase slots on the rail network on which a freight train can travel, and their options are rather limited: a freight train travels or is cancelled. This dispatching policy is based on the principle of predictable transportation. Discussion of this concept is covered in the next section.

The prime objective of *structured (scheduled) operation* is that freight trains are thought of being as reliable as passenger trains. All freight trains operate on strict fixed timetable even if they run as reduced formations. There may be situations in which a single road locomotive is redeployed even when it may be required somewhere else in the rail network in order to pull a scheduled freight train formation and thus prevent this operation from failure.

A shortcoming of structured operation is that it requires integrated, reliable, detailed, efficient operating plans. The rail freight system that practices scheduled operation is expected to serve its customers just like the rail passenger system does. However, one should not forget that the passenger trains normally run on strict fixed schedule but they may run without any single passenger, which is quite costly for the company.

It appears that structured operation fits plausibly within the liberalized market because it gives an explicit priority to the customer needs. However, if an operation fails, it may have a detrimental impact on the entire service and the client will not receive the delivery at the appointed time. In this situation, the service quality can decline rapidly. Therefore, there might be a schedule that is the envy of the world but this schedule is worthless if the railway fright system cannot deliver it on a routinely reliable basis. This situation may become worse if the schedules developed at tactical management level are unrealistic and impractical because they are developed without regard to the maximum processing capabilities of the components of the rail network (such as: rail yards, rail stations and junctions). The operations are not then able to fulfil the schedules, which causes chaos on the rail network. In order to avoid such awkward situations reliable tools for analysing and evaluating freight train operations in a network are needed. This paper provides such a tool.

1.2. Motivation

The rail freight operator under study is CP – Carga "*Comboios de Portugal*" (we shall use CP – Carga for simplicity). CP Carga aims to run its freight trains on strict fixed schedules. This operator fulfils "*annual*" and "*weekly*" planning.

At *annual planning* the so-called "annual input" is specified. The annual input consists of types of freight, demand origins/destinations per type of freight and tonnage to be transported during next year. Based on the annual input the Planning Department of CP – Carga develops a supply production scheme to satisfy the annual customer demand. The supply production scheme is a proposal of how the annual customer demand should be served during the coming year and is prepared considering recent historical reviews and the transportation plan in operation. At this stage, fixed schedules for some of the freight trains are stipulated. These schedules are further adjusted during the weekly planning.

What is observed is that the annual schedules of freight trains are constructed on the basis of an exaggerated predicted tonnage and therefore more freight trains are planned than the rail freight system is actually able to produce. It appears that during the annual planning process the maximum capacity of Portuguese rail freight network is not explicitly considered. An explanation for this phenomenon is that in the beginning of the year the client declares more tonnage than is really intended to be transported. It might be explained by the fact that CP Carga does not charge its clients for cancellation of scheduled freight trains. It is believed that this situation gives "more flexibility" to the client. However, it is to the detriment of the whole rail freight system.

At *weekly planning* the client together with the Commercial Department of CP – Carga set up the weekly demand for transport, i.e., types of freight, demand origins/destinations per type of freight and tonnage as well as frequencies. After having stipulated the weekly demand for transport, the Commercial Department of CP – Carga submits the stipulated figures to the Planning Department. Next based on the stipulated figures the planners develop the production scheme for the coming week.

The production scheme is a detailed plan for the movement of freight trains in the whole rail freight network. This plan consists of the freight trains schedules and every week it is sent to the Operations Department for implementation via the information system of CP – Carga called "TrainOffice".

It should be noted that the weekly planning is performed totally on a manual basis. What is observed is that the weekly planning is fulfilled without regard to the maximum processing capabilities of the components of the railway network (such as: lines, rail stations, rail yards and junctions). There is no instrument for it. The schedules developed every week are not analysed and evaluated before implementation. There is no instrument for it either. Therefore, some suggestions for the freight train movement at planning level still appear to be unworkable with respect to the maximum processing capabilities of the components of the railway network.

CP – Carga aims to practise a strict fixed (scheduled) operation, however because of some unworkable schedules the strict fixed operation is, in practice, a chaotic one. This is an awkward situation and contributes to low utilization of resources and low operating efficiency. As a result CP – Carga incurs a significant increase in long term average costs. We believe that one possible way to tackle this situation is to provide a reliable tool that can be utilized for analysing and evaluating freight train operations in a rail network.

1.3. Objectives

The main objective of this paper is to provide a mesoscopic simulation modelling methodology for analysing and evaluating freight train operations in a rail network by using an event-based simulation software.

1.4. Paper organization

This paper is written in a cumulative fashion and is organized as follows: in Section 2 concepts for studying freight train operations in a network are discussed; this section also includes a literature review. In Section 3 a brief presentation of technical aspects in simulating with SIMUL 8 is given. In Section 4 a discussion on how the decomposition approach is employed for modelling freight train operations in a rail network is presented. A mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a rail network is provided in Section 5. Section 6 consists of a case study demonstrating the application of the simulation modelling methodology developed. This paper concludes with synthesis, conclusions and a discussion of future work in Section 7.

2. Background and literature review

Using either improvised operation or strict fixed schedules, rail freight operators fulfil network-based businesses, e.g., they serve many clients with different demand origins and demand destinations with the same resources. A network-based business requires a network-wide service policy. The analysis of “network-wide service policy” by rail falls within the concept of network models. Here, *optimising network models* and *simulation network models* have been generally used.

Optimising network models have been widely used in resolving vehicle routing problems. Usually, the network is presented as a graph with finite number of nodes and arcs. The nodes replicate the transport facilities. The arcs represent the physical links between the facilities. The nodes and the arcs are characterized with physical capacity and processing capability. These two variables specify the constraints of the optimisation task. In the network, there are vehicles routing with the purpose of satisfying a given demand. The objective is to define an optimal routing of the vehicles along the possible itineraries in the network with respect to some objective functions such as minimizing costs, minimizing waiting times, maximizing vehicle utilization, maximizing throughput and the like. However, in the context of rail freight transportation, one must consider the heterogeneous freight traffic, the sequence and repetitive regrouping of freight car groups when moving from its demand origins towards its demand destinations as well as the very significant non-linearity of transport costs associated with the need for road locomotive(s), independently of having to move one freight car or (say) 20 freight cars. Therefore in order to implement optimising network models for analysing rail network behaviour the rail network has to be transformed into a plausible shape for optimisation. Normally, this is achieved with heuristics, auxiliary networks and/or processes to represent the complex operations, relative priorities in providing the service, groups of freight cars travelling in the same train as well as time–space attributes corresponding to gauge, length, running times, operating times, etc. Optimising network models for analysing integrated rail network services and multiple-flow routing are reported, e.g., by Assad [3,4], Crainic et al. [5], Crainic and Roy [6], Fernandez [9], Razmov [29] and Ahuja et al. [2]. These models identify with great precision the “bottlenecks” (e.g., groups of rail sections with “minimum-cut-values”, which is the group of tracks whose sum of capacities “for parallel utilization” is minimal, thus defining the network capacity) in the network. They reveal benefits and losses accumulated through small almost insignificant changes in the entire rail network and therefore they are very useful to support operating processes that require “prompt decision-making”. Daily operations with freight trains and optimising network models are beyond the scope of this work and therefore we shall not discuss them any further. Instead, we focus on simulation network models, which are more appropriate for our purposes.

Simulation network models are evaluation tools which can be employed to evaluate different scenarios to run the system, processing capabilities of the system and potential new network-wide service policies. Here the decomposition approach has been broadly applied to divide the network under study into its components and investigate the performances of each component in greater detail.

There have been many different rail yard models. Analytical queueing models and simulation models have been developed and used to study rail yard performances (e.g., see [11,27,28,14,15,10,31,18,20,21,1,23,22]). For our purposes, however, the separate models are incorporated in a way to replicate the rail network under study. This way the global impact of a full set of service policies in the rail network is not neglected.

Simulation rail network models include the use of simulation software packages that operate with comprehensive data input. The input data encompasses a set of network service policies including infrastructure characteristics, itineraries, arrival rates, service rates, incorporated interruptions, etc. The results obtained by the simulation models strongly depend upon the data input.

In order to make the best use of simulation, a specific simulation tool is required. For instance, the planning of the Dutch railway service is fully supported by the Decision Support System DONS (Designer of Network Schedules). In order to evaluate the robustness of network timetable planning, a simulation tool called "DONS-Simulator" is available, which is equipped with its own database [12]. The DONS-Simulator is built on the template technology of the Arena simulation tool [32].

In North America, simulation software is commonly used for determining the railway infrastructure changes required for a change in traffic as well as in support of rationalization plans. The simulation process is heuristic. The infrastructure for subsequent simulations is modified in ways suggested by the analysis of the earlier simulation outputs. The process is repeated until an acceptable result is achieved, as determined by analysis of the simulation output estimates. A simulation clock measures the passage of time for all calculations and simulated activities [34].

In the course of the successful development of modern computers and software, computer-aided simulation models have been developed to support long-term railway planning in Germany [26]. The macroscopic evaluation tool Network-Evaluation-Model – NEMO and the microscopic simulation tool RailSys are available for evaluation of both railway network capacity and future rail infrastructure scenarios including scheduled passenger and freight traffic [16].

Another user-friendly railway simulation product is "OpenTrack". This software operates with three modules of input data (rolling material, infrastructure and timetable) and can answer many different questions concerning railway operational aspects. In general, predefined trains move on a designed track layout according to a given timetable data [24].

However, when no specific simulation software is available, one should investigate, choose and adapt an existing one for this purpose. For instance, Dessouky and Leachman [7], Dessouky et al. [8] and Lu et al. [17] developed simulation modelling methodologies to assess the rail track infrastructure in dense traffic areas using SLAM II Simulation Language. They aimed to determine the best track configuration to meet future demand. In these methodologies the freight train movement is replicated as a stochastic process; the passenger train movement is replicated as a fixed schedule. The majority of the classified trains are assumed to arrive by Poisson arrival process. The arrival times of a few trains are predetermined and assumed to be known as a given item. For most studied terminals, consideration is given to the limited capacity of tracks for trains to wait for loading and unloading. The layover time depends on the terminal; some of them are modelled as a fixed time. The train movement into and out of the intermodal terminals as well as the train dwell times can vary widely according to the terminal configuration. The storage time is modelled as an exponential random variable with the mean equal to 1 day. Normally modifications to the current track configuration of rail network are suggested in order to handle an increased demand.

Within the context of this work we provide a mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a rail network implemented using the SIMUL 8 event-based computer simulation platform. Based on the concept presented in Marinov and Viegas [22] for analysing and evaluating flat-shunted yard operations, we now build upon this analysis and yard simulation models by integrating three flat-shunted yards operating in a network.

3. Simulating with SIMUL 8 and interpretations

3.1. Foundation

To secure the objectives of this discussion we conducted a visual simulation modelling experiment using the SIMUL 8 computer package for event-based simulation. A simulation rail network model is developed that takes the shape of queueing networks. The components of the queueing networks are interconnected queueing systems that interact and influence one another, so that the global impact of individual and all freight train operations in a network is captured.

3.2. Attributes

We use a set of Work Centres (i.e., servers) and Storage Areas (i.e., buffer or queues) to build up the simulation rail network model [30].

