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Simulation of railroad terminal operations and traffic control strategies in critical scenarios

Angela Carboni[a*], Francesco Deflorio[a]

[a]*Politecnico di Torino, Dept. DIATI, Corso Duca degli Abruzzi, 24, Torino 10129, Italy*

Abstract

Railroad terminals contribute to the competitiveness of intermodal transport and play an important role in the transport chain to achieve seamless cross-modal processes, because they must guarantee a fast, safe, and efficient transfer of intermodal loading units. The equipment required, such as gantry and mobile cranes can be critical to the terminal process. However, numerous cranes cannot be designated to guarantee a high level of redundancy, because of their relevant cost.

This paper presents a micro-simulation approach for evaluating the resilience of typical railroad terminals in a critical scenario, such as the temporary unavailability of a gantry crane. Resilience can be defined as the capability of the system to recover its functionality despite a disruption and a gating strategy is proposed in this case to maintain the desired level of service inside the terminal. Therefore, this traffic control strategy is investigated to ascertain its ability in enhancing the terminal resilience when a disruption occurs in a process.

The proposed simulation method is not only used for performing a typical sensitivity analysis under disturbed conditions, but also for assessing the flexibility of the simulated terminal. A comparison is performed for a baseline traffic scenario in equilibrium conditions by setting equal average values for the arrival and service rates, thereby exploring the operation of the infrastructure near its capacity.

In the simulation tool, the relevant features of the typical phases of the internal process are represented, and the traffic flow data of truck arrivals are disaggregated based on specific operations using dedicated service lines. To compare the modeled scenarios, some quantitative key performance indicators (KPIs) are selected and quantified in terms of quality and energy impacts.

Keywords: freight transport; railroad terminal; resilience; simulation; traffic control.

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1. Introduction

A railroad terminal contributes to the competitiveness of intermodal transport and plays an important role in a transport chain by facilitating seamless cross-modal processes. For this reason, its resilience is essential for the reliability and robustness of the entire transport system. A crane disruption during the train loading process, as analyzed in this study, not only affects the terminal operations but also the quality of various freight transportation services associated with the terminal. Moreover, perturbations may also propagate the rail and road network.

The terminal processes and a possible equipment breakdown are simulated using a traffic microsimulation tool that was also used in the study conducted by Barcelo et al. (2005) to analyze traffic conditions in a port for roll-on/roll-off (RO/RO) loading operations, and their goal was to develop a methodology for estimating the performance of maritime terminals based on a microscopic simulation approach reproducing the behavior of the demand in terms of vessel arrivals and departures and reproducing the loading and unloading processes in detail. A micro-simulation model using the *Paramics* tool was presented by Lee et al. (2012) to model truck movements within a port area. They examined different scenarios by changing the transportation demand, and they provided a decision support system to determine the yard truck fleet size for transshipment operation optimization. A similar tool was used in the report presented by Cao et al. (2013) wherein the focus was on the maritime terminal gates because of their contribution to the traffic congestion problem during rush hours of the day. They also underlined the link between gate issues and environmental effects stemming from idling trucks. In the literature, both analytical and simulation methods can be used to perform analyses and compare terminal scenarios (Ricci et al. (2016)). Baldassarra et al. (2010) developed a model for an intermodal terminal using discrete-event software to calculate the total transit time and identify bottlenecks. The same goals were investigated by Dotoli et al. (2014) with a discrete-event approach to model an intermodal freight terminal in a timed Petri net framework. Rizzoli et al. (2002) also used a discrete-event simulation model, applying MODSIM III to represent the main terminal components as road and rail gates, platforms, and storage areas, and then calculating the terminal throughput. Zehendner and Feillet (2014) ran experiments with an optimization model and a discrete-event simulation model to evaluate the benefits of a truck appointment system; this is similar to the study conducted by Zhao and Goodchild (2010). Other applications of discrete-event simulation software were reported in a paper by Mathias et al. (2018), where a model applied in the Port of Leixoes is used to study the flows of cargo and equipment along the container terminal for identifying bottlenecks in specific areas. Following a wider approach, the main goal of Antognoli et al. (2018) was to develop methods such as analytical and discrete-event simulation models to evaluate the performance of different types of rail freight terminals. Through a simulation tool, Garcìa (2016) compared several railroad terminals to analyze different performances. To model a specific intermodal terminal for gateway operations, a graphical simulation software was proposed by Dalla Chiara et al. (2013) to evaluate the terminal performance, also in the case of crane downtime.