The *Work Centres* serve work items which are the "clients" of the system. In our case the Work Centres are used to replicate the operating processes with freight trains, or in other words this is where a freight train is served by a component of the rail network. Each Work Centre is characterized with inbound traffic, service pattern and outbound traffic. The inbound traffic is the number of freight trains that require for service in the Work Centre. The service pattern follows a particular distribution which means information is obtained by observations, real data collection and statistical analysis. The outbound traffic is the outcome of the Work Centre and is routed to other Work Centres and Storage Areas in a variety of ways (meaning to a subsequent Work Centre, or to a Storage Area waiting for next operation, or to leave the system when the total service of the freight train is completed).

The *Storage Areas* are attributes used to replicate where the freight trains are held while waiting to be processed by a given component of the rail network. All Storage Areas are controlled by their capacity.

When a freight train leaves the rail network its service is assumed as terminated. In SIMUL 8 this event is replicated by an attribute called *Work Exit Point*.

To generate the work items (in our case the freight trains) an attribute called *Work Entry Point* is employed. This attribute is characterized with arrival pattern. The arrival pattern may be subordinated to a familiar theoretical distribution, an empirical distribution or a time-dependent distribution. The latter is the basis of our case.

3.3. Arrival pattern: time-dependent distribution

Time-dependent distributions are very useful for modelling systems that do not reach steady state. A rail freight system that runs its freight trains on strict fixed schedules is such a case. This is because the freight train arrivals vary over a regular cycle and the system deals with predictable variability, predictable queues and quasi-steady state regimes of work. In predictable variability there are busy periods which alternate with quiet periods. In busy periods queues tend to build up. In quiet periods queues correspondingly tend to reduce. Or in other words, in predictable variability quiet periods can cancel out busy periods.

3.4. Routing

Routing of work items in the network is specified by “Work Flow Arrows”, which is to indicate the paths (“from Work Entry Point to Storage Area or to Work Centre”, “from Work Centre to Work Centre”, “from Work Centre to Storage Area” and so on) for the freight trains moving through the (sub)components of the railway network. An important feature here is that when there is no Storage Area (i.e., there is no buffer to queue) between two successive network components, but there is a direct link between them, by default the freight trains do not move from the first subsystem to the second until the second subsystem is ready to start processing them.

3.5. Transient period

By default SIMUL 8 insets transient periods in the beginning of every simulation run. A transient period means the simulation experiment begins without any work items being in the system. This causes the results to be biased and must be avoided. In order to avoid the transient period in the simulation experiment, a *warm-up* period is set up.

3.6. Collection of results

The results are collected by multiple replications (also called multiple runs) which form trials. The number of replications that a single trial consists of is set up through a “*conduct trial*” option.

3.7. Measures of system performance (MOPs)

Aspects used to measure system performance are: total number of freight trains processed by a given Work Centre, number of freight trains in a given Storage Area, queueing (waiting) time per freight train on average for the period of the experiment, utilization levels of the rail network subcomponents, utilization rates of system resources, etc.

4. Decomposition approach

For simulation modelling purposes we employed the decomposition approach. Dividing a rail network in different parts for research is a practical approach that has already proven its level of credibility. One is allowed to divide the rail network under study into its components, but it must be always considered that all components which are regarded separately belong to one network [25].

In implementing the decomposition approach the important issue is that the accuracy of the model is dependent on how the decomposition is made [7]. Decomposing the system being studied into small components provides for a more detailed representation of its performance. However, a too fine decomposition may meaninglessly complicate the model without much gain in accuracy and useful information for evaluation, analysis and adequate decision-making. Consequently, a very important issue is to determine the appropriate level of decomposition to include in the simulation model.

A rail network can be decomposed into rail yards (either flat-shunted and/or hump), rail freight terminal, rail lines (double and single-track), junctions, and rail passenger stations. By inference, which of these components are included depends on the rail network layout. Our simulation rail network model consists of three flat-shunted rail yards, five rail freight terminals, seven railway double lines and eight rail passenger stations. It should be noted that this model does not include single rail lines and junctions.

Furthermore, depending on the required level of analysis some of the rail network components may be further decomposed. For instance, a rail yard may be further decomposed into its components, such as: Arrival Yard, Shunting Zone, Departure Yard, Locomotive Workshop and Car Yard. In this way, one is able to obtain measures of performance per rail yard component and also for the whole rail yard as a separate system (e.g., [27,28,33,22]).

In this paper, for simulation modelling purposes we further decompose the rail yards (three in total) being part of the rail network under investigation into their components. The adopted concept is presented in detail elsewhere [22] and therefore we shall not repeat its presentation here.

The rail yards play a very important role in providing "network-based" services with freight trains. In practice it has been shown that the rail yards are the major sources of delay in the rail freight networks. Because of the "up-stream down-steam" flow nature of the rail freight system, a malfunctioning rail yard may compromise the entire service, causing up-stream delays and downstream idle periods. In such awkward situations, the final product of rail freight service rapidly deteriorates and the system is forced to incur a significant increase of long term average costs and possible loss of traffic to the competition. Therefore in order to save time and investigation effort, when one aims to analyze and evaluate freight train operations in a network, it is preferable and more productive to begin by analysing rail yards. In this work, we explicitly focused on flat-shunted yards performing in a network.

5. A mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a network

The employed concept in developing the mesoscopic simulation modelling methodology provided below is to follow the flow of freight trains moving within the components of the rail freight network. In this way the global impact of the complex freight train movement in a network is captured. It is also of significant interest to examine in greater detail the level of influence between the components of the rail network in question as well as allocation of workload over this network. For instance, one may focus on examination of both the level of influence between the rail yards in the network and the allocation of the workloads of these rail yards. One may also take a step further and try to evaluate how the rail freight network performs in the conditions of both improvised operation and structured operation. This issue must not be neglected because it raises an important discussion on towards which basic production pattern the system should be focused on. In terms of some rail freight operators it may be obvious, but in terms of others it may not be, recalling that the railway freight operator under study rarely fulfils the scheduled operation with its freight trains. Therefore it is important that such simulation network models have to take place in order to indicate the negative effect of the unworkable or impractical schedules and chaotic services on the system resulting in low levels of production, low level of system utilization, long uncontrollable queues and significant costs incurred for the company. A more extensive discussion of these important issues is provided later. Here, we have concentrated on the constructive aspects for developing a mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a network using, in particular, the SIMUL 8 event-based simulation computer package, as follows:

(i) There are n freight trains originated over the railway network. These n freight trains are to provide the freight transportation service for the period of experiment.

(ii) The freight trains (which are our work items in the SIMUL 8 environment) are generated by m Work Entry Points. For our purposes these Work Entry Points are named "Generators". The Generators are numerated from 01 to n. The generation pattern of freight trains is controlled to replicate the required freight train arrivals subject to the objectives of conducted experiment. One is able to consider the generation of freight trains to follow a theoretical distribution, an empirical distribution or a time-dependent distribution.

For the objectives of this discussion we controlled the generation patterns to replicate both scheduled freight train arrivals and improvised freight train arrivals by employing time-dependent distributions. The measure of performance observed is the number of freight trains generated per Generator for a certain period of time, i.e., the period of the experiment.

(iii) In order for a more detailed representation to be achieved, as mentioned also above, the railway network dedicated to freight transportation is divided into components such as: rail yards (either flat-shunted and/or hump), rail freight terminals, railway lines (double and single-track), junctions, and rail passenger stations. In the simulation network model each component is codified by an adopted rail facility name and code. The components are included in the model depend on the railway network layout being simulated.

(iv) The railway network components have different characteristics and functions. Therefore for the plausible replication of the railway network being modelled a detailed data collection describing the characteristics and functions of each component is required (e.g., one should collect detailed information for the physical characteristics of the rail facilities, a number of operations per operating process, personnel involved per category, dwell times, throughput times, etc. to be inputted in the model).

Next, the focus is on the components of the rail freight network, as follows:

(v) The rail freight terminals are facilities in which loading and unloading processes with freight trains are fulfilled. They are characterized with finite capacities seen in a limited number of tracks. A limited number of terminal tracks are modelled by inserting Storage Areas with finite capacity equal to the number of available tracks. It is assumed that the loading and unloading tracks may also be used for freight trains to queue. Depending on the technical configuration of these facilities, it may also be assumed that only one freight train at any time can occupy any available track. The operating processes at the rail freight terminals are modelled by inserting a Work Centre(s). Service times vary in accordance with the technical configuration, available equipment and adopted work technology. Measures of terminal performance include the number of total entered freight trains, queueing times, the number of processed freight trains, the percent of time for which the rail freight terminals are either awaiting work, working, blocked, or stopped.

(vi) Double railway lines are modelled by separate Work Centres, inserting Work Centres to replicate the train movement for each direction. The number of Work Centres depends on the desirable level of decomposition. The travel time on a track is identical with the service time considered in Work Centre(s). Travel times vary according to the line length, traction, alignment, slope, number and radius of curves. The travel times of the freight trains can be taken from the actual timetable.

(vii) The concept for replicating single rail lines is that the freight trains travel in the two directions using the same track. Thus, a single railway line is modelled by single Work Centre(s) that represents the freight train movement on both directions. Travel times are deterministic, but with an added random component. The distribution describing the random component is an input to the model. This concept has been supported in the work of Dessouky and Leachman [7].

(viii) Here the focus is on rail yards. At this point of the simulation modelling methodology an entire (say) micro level simulation modelling methodology at mesoscopic level of analysis may take place. Such a methodology is extensively presented elsewhere [22] and therefore we shall not provide a detailed description here. Instead, more details are provided in Section 6 “Case Study” of this paper.

(ix) The junctions are facilities that merge or split two or more railway lines. Depending on the technical configuration, available infrastructure and adopted work technology the train operations at junctions can be modelled by one or two Work Centres as well as Storage Areas in order to replicate the limited number of tracks and the places where a train may wait to meet another train. Either way, the replication of these facilities (i.e., the number of Work Centres and Storage Areas inserted) strongly depends on the layouts of the junctions being modelled.

(x) Passenger rail stations have an auxiliary function in the rail freight movement. The freight trains that bypass some terminals/yards use the main lines of passenger rail stations. They are modelled by Storage Areas with a finite capacity equal to a number of rail station lines and Work Centre(s). Service times inserted in the Work Centres are the scheduled times of the trains passing through the passenger rail stations without stopping.

(xi) In order to indicate where a freight train(s) leaves the system and practically terminates its service, l Work Exit Points are used. Measure of performance observed is the number of freight trains left the system through the l Work Exit Point.

By implementing the foregoing mesoscopic simulation modelling methodology one creates event-based simulation models for analysing and evaluating operating processes with freight trains in a rail network.

An important part of the simulation modelling process is the calibration and validation of the created models. This can be done by comparing the results obtained from the model with data collected from the real system. If the rail operator does not collect and maintain operational data suitable for the calibration and validation of the simulation models, then data can be collected through observations and interviews with the operational personnel (e.g., yard crews). Calibration and validation of the simulation model can then be achieved by employing analytical techniques.

For the purposes of this study data has been collected through observations of the flat-shunted yards in question and interviews with the managers of the yard crews. Average values of operating times and waiting times have then been estimated. Analytical models employing G/G/m queues have been developed. The results obtained from the G/G/m models have been used to calibrate the simulation models developed. A detailed discussion of G/G/m models for analysing yard performances is presented in Ref. [20] and therefore we shall not discuss this issue further within this paper. Also, the raw data collected and used throughout this work have intentionally not been presented in full operational detail. This is to ensure the security of confidential information provided by the railway freight operator under study “CP Carga”, and also ensures this study does not violate any current strategic actions and agreements in which the railway freight operator under study is involved.

After the simulation models are created and calibrated, a number of simulation trials can be run and the system behaviour can be examined under different conditions and traffic rules. By these means it is possible to obtain performance measures for any component or even subcomponent of the rail freight network separately. The results obtained should be validated by the operational personal and/or rail freight planers.

For the objectives of this discussion the focus is on the component “*rail yard*” and its subcomponents, such as: Arrival Yard, Shunting Zone, Departure Yard, Locomotive Workshop, and Car Yard. The measures of yard performance are obtained and the similar yards’ subcomponents are compared. Also, it is necessary to evaluate rail yards performing in a network

Fig. 6.1. Rail network under study (in bold black).

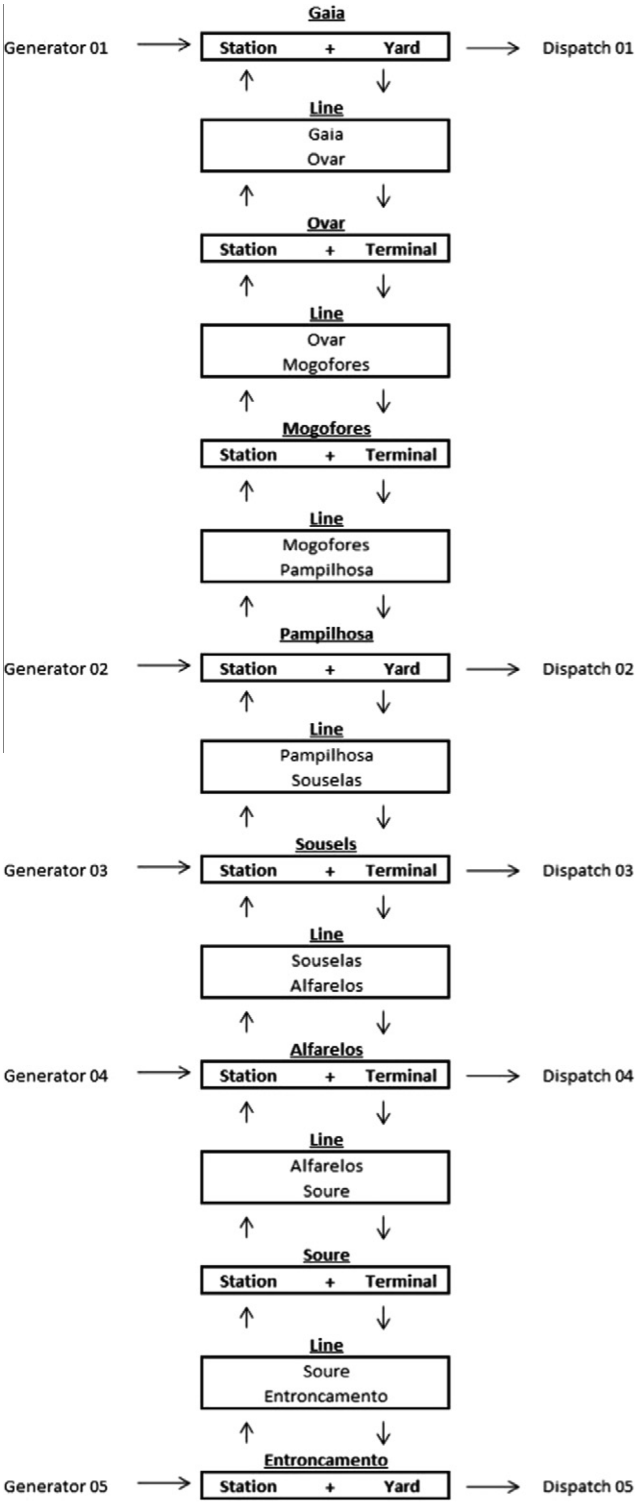
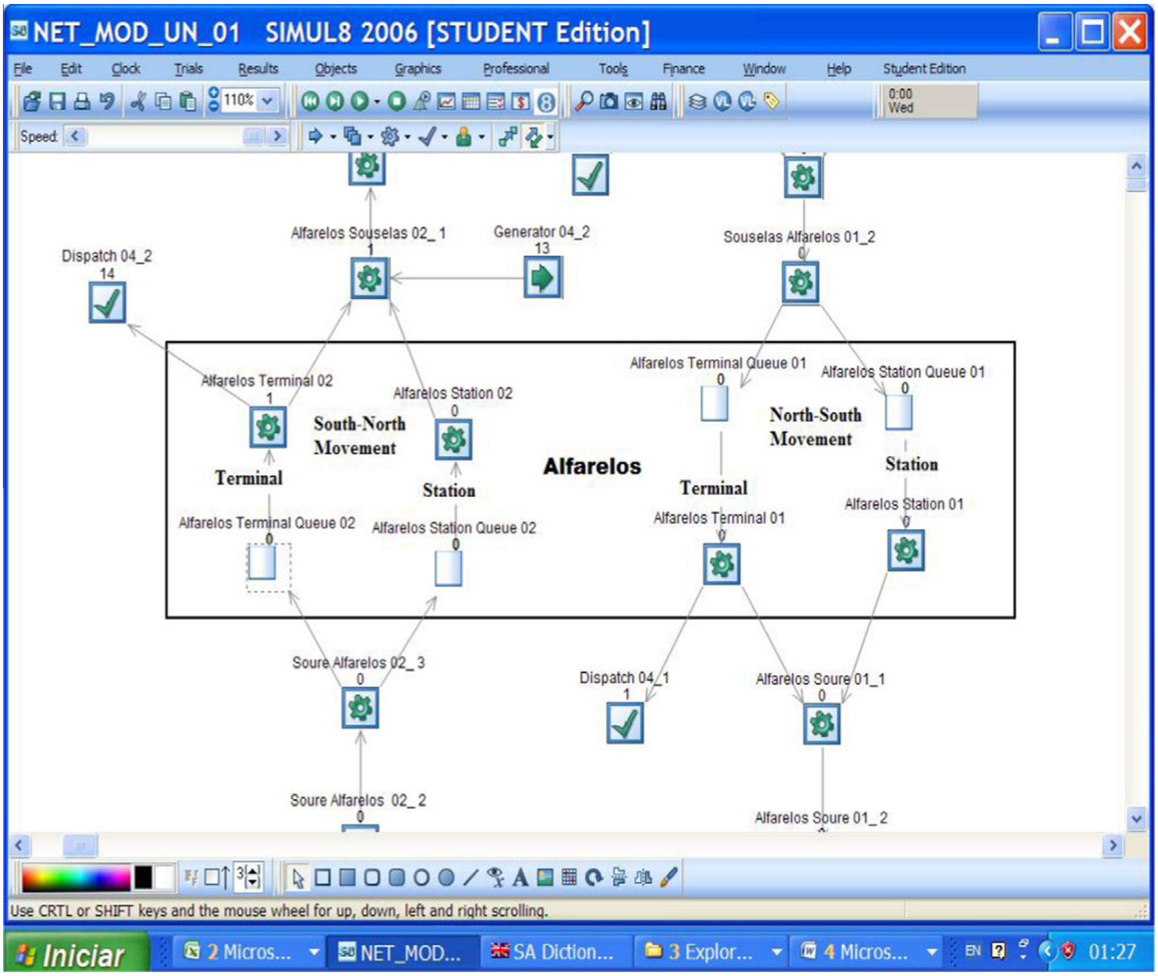


Fig. 6.2. Rail network decomposition.

through aggregate measures of yard performance [19] such as: total number of freight trains entered in the rail yards in the network; total number of freight train processed by the rail yards in the network; total average queueing time in the rail yards in the network per freight train for a certain period of time.



Use CRTL or SHIFT keys and the mouse wheel for up, down, left and right scrolling.

Fig. 6.3. A screenshot showing the replication of Alfarelos rail facility in SIMUL 8.

6. Case study: freight train operations in a network consisting of three rail yards

6.1. Description

In this section the analysis was based on a real world situation with freight trains operating in a rail network. In particular the focus was on operating processes with freight trains at three rail yards which belong to one rail network. The main rail line that connects these three yards is "Linha do Norte", in Portugal. The three yards are Gaia, Pampilhosa and Entroncamento; and all of them are flat-shunted yards. The three rail yards and the line connecting them are shown in Fig. 6.1 with bold black lines connecting grey rings. These rings indicate where the three yards under study are situated on the territory of Portugal.

Linha do Norte is an electrified double track line. This line is the rail connection between the two biggest cities in Portugal, Lisbon and Porto. All categories of Portuguese trains run on this line. It is not intended to enter into greater detail here, recalling that this study deals with analysis and evaluation of freight train operations in a network, where the emphasis is placed upon the performance of three rail yards being part of the same network. What is of importance is that the global impact over the rail network is captured. This is made feasible by our event-based-oriented simulation model, where freight train movements were simulated from Gaia rail facility to Entroncamento rail facility and vice versa. Next, it was possible to aggregate measures of yard subcomponent performance as well as other yard production measures estimated by the rail freight network simulation model. It should be noted that only rail facilities open for rail freight operations were considered in the network. Way rail stations in which the freight trains do not stop are considered as a part of the line.

For research purposes the decomposition approach is implemented. A schematic presentation is shown in Fig. 6.2. The rail network under study is split as follows:

- Three rail yards – i.e., Gaia, Pampilhosa and Entroncamento.
- Eight railway stations – i.e., Gaia, Ovar, Mogofores, Pampilhosa, Souselas, Alfarelos, Soure and Entroncamento.