Kurapati et al. (2015) defined the operational resilience of a system as the ability to respond to the actual, monitor the critical, anticipate the potential, and learn from the factual. The authors proposed several test sessions of a multiplayer tabletop game to investigate potential strategies for disruption management in a seaport. According to Nair et al. (2010), resilience is the ability to perform short-term recovery actions to mitigate negative effects. Their approach, proposed for intermodal terminals and ports, is similar to that proposed in this study, but the method is different. In fact, their link-based model covered three steps comparable with those proposed below: a network representation of the base system, the development of a disruption scenario (with an analysis of perceived risk and magnitude), and an evaluation of all recovery tools (and defining the time and cost needed to execute them). In their network model, the disruption scenarios such as arson and flooding were simulated as a reduction in link capacity and an increase in travel time. The recovery solution, on the contrary, can improve link capacity and travel time, but it involves implementation costs and activation times. As stated by Tamvakis and Xenidis (2012), the resilience in a transport system represents the ability to react to stresses which test its performance. First, they described the main transportation system and its internal and external components such as loading cranes. Then, they assessed the system's resilience using entropy theory. The main goal of a paper by Swieboda (2016) was to determine the intermodal transshipment node resilience. She defined resilience as the ability to reduce the likelihood of interruption its effects, and the time taken to return to an appropriate level of service. The author suggested that among the factors influencing resilience at an intermodal terminal such as efficiency, adaptability, and robustness, the most effective factors were redundancy and flexibility. The former can be defined as the ability to maintain system functionality in consideration of reserve resources, whereas the latter is the ability to change and adapt to new scenarios.

The method adopted in this study is a micro-simulation approach that provides a tool for evaluating the resilience of typical railroad terminals in a critical scenario, and it estimates the effects of possible recovery actions on a road sub-system. To implement this method, three main scenarios are investigated by simulation:

- S0, the baseline scenario, used to build the reference model of the terminal, considering an equilibrium condition between service and arrival rates.
- S1, the disruption scenario, used to simulate a possible crane failure, which is managed by shifting the related freight operations to a closer crane.
- S2, the recovery scenario, used to simulate the effect of a simple traffic control strategy proposed to mitigate negative conditions at the crane queues, and to support the terminal retrieval.

In a case of intense traffic, the bottleneck caused by an equipment failure may affect other parts of the terminal process, the interfaces between terminals and roads, and railway vectors such as train departures. Even before these effects, safety problems may arise owing to the accumulation of vehicles in the terminal area waiting to be served by the available crane, and these problems are also simulated.

2. Critical scenarios in railroad terminal process

The main terminal operations can be grouped as follows: handling operations by specific equipment, terminal area management, incoming/outgoing movements for trains, and incoming/outgoing movements for road vehicles. The key services in a typical railroad combined transport terminal, focusing on road vehicles, are as follows (Fig. 1):

- Check-in operations for trucks entering the terminal. These operations include inspection procedures and document management for goods and drivers; these two operations can be performed in separate places. (*CK_IN_PHY* and *CK_DOC*)
- Loading or unloading operations under cranes from the truck to the railway wagon or vice versa, including in special areas in case of technical stops, or in parking lots for semitrailers. (*CRANE x*)
- Check-out operations for trucks leaving the terminal. (*CK_OUT*)

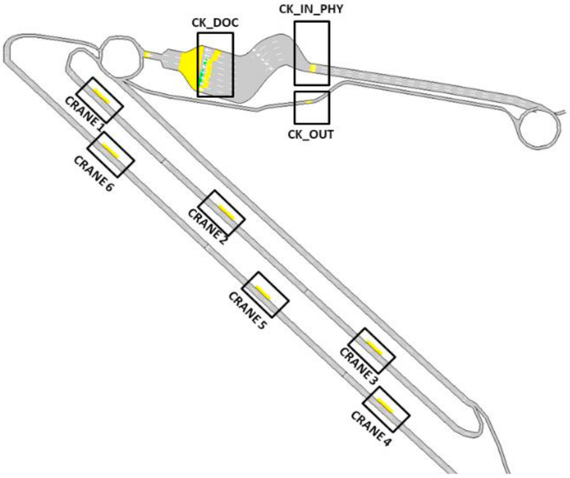
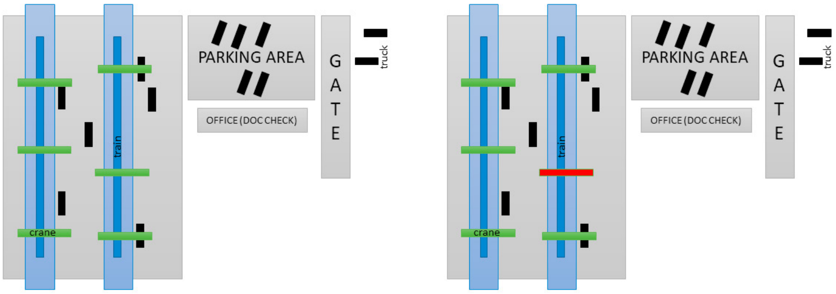