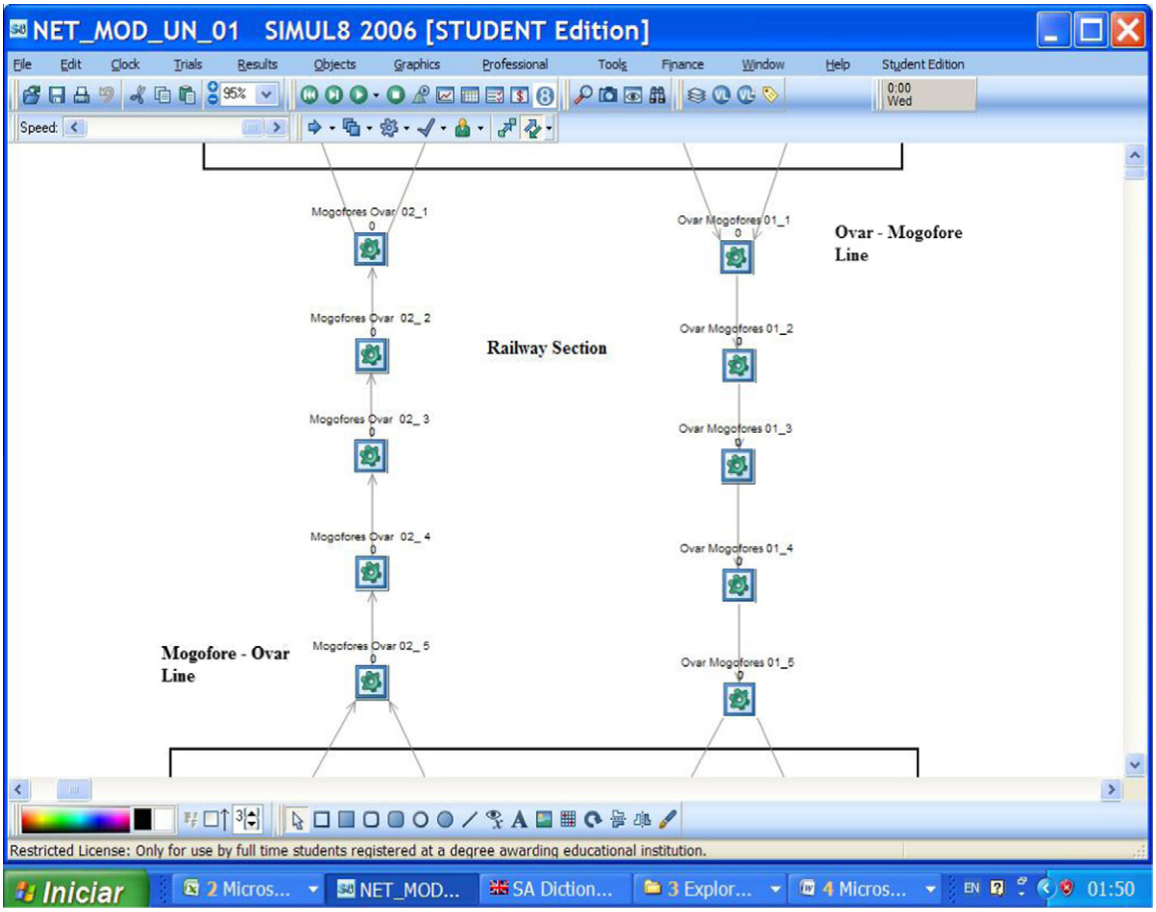


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Fig. 6.4. Modelling attributes of Ovar–Mogofores line in SIMUL 8.

- Seven lines or rail sections.
- Five rail freight terminals – i.e., Ovar, Mogofores, Souselas, Alfarelos, Soure.

Most of scheduled freight trains run from rail yard to rail yard without intermediate service activity on the line. There are a few daily freight trains operating as multi-stopping trains (also called liner freight trains) that serve the rail freight terminals being part of the rail freight network.

It is essential to restate that freight trains are generated in SIMUL 8 by "Work Entry Point" Attributes and it is possible to indicate when the freight trains leave the system by "Work Exit Point" attributes. These attributes are Generators and Dispatches, respectively.

More specifically, in the network there are five places in which generations of freight trains occur and five places in which the freight trains leave the network. The "Generators and Dispatches" are numerated form 01 to 05 and in Fig. 6.2 they are indicated, as follows: Generator 01/Dispatch 01 – Gaia; Generator 02 – Pampilhosa; Generator 03/Dispatch 03 – Souselas; Generator 04/Dispatch 04 – Alfarelos; and Generator 05/Dispatch 05 – Entroncamento. Here, the generation processes of freight trains are subordinated to time-dependent distributions. In general, two experiments are conducted. In the first experiment the generation of freight trains is subordinated to time dependant distribution with uniform inter-arrivals. This makes it possible to study the effect of the scheduled operation on the "yards-in-network" performance. In the second experiment we consider time-dependent freight train generations with exponential inter-arrivals; this makes it possible to study the "yards-in-network" performance in terms of improvised rail freight operation.

Next, before proceeding with the experiment further explanations are provided of how the rail freight network components are replicated in SIMUL 8 environment. It is, as follows:

6.1.1. Rail freight terminals and railway stations

The *rail freight terminals* in the network are situated close to the rail passenger stations. These rail facilities are replicated by two Storage Areas and two Work Centres, where one Storage Area and one Work Centre replicate the North–South operation and one Storage Area and one Work Centre replicate the opposite operation. The Storage Areas are set up with finite

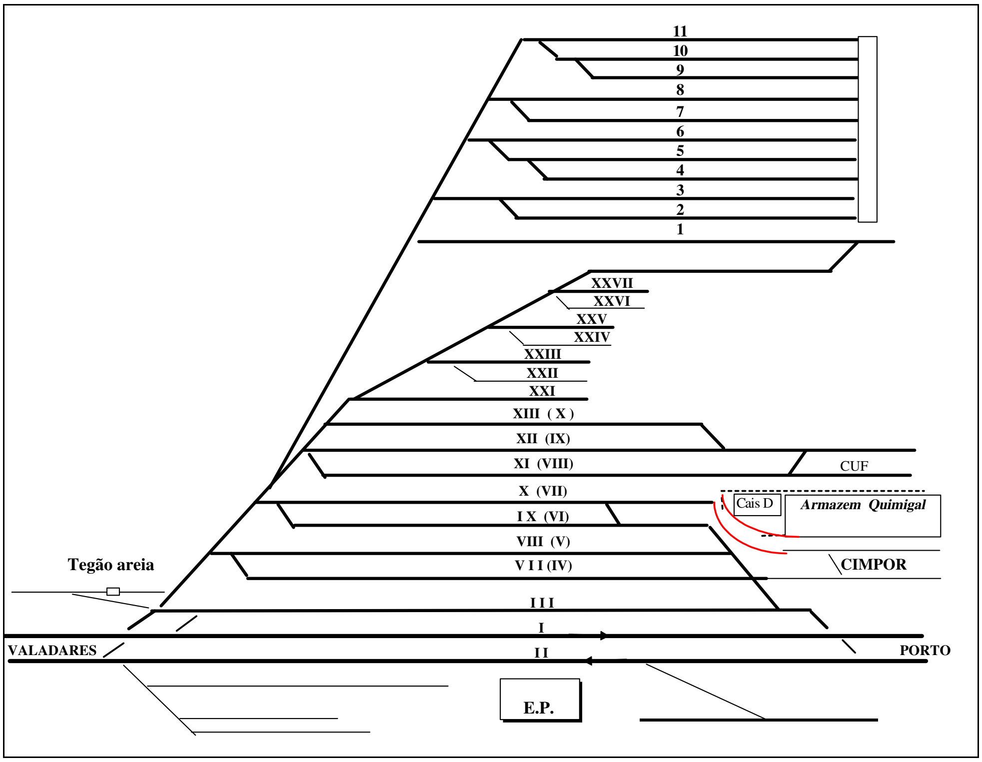

Fig. 6.5. Layout of Gaia rail yard. *Source*: Department of Planning and Control, CP Carga.

capacities equal to the number of terminal tracks. The service times in the Work Centres are set up equal to the dwell terminal times of freight trains. These times vary according to the terminal configurations and work technologies employed. It should be noted that the dwell terminal times used in the model are supplied by the planning personnel of CP Carga.

The *rail passenger stations* are also replicated by two Storage Areas and two Work Centres, where one Storage Area and one Work Centre replicate the North–South train movement and one Storage Area and one Work Centre replicate the South–North train movement. The Storage Areas are used to replicate the limited number of station platform tracks. The Work Centres replicate the movement of freight trains through the rail passenger station. Thus, the service time in the Work Centres are set up equal to the running times of freight trains through the station involved.

Fig. 6.3 depicts how “Alfarelos” rail freight terminal together with “Alfarelos” rail passenger station are produced in SIMUL 8 environment. The attributes in the outlined area belong to “Alfarelos” rail facility. The empty graphic tanks are the Storage Areas; the attributes with the gears are the Work Centres, which are properly grouped to replicate North–South and South–North train movement.

6.1.2. Lines and travel times

The *lines* (railway sections) between the rail stations are replicated by a number of consecutive Work Centres. It is assumed that the time for service at such a Work Centre corresponds to the travel time of a freight train through a given rail section. For instance, the Ovar–Mogofores line is modelled by five consecutive Work Centres as shown in Fig. 6.4. For the rail freight network simulation modelling purposes, the travel times of freight trains over the lines are taken from the actual timetables of rail freight operator under study (i.e., CP Carga, Portugal).

6.1.3. Rail yards

There are three rail yards in the rail freight network under study. These are Gaia, Pampilhosa and Entroncamento. The operating processes with freight trains at Gaia and Pampilhosa rail yards are identical. The layouts of these two facilities are shown in Figs. 6.5 and 6.6. Either Gaia or Pampilhosa employs: one shunting crew that fulfils the reassembly process, one classification person and one inspection person at any time.

The throughput line of these two yards is identical, as follows: the inbound freight trains arrive on only few tracks that specify the yard arrival area or in other words this is the Arrival Yard. There a shunting person is required to cut the road locomotive from the composition. After having cut the road locomotive, the locomotive usually goes to a designated area within the yard limits to wait for its next assignment. This area is designated the Locomotive Workshop of the yard. Next, classification of freight cars is fulfilled by a classification person, i.e., the classification person walks around the composition

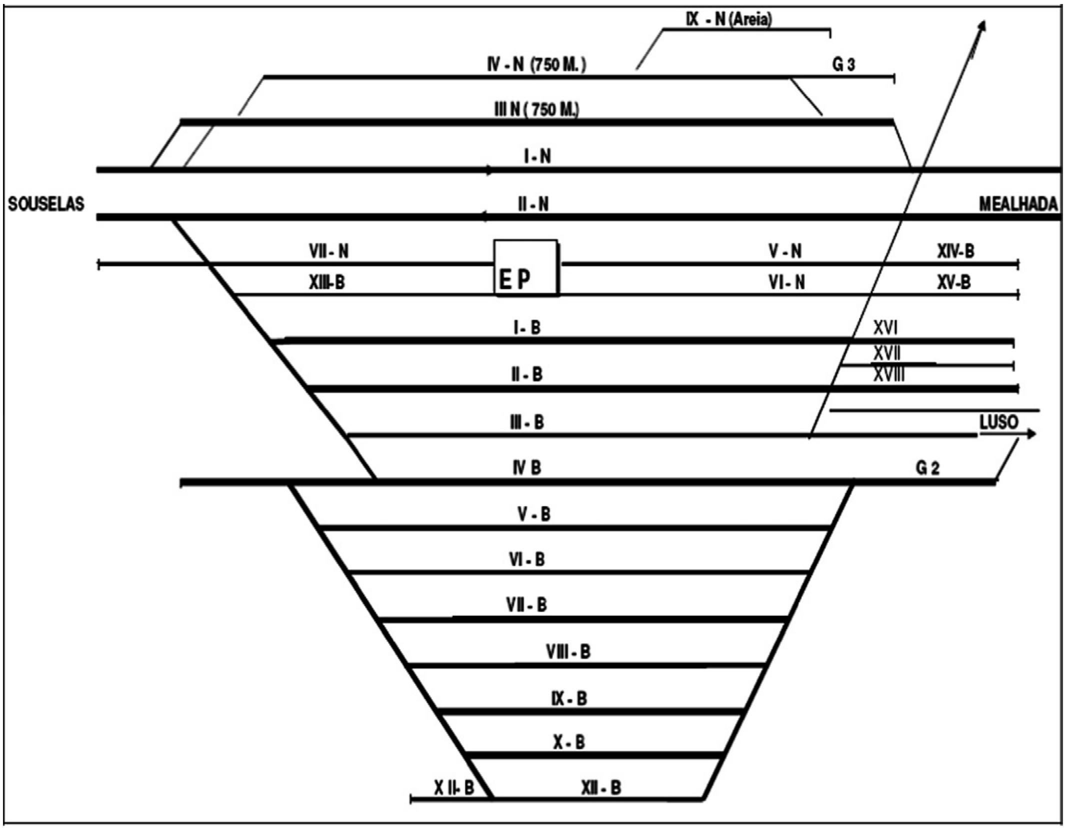

Fig. 6.6. Layout of Pampilhosa rail yard. *Source*: Department of Planning and Control, CP Carga (improved by the authors).

to be shunted indicating the next destination of each freight car (either empty or loaded). According to the indications provided by the classification person the reassembly operation is executed by a shunting crew.

Before beginning the first part of the reassembly operation, which is the breaking down of freight train, however, the composition undergoes a technical inspection, meaning the running conditions of each freight car are verified by an inspection person. If defects or failures on freight cars are detected the inspection person indicates these freight cars to be withdrawn. Usually, freight cars found having defects are stored temporarily on tracks specified for storage. These few tracks define the Car Yard area which is not strictly defined and therefore is considered as a part of the Shunting Zone of the yard.

Next, the breaking down operation is fulfilled, meaning the composition is broken down into freight car groups on some tracks that specify the Shunting Zone of the yard. The breaking down operation is followed by the second part of the reassembly operation, which is the making up of the outbound freight trains or in other words this is to assemble a new freight train composition. The making up of the outbound freight trains is fulfilled by the same shunting crew that breaks down the inbound freight train.

Next, the new train formations are positioned on tracks that specify the departure area of the yard (i.e., Departure Yard), where they wait for a road locomotive to arrive and to be connected. In daily operation of CP Carga the road locomotive drivers are responsible to verify the conditions of road locomotives and a technical inspection of each road locomotive is executed by the locomotive driver before every locomotive duty.

In the meanwhile the freight cars of the newly assembled formation are inspected again for departure. After having arrived and put the road locomotive on the formation, the full brake test is fulfilled. If defects or failures on outbound freight train are detected, then a further dis-assembly process is required. If problems are not detected the conductor of the road crew puts the beacon on the rear of the train formations and the outbound freight train is ready to leave the yard. The operation on leaving the yard is assisted with a traffic worker and is completed after having received a "green" signal given by the line dispatcher.

Based on the throughput line of these yards it is possible to split them into areas for modelling purposes. These areas are Arrival Yard, Shunting Zone, Car Yard, Locomotive Workshop and Departure Yard. Each yard area consists of a number of subsystems. Each subsystem replicates a given operation (e.g., one subsystem for cutting the road locomotive, one subsystem for classification and inspection called "commercial and technical inspections", one subsystem for breaking down called "breaking down", one subsystem for brake test before departure called "train-engine operations", one subsystem to replicate the departure of freight train called "leaving the yard" and so on). In SIMUL 8 environment, all the subsystems of the

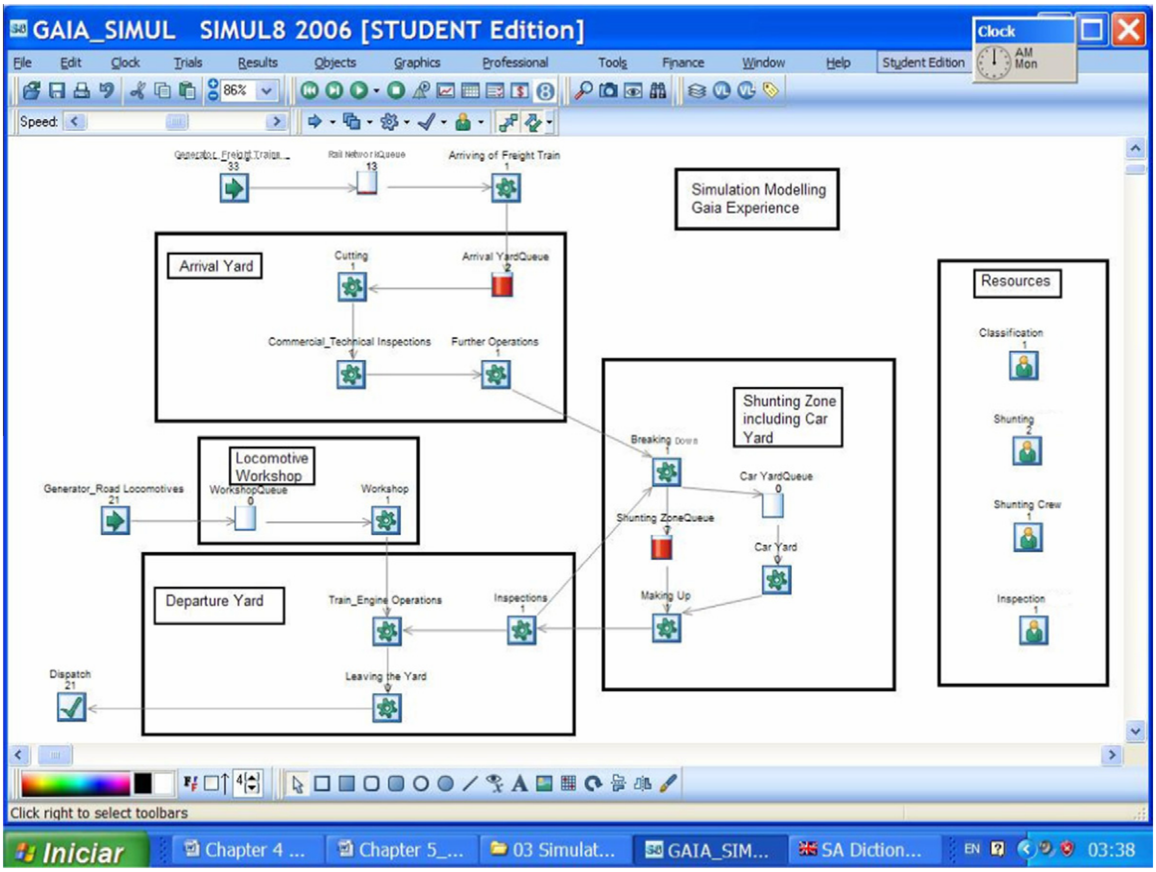

Fig. 6.7. A complete screenshot of Gaia rail yard (SIMUL 8 animation window).

specified yard areas are replicated by individual Work Centres consisting of the proper characteristics of the subsystem being replicated. In order to replicate the limited number of tracks within each yard area, Storage Areas are inserted.

Thus, a complete screenshot of the SIMUL 8 animation window of Gaia rail yard can look similar to Fig. 6.7. Note that all yard areas and subsystems are properly named. The routing through yard areas and subsystems is demonstrated by arrows and following the arrows' courses it is possible to recognize the throughput line of the yard. The subsystems are grouped in a way that clearly shows which subsystem belongs to which yard area, how many there are and whether or not there is a Storage Area. Note that there is no Storage Area in the Departure Yard of Gaia. This is because the making up of freight train and all the subsequent operations on outbound freight train departure are fulfilled on the same track, meaning the tracks used for making up and departure operations overlap. This phenomenon requires no Storage Area in Gaia Departure Yard. The yard personnel (i.e., classification person, inspection person and shunting crew) that perform the yard operation are grouped on the left (figure's projection – under the title "resources"). As was mentioned, it was possible to obtain and observe the rates of their utilization.

The throughput line employed in Entroncamento rail yard does not differ significantly from Gaia and Pampilhosa yards. The layout of this yard is shown in Fig. 6.8. However, there is a distinguishing feature, as follows: the classification work of the freight cars is fulfilled by two employees. The shunting work is performed by two shunting crews, meaning there are two shunting locomotives at any time. The inspection work is executed by two employees as well. Hence, this yard employs two yard crews at any time but none of those pair of working resources work simultaneously on the same freight train.

The animation window of Entroncamento yard in SIMUL 8 environment can look similar to Fig. 6.9, where the different yard areas are outlined clearly. Note that there are two independent throughput lines. One line consists of subsystems indicated with 1 and another line consists of identical subsystems but indicated with 2. Thus, due to the current practice of the operating process with freight trains at Entroncameto flat yard, freight trains travel through the yard following the basic sequence of operations performed by the subsystems indicated with 1 or the subsystems indicated with 2. By inference, there is one classification person, one shunting crew and one inspection person that work in the relevant subsystems of the one throughput line and there is another classification person, another shunting crew and another inspection man that work in the relevant subsystems of the other throughput line. For the sake of simplicity and clearness, these pairs have been named as Classification person 1 and Classification person 2, Shunting crew 1 and Shunting crew 2, Inspection person 1 and Inspection person 2. These names are used throughout the following sections.

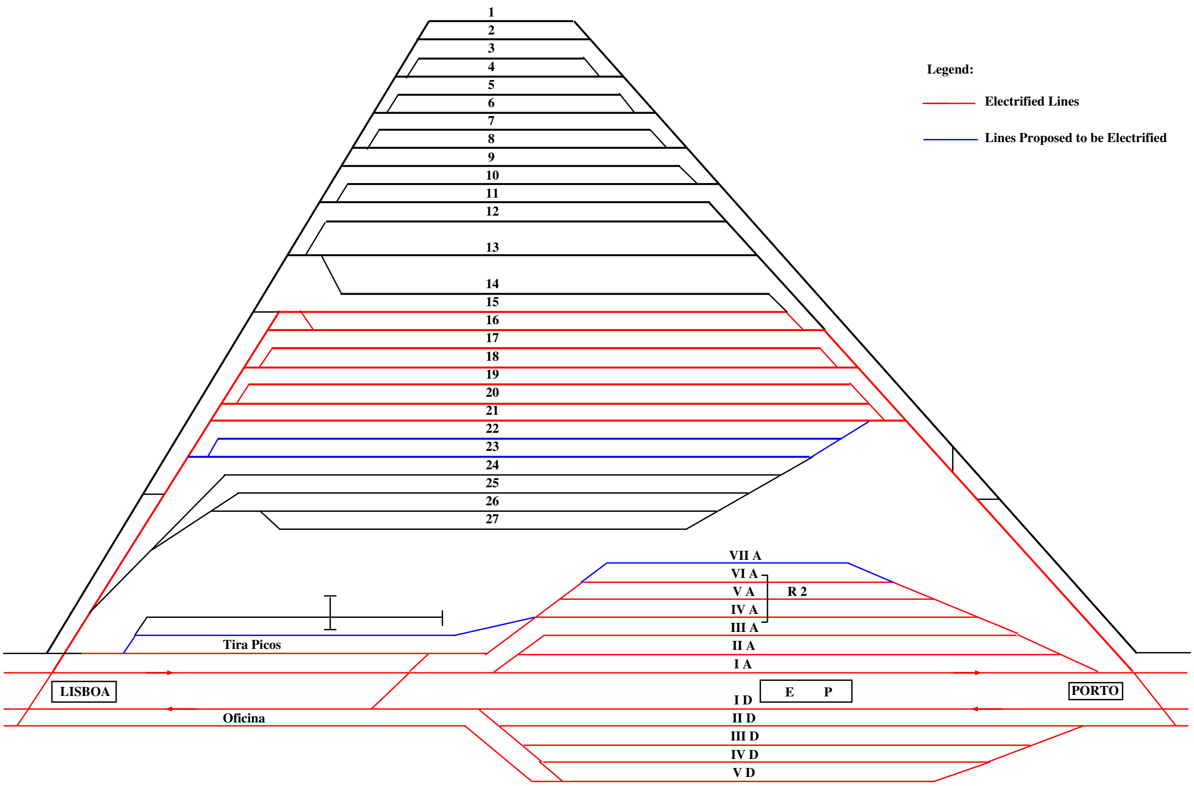

Fig. 6.8. Layout of Entroncamento rail yard. *Source*: Department of Planning and Control, CP Carga.

In the real world, the rail yards are linked to the adjacent rail line by two or more leads. The freight trains use these leads to arrive and leave the yard. Therefore it was necessary to set up in a proper way links between the arriving and leaving yard subsystems and line subsystems. For instance, in Fig. 6.10, it is possible to observe how Pampilhosa rail yard is linked to the adjacent rail line.

6.2. Application and results

The railway freight operator under scrutiny is focused on scheduled freight train operation but the Operations Department encounters difficulties to produce the schedules. Considering this it has been necessary to analyse the effect of schedule deviations and the results obtained are presented in the following sections. For investigative purposes it was necessary to employ time-dependent distributions to replicate the freight train arrivals. There are five places in the network where freight trains get-in/get-out. The freight trains are generated by SIMUL 8 "Work Entry Points" attribute. For clarity they were designated Generator 01, Generator 02, ... Generator 05. The arrival patterns set up in the 01–05 Generators are given in Table 6.1.

In this experiment two simulation trials have been conducted. Each trial consists of 1000 simulation replications (also called "simulation runs"). The results obtained from the two trials are analysed and compared below. In order to avoid the transient period in the simulation, it was necessary to set up a Warm-up period of 24 h (1440 min). The averages and the standard deviations for each of simulation trails have been calculated. The 95% confidence limit ranges for each trail have been calculated with the 0.5 width of the confidence interval determined by default to be no more than 5% of the average value in all cases. In the following sections the average values are presented.

Recalling the two simulation trials, in the first trial small, say, insignificant deviations from the freight train schedules are considered. This is replicated by inserting uniform inter-arrivals. In the second trial significant deviations from the schedules are considered. It was possible to replicate significant deviations using exponential inter-arrivals. For simplicity these were designated the first trial – "insignificant deviation (ID)" and the second trial – "significant deviation (SD)".

In order to analyse the results obtained from the two simulation trials, a number of comparisons focusing on identical subsystems were made. To begin with the percent of time in which three identical rail yard subsystems were either awaiting work, working, blocked or stopped was examined. This was designated as the measure "State of Yard Subsystem". The three subsystems under observation are: commercial and technical inspections in Arrival Yards; Breaking Down of Freight Trains in Shunting Zones; and Train-Engine Operations in Departure Yards. Chart 6.1, from a) to c), compares the results

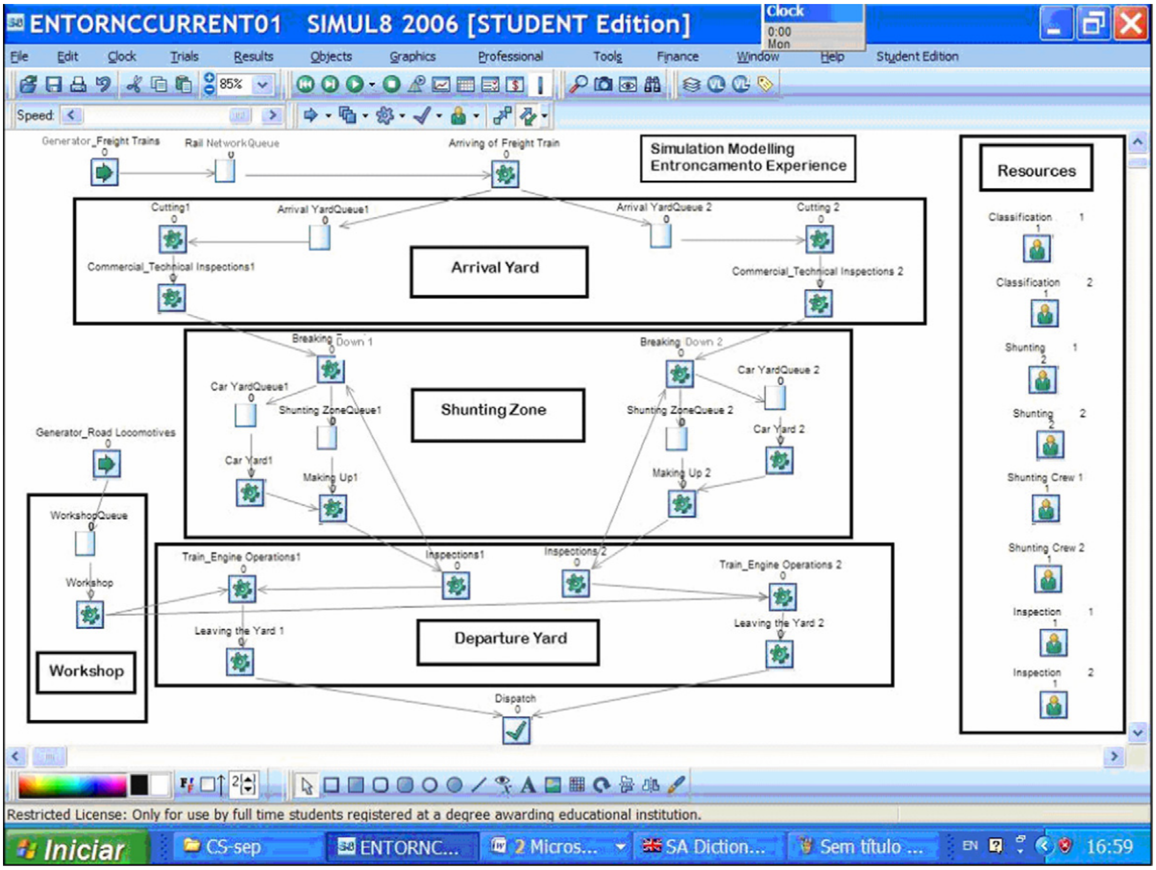

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Fig. 6.9. A screenshot of Entroncamento rail yard within SIMUL 8 animation window.

obtained from the two trials. Generally speaking, the yard subsystems in question demonstrated significant percent of time awaiting work and a low percent of time actually working. This is an indication that low levels of utilization are expected.

Looking at the charts drawn one observes similar results in the context of Gaia and Pampilhosa subsystems' performance. The results obtained from the two simulation trials are interpreted, as follows:

- yard subsystems under insignificant schedule deviation show lower percent of time awaiting work than the subsystems performing under significant schedule deviation;
- yard subsystems under insignificant schedule deviation show higher percent of time actually working than the subsystems performing under significant schedule deviation;
- yard subsystems under significant schedule deviation appear to be more saturated than yard subsystems under insignificant schedule deviation.

Within the context of Entroncamento subsystems performance, however, the situation appears to be on the other way around for the subsystems dedicated to Commercial and Technical Inspections and breaking down of freight trains. This apparently strange fact requires further examination. Therefore the yards' queues were investigated. In Table 6.2 the results obtained for the average queue sizes for both insignificant deviation and significant schedule deviation are given. A key feature is that when the schedule deviations are insignificant (Table 6.2, first column, "insignificant deviation") the subsystems maintain relatively low queue sizes. It should be noted that low queue sizes result in short queueing times, which is of no little interest to the system.

In Chart 6.2 the queueing times in Arrival Yards and Shunting Zones of the three rail yards under study for the two trials (i.e., ID and SD) are compared. The longer time in the queue in the significant schedule deviation trial is apparent for most yard subsystems. This difference in the queue results is most apparent in terms of Entroncamento rail yard. For instance, the second shunting queue of Entroncamento in ID trial shows "time in queue" up to 3.25 min. In the significant schedule deviation trial, however, this result is up to 58.73 min, approximately one hour. It appears that this is the queue in Entroncamento yard that requires the pair of working resources acting within the yard at any time. Further, this would suggest that the

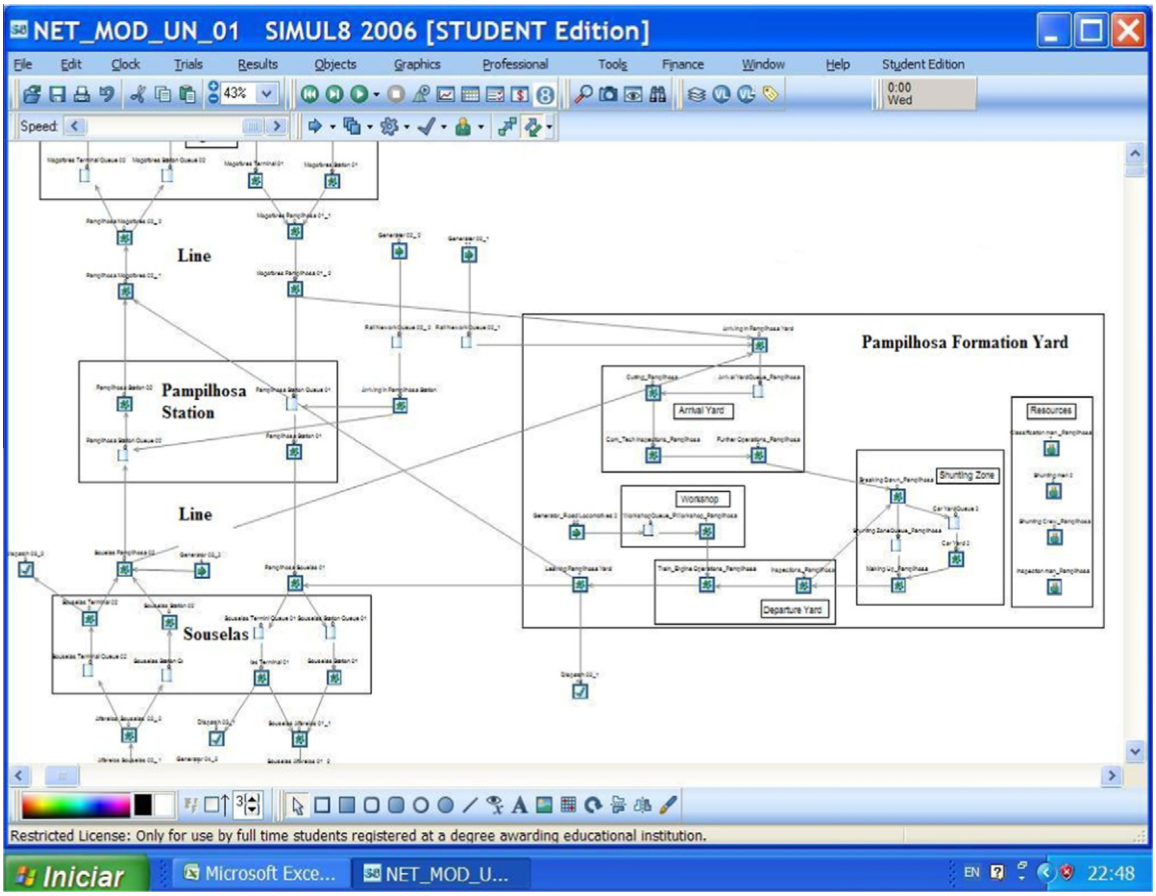

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Fig. 6.10. A screenshot of SIMUL 8 animation window showing attributes of Pampilhosa yard linked to attributes of the adjacent rail line.

railway freight operator currently tries to resolve its operation problems by adding personnel; not by focusing on reduction of variability in freight train movement as well as fulfilment of its schedules.

It is worth mentioning that, because of the element of predictable variability imposed by the schedule, the states of yard subsystems do not appear to be directly correlated with the queueing times and lengths. The states of yard subsystems depend on arrival and departure pattern of freight trains over a certain period of time, allocation of resources and production scheme of the movement of freight trains in the railway network. On the other hand the queueing times and lengths in rail freight yards are subordinated to the phenomenon of cyclic queue in which the queue may only grow and not shrink over a certain period of time (e.g., see [18]). Therefore, for the accuracy of the analysis, arrival and departure processes, utilization rates, and workloads have to be examined; discussion of which comes next.

Also, as a next step, it is possible to speak of schedule reliability problems, a subject not touched on here, as the work is underpinned with the actual timetable supplied by the Planning Department of CP Carga as input. This topic is of interest for further research and should be conducted after having accomplished and experienced, to some extent, the structured freight train operation over the rail network. It should not be forgotten that there may be a schedule that is at the envy of the world but this schedule is useless if the operation unit cannot produce it.

In the following section the utilization rates of yard personnel were examined. More specifically, it was necessary to examine the utilization rates of classification persons, shunting crews and inspection persons. In Table 6.3 the utilization level estimates for the ID and SD simulation trials are given. Note that in the insignificant schedule deviation trial the utilization rates of Gaia and Pampilhosa personnel appear to be identical and as a whole they are higher than those estimated in the significant schedule deviation trial. The situation in Entroncamento yard differs, however. The utilization levels of Entroncamento personnel demonstrate higher values in the significant schedule deviation trial by comparison with the same estimates obtained in the insignificant schedule deviation trial. In order to clarify *the reason* for this situation, it was necessary to look at the workloads of the rail yards under study.

In Table 6.4 the yard workloads obtained from the conducted experiment are given. Note that the Gaia and Pampilhosa workloads, seen in the number of freight trains entered and left the yards, are significantly lower in terms of significant schedule deviation than those obtained in insignificant schedule deviation.

Table 6.1
Time-dependent distributions to replicate arrival patterns of freight trains: Gaia, Pampilhosa, Souselas, Alfarelos and Entroncamento.

Periods	Freight train arrivals
Time-dependent distribution, Generator 01 (Gaia)	
From 0:00 to 11:00	0
From 11:00 to 12:00	2
From 12:00 to 13:00	0
From 13:00 to 15:00	3
From 15:00 to 16:00	0
From 16:00 to 19:00	3
From 19:00 to 20:00	0
From 20:00 to 23:00	2
From 23:00 to 24:00	3
Time-dependent distribution, Generator 02 (Pampilhosa)	
From 0:00 to 01:00	0
From 01:00 to 02:00	1
From 02:00 to 11:00	0
From 11:00 to 12:00	1
From 12:00 to 14:00	0
From 14:00 to 15:00	1
From 15:00 to 18:00	0
From 18:00 to 19:00	2
From 19:00 to 20:00	0
From 20:00 to 21:00	1
From 21:00 to 24:00	0
Time-dependent distribution, Generator 03 (Souselas)	
From 0:00 to 11:00	0
From 11:00 to 12:00	1
From 12:00 to 13:00	0
From 13:00 to 14:00	1
From 14:00 to 19:00	0
From 19:00 to 20:00	1
From 20:00 to 24:00	0
Time-dependent distribution, Generator 04 (Alfarelos)	
From 0:00 to 01:00	0
From 01:00 to 02:00	2
From 02:00 to 05:00	0
From 05:00 to 06:00	1
From 06:00 to 09:00	0
From 09:00 to 10:00	3
From 10:00 to 14:00	0
From 14:00 to 15:00	1
From 15:00 to 21:00	0
From 21:00 to 24:00	3
Time-dependent distribution, Generator 05 (Entroncamento)	
From 0:00 to 01:00	0
From 01:00 to 02:00	1
From 02:00 to 03:00	0
From 03:00 to 04:00	1
From 04:00 to 08:00	0
From 08:00 to 10:00	3
From 10:00 to 11:00	0
From 11:00 to 13:00	4
From 13:00 to 15:00	0
From 15:00 to 18:00	4
From 18:00 to 19:00	0
From 19:00 to 20:00	4
From 20:00 to 21:00	0
From 21:00 to 24:00	5

The obtained workloads in Entoncamento, however, appear to be similar in the two simulation trials, meaning in both ID and SD. This verifies once again that in equally likely workloads the performance of the rail yard is highly dependent on the fluctuations in the arrival process of freight trains. Chart 6.2 supports this statement, showing that the yard queue behaviour is subordinated to the type of the network freight train production pattern in execution. In general, this suggests that:

- The more structured and scheduled the network freight train operation is, the lower the yard queue becomes.
- The more chaotic and disorganized the freight train movement becomes, the larger the yard queue grows.

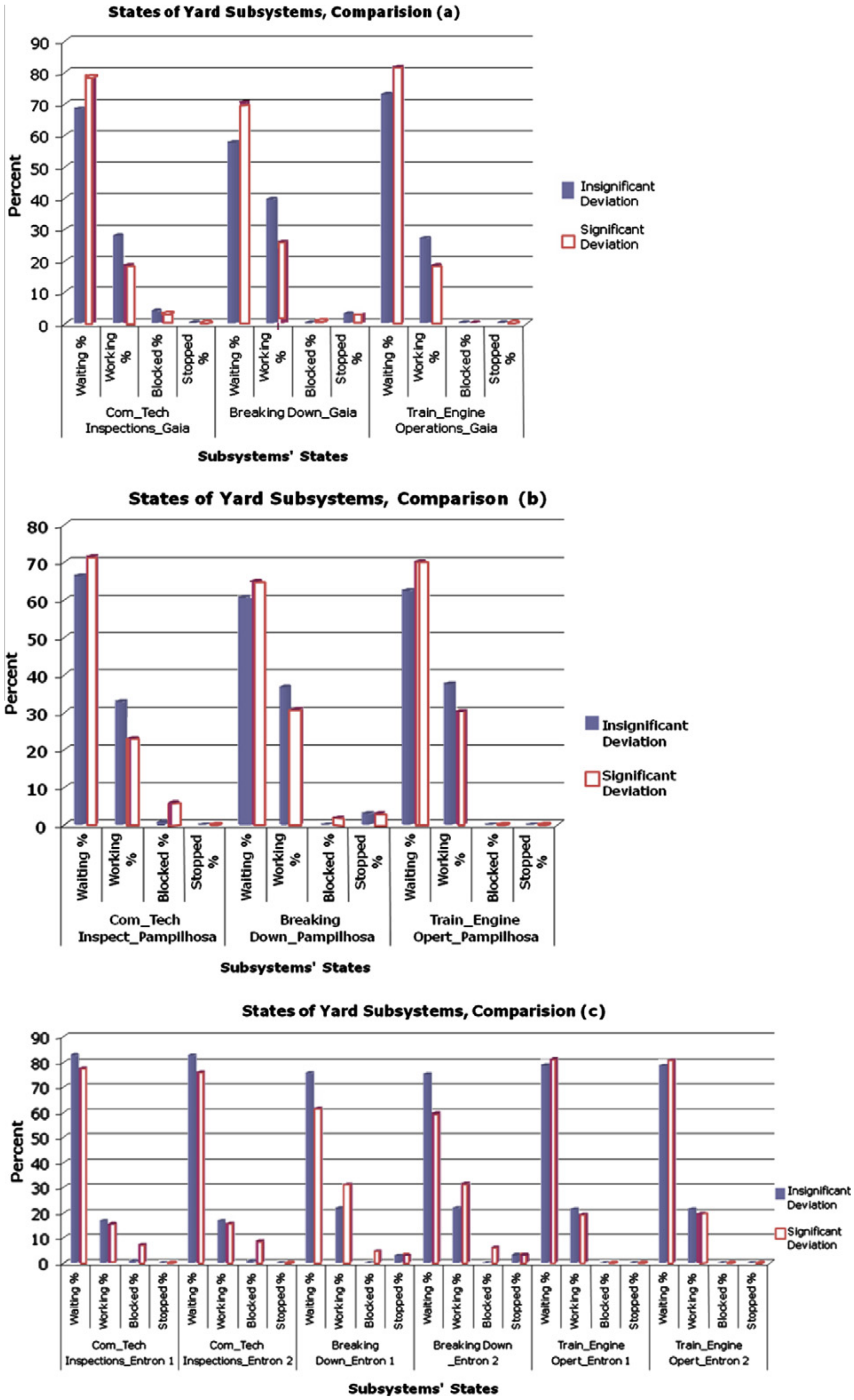

Chart 6.1. "ID vs. SD" – comparisons of the results obtained for "states of yard subsystems": (a) Gaia; (b) Pampilhosa and (c) Entroncamento, *According to the current practice of CP Carga there are pairs of working resources in operation in Entroncamento yard. Therefore, here are the results obtained for the states of six yard subsystems.

The time in queue is a direct waste which is very costly for the railway freight operator and the customer alike. The chaotic uncontrolled freight train operation over the rail network causes the queues to materialize and hence forces the system

Table 6.2
“ID vs. SD” average yard queue lengths.

Simulation object	Insignificant deviation Average	Significant deviation Average
Average queue sizes, three formation yards		
Arrival Yard Queue Gaia	0.02	0.07
Shunting Zone Queue Gaia	0.48	0.37
Arrival Yard Queue Pampilhosa	0.05	0.11
Shunting Zone Queue Pampilhosa	0.2	0.55
Arrival Yard Queue 1 Entroncamento	0.0006	0.07
Arrival Yard Queue 2 Entroncamento	0.0008	0.09
Shunting Zone Queue 1 Entroncamento	0.04	0.83
Shunting Zone Queue 2 Entroncamento	0.04	0.94

Table 6.3
“ID vs. SD” utilization rates of yard personnel.

Simulation object	Insignificant deviation Average	Significant deviation Average
Utilization rates of personnel, three rail yards (in %)		
Classification person – Gaia	27.8	18.56
Shunting crew – Gaia	58.8	38.8
Inspection person – Gaia	52.04	34.66
Classification person – Pampilhosa	28.89	22.91
Shunting crew – Pampilhosa	59.91	50.16
Inspection person – Pampilhosa	51.84	42.31
Classification person 1 – Entroncamento	16.63	15.36
Classification person 2 – Entroncamento	16.72	15.57
Shunting crew 1 – Entroncamento	30.68	44.10
Shunting crew 2 – Entroncamento	30.84	44.44
Inspection person 1 – Entroncamento	30.13	34.64
Inspection person 2 – Entroncamento	30.3	34.99

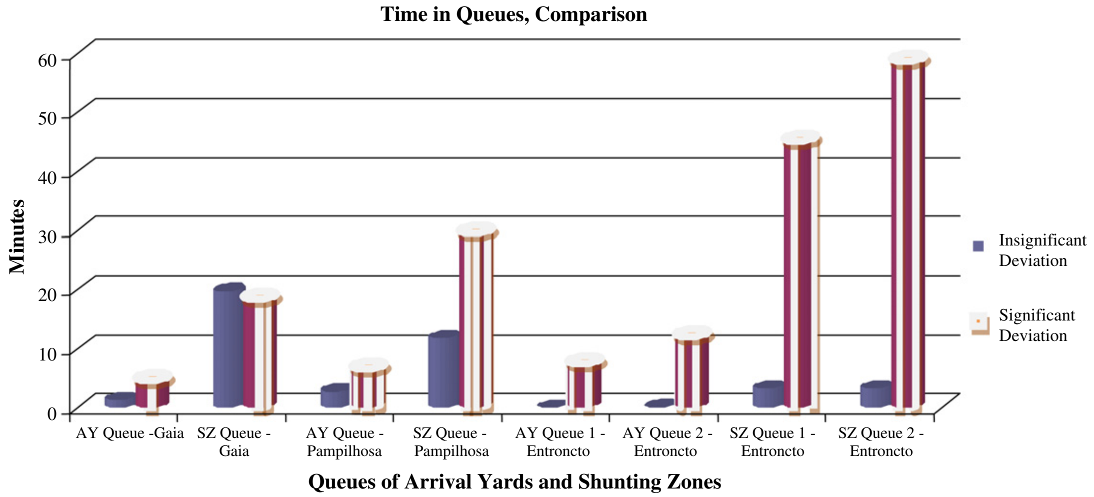

Chart 6.2. “ID vs. SD” queueing times in rail yard subsystems, *AY – Arrival Yard; SZ – Shunting Zone.

to suffer significant unjustifiable monetary losses. Therefore, the effort should be towards a controlled fixed freight train service; not towards adding extra operational yard personnel. If a significant schedule deviation is the case, then the operational yard personnel cannot contribute a lot to the efficiency of the entire freight train operation. The senior management should bear this in mind when decisions of this type are made.

Further, it should be noted that the results obtained from our experiment indicate loss of business when significant schedule deviations occur more often. Loss of business is intimately connected with reduction of revenue, idle systems,

Table 6.4
"ID vs. SD" rail yard workloads.

Simulation Object	Insignificant Deviation Average	Significant Deviation Average
Workloads of rail yards		
Freight trains entered in Gaia	22.9	15.3
Freight trains left Gaia	22.25	15.07
Freight trains entered in Pampilhosa	23.73	18.84
Freight trains left Pampilhosa	24.01	19.20
Freight trains entered in Entroncamento – 1st line	13.7	12.7
Freight trains entered in Entroncamento – 2nd line	13.7	13.02
Freight trains left Entroncamento – 1st line	13.6	12.24
Freight trains left Entroncamento – 2nd line	13.7	12.48

Table 6.5
"ID vs. SD" aggregate yard measures of performance.

	Insignificant deviation Total average	Significant deviation Total average
Aggregate measures of network yard performances		
Freight trains entered in the yards (number)	74	60
Freight trains left the yards (number)	74	59
Queueing time in the Arrival Yards (min)	4.16	30.64
Queueing time in the yard Shunting Zones (min)	38.11	151.8

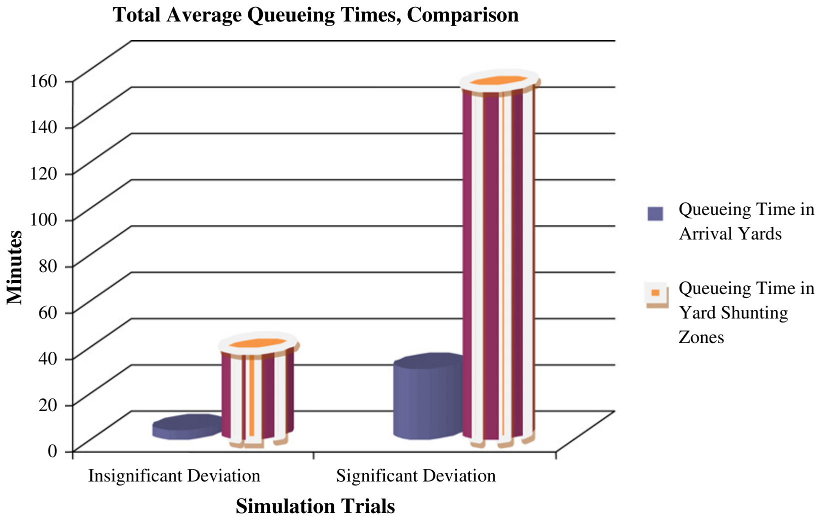

Chart 6.3. "ID vs. SD" graphical comparisons of aggregate queueing times in rail yard subcomponents.

deterioration of static resources, and in most cases the company gets a bad name as a service provider. Loss of business in terms of rail freight transportation is seen in reduction of freight trains over a certain period of time.

In Table 6.4 (as well as Table 6.5) it is observed that within 24 h the estimated number of freight trains served within the insignificant schedule deviations is larger than the estimated number of freight trains served within the significant schedule deviations. Consequently, schedule deviations reduce production, i.e.:

- The greater the deviations of freight train schedules become, the smaller the number of freight trains served.

As a final step, several aggregate measures of yard performance in a rail network are required, such as: total freight trains entered in the yards in the network; total freight trains left the yards in the network; total time in arrival yard queues in the network; total time in shunting zone queues in the network. The aggregate measures obtained from ID and SD simulation trials are given in Table 6.5. Further, Chart 6.3 graphically compares the aggregate queueing times estimated for the two trials.

Table 6.6
Daily and annual total average costs incurred because of time in yard queues.

		Insignificant Deviation	Significant Deviation
Estimation of total average costs because of time in yard queues			
Inputs			
Freight trains per day (on average)	Number	74	60
Assumed average number of cars in a freight train	Number	27	27
Assumed cost per single freight car in queue	Euro/hour	0.7	0.7
Estimated aggregate average time in Arrival Yards' queue	Hour/train	0.07	0.51
Estimated aggregate average time in Shunting Zones' queue	Hour/train	0.64	2.53
Costs			
Estimated total costs per day due to time in Arrival Yards' queue	Euro	96.97	579.10
Estimated total costs per year due to time in Arrival Yards' queue	Euro	35393.91	211370.04
Esimated total costs per day due to time in Shunting Zones' queue	Euro	888.35	2869.02
Estimated total costs per year due to time in Shunting Zones' queue	Euro	324245.60	1047192.30
Esimated total costs per day due to time in yards' queues	Euro	985.31	3448.12
Estimated total costs per year due to time in yards' queues	Euro	359639.50	1258562.34

The difference between the aggregate ID and SD measures is apparent. The aggregate queue in a situation of insignificant schedule deviation is much smaller than the aggregate queue in significant schedule deviations. This indicates that the disciplined freight train operation over the network is much lower-cost operation than the improvised disrespect-of-schedule freight train operation.

In conclusion, we provide rough estimates of the average total costs incurred by the company because of "time in queues". The costs because of "time in yard queue" could be computed by the following formula:

$$C_{queue}^{cars} = m_c * c_{queue}^{single,car} * \left[N_{freight,trains}^{period} * \left(W_{queue,G1}^{freight,train} + W_{queue,G2}^{freight,train} + \cdots + W_{queue,Gn}^{freight,train}\right)\right] \tag{6.1}$$

where C_{queue}^{cars} – accumulated costs of freight cars because of time in queue. mc – number of freight cars per freight train on average and $c_{queue}^{single,car}$ – generated cost of single freight car per time unit spent in queue. The value of generated cost of single freight car per time unit spent in queue is supplied by the accounting department of CP Carga and for the objectives of this computation is considered on average. $N_{freight,trains}^{period}$ – number of freight trains served by yard for a certain period. $W_{queue,G1}^{freight,train} + W_{queue,G2}^{freight,train} + \cdots + W_{queue,Gn}^{freight,train}$ – total time in queue per freight train on average.

The total average costs incurred per day and per year are given in Table 6.6.

In the situation of significant schedule deviations 60 freight trains for 24 h entered in the three rail yards in question. This causes the total average time in the Arrival Yards of these yards to come up to 35.64 min per freight train. Further, this phenomenon causes approximately 152 min total queueing time on average per freight train in the Shunting Zones of the yards in question. These yard queues force the railway freight operator to experience an incremental amount of daily costs, which in the end of the year becomes a significant economic penalty. After having assumed 27 freight cars in freight train composition on average, at a 0.7 Euros cost on average incurred per freight car per hour being in queue it was estimated that the total costs incurred per day because of time in the three yards' queue to come up to 3448 Euros and adds up to 1,258,562 Euros in the end of the year. All these costs accumulated because the freight train operation was performed without respect to what was scheduled. Moreover and perhaps more worrying this cost does not include the additional loss of revenue that may be incurred if some clients are deceived by the quality of service and stop using the railway system for their freight transportation needs.

On the other hand, in the situation of insignificant schedule deviations 74 freight trains for 24 h entered in the three yards in the network. This indicates that the system serves 14 freight trains more in comparison with the previous situation. Further, note that the yards experience relatively low-queues. The total average queueing time comes up to approximately 40 min per freight train to queue in the yards. In equally likely conditions it has been estimated that because of this yard queue the system will incur total costs of up to 985 Euros/Day, which will add up to approximately 359,640 Euros in the end of the year. This amount of money is much smaller than the annual incurred costs estimated in the disrespect-of-schedule situation. And we believe that this money may further be reduced through optimisations and other means.

7. Conclusion

7.1. Synthesis and conclusions

A mesoscopic simulation modelling methodology for analysing and evaluating freight train operations in a rail network is developed. A product of this methodology is a visual simulation rail network model implemented using SIMUL 8 computer package.

For the purposes of this discussion, two situations are studied:

1. Freight train movement characterized with insignificant deviations from schedules.
2. Freight train movement characterized with significant deviations from schedules.

Our rail network simulation model suggests that:

- Rail freight systems, yards in particular, under insignificant schedule deviations show lower percent of time awaiting work than the rail freight production systems performing under significant schedule deviations.
- Rail freight systems, yards in particular, under insignificant schedule deviations show higher percent of time actually working than the rail freight production systems performing under significant schedule deviations.
- Rail freight systems, yards in particular under significant schedule deviations appear to be more saturated than rail freight systems under insignificant schedule deviations.
- The more structured and scheduled the network operation with freight trains is, the lower the queue in the rail network becomes.
- The more chaotic and disorganized the freight train movement becomes, the larger the queue in the rail network grows.
- The greater the deviations of schedules become, the smaller the number of freight trains served.
- The more structured the network operation with freight trains is, the lower the queue in the rail network becomes. Hence, the amount of costs incurred for the company is lower, and vice versa.

7.2. Future work

In this paper flat-shunted yard performances in a network have been analysed and evaluated. Advisable continuation of this research should consider the life cycle of these facilities and forecast their performances in a network.

A study that would analyse in detail the delays of CP freight trains as well as the reasons of frequent occurrence of those delays is suggested. This problem is crucial for accomplishing strict, disciplined operating processes with freight trains within the railway network.

Studies dealing with schedule reliability problems are also suggested for further research. Such studies would involve network freight train operations that explicitly consider the dwell times in loading/unloading terminals and rail yards, optimised road locomotive movements, optimised freight train sizes, etc.

The scheduling of road locomotives to assembled formations in the flat-shunted yards is an issue that is one of the most difficult tasks of the railway freight transportation management. Its solution depends on many factors, such as: the size of the available road locomotive fleet, type of traction over the railway network, locomotive haulage distances and cycles of maintenance.

An economic/commercial overview study needs to be undertaken. This should include issues, such as: the costing to process individual freight cars, the yard dwell time/processing taking too long and making rail a less attractive option for freight, the economic benefits of running block-trains and the economic benefits of reallocating recourses within the rail network.

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