Fig. 1. Terminal simulated layout and trucks activities locations.

The model focuses on all the elements that affect the traffic related to the road side of the terminal and to simplify the simulation, the railway traffic is not considered. The traffic flow is implemented in the selected simulation tool to reproduce interactions among vehicles and flow interruptions at points where services are provided.

An intermodal terminal can be seen as a system composed by sub-processes linked with each other, with different points of interaction. For example, the train loading operations and departure can be influenced by the equipment performance and truck arrival scenario. Thus, a possible disruption of a terminal's sub-process can have consequences, both on the other sub-processes inside the terminal, and on the intermodal chain. The proposed disruption scenario simulates a temporary service interruption of one crane out of six, as shown in Fig. 2, and implies some rearrangements of the process to reduce operational delays and queues.



(a) (b)

Fig. 2. (a) Scheme of typical terminal layout in base scenario; (b) in disruptive scenario (crane failure = red color).

To recover the loading /unloading process of the train, it is assumed that the workload planned for the unavailable crane can be temporarily performed by the following crane in the lane. In this way, the same train can be loaded at the planned track, without added maneuvers, assuming that operational areas of the two cranes can be overlapped. However, this recovery scenario can be critical for the terminal performance in terms of both safety and security, owing to the higher number of heavy-duty vehicles parked in the limited area for the loading and unloading of intermodal transport units (ITUs), and in terms of the comfort for truck drivers, who may increase their waiting time at cranes owing to the decrease in service rate. Thus, a simple traffic control strategy is proposed to implement a reasonable and practical compromise between the needs of the users and those of terminal operators, by stopping the vehicles in a parking area (CK_DOC in Fig. 1) for 6 minutes (twice the average cycle time of the crane) when the maximum queue at crane 1 is greater than 3 vehicles. This setting for the control parameters has been determined via trial and error to avoid both the parking area saturation and an increase of the entry queue.

3. Method

Considering that the proposed method focuses on traffic interactions concerning connecting roads, vehicle queues, and energy consumptions, a microsimulation tool has been selected to determine realistic behavior and enhance the results obtained by modelling the terminal process with discrete-event simulation.

A typical terminal for the transshipment of ITUs between railway and road is simulated using Aimsun® as a traffic microsimulation tool. The chosen terminal layout was based on OpenStreetMap data of a large-size Italian terminal: Hupac Busto Arsizio-Gallarate. The terminal part simulated in the microsimulation model is shown in Fig. 1 wherein the activities and locations of the trucks are identified and represented. The truck flow is simulated using public transport lines, as proposed in Carboni and Deflorio (2017), with specific stops where several terminal sub-processes are carried out, which require typical predefined durations. The eight service lines are chosen to reproduce the truck flow based on the characteristics of the mission (delivery, collection, or both), and by varying the destination cranes for the transfer, as reported in Table 1. Any microsimulation experiment is composed of ten replications for a one-hour simulation period. The statistics are collected after every five minutes, and the indicators for the comparison are calculated based on the average values. The layout of the parking area for document control (CK_DOC in Fig. 1) requires an accurate geometric definition of road sections during the modelling phase to avoid the generation of unrealistic traffic conflicts in simulations.

Table 1. Operation order* for cranes and relation with lines

	Crane					
Line	1	2	3	4	5	6
1			I			
2						I
3		I				
4					I	
5	II		I			
6		I			II	
7	II			I		
8				I		II

* I= first; II=second

3.1. Traffic scenario

The baseline scenario (S0) is set using the parameters reported in Table 2, so as to consider the system in near-capacity and under-saturation conditions. In the crane failure scenario (S1), the input traffic demand is the same, but crane 2 is put out of service after approximately one half-hour of the simulation period, thus removing the stop and simulating the deviation of the transshipment operation to crane 1. This constraint is related to the chosen terminal layout, as previously mentioned. According to the line configuration described in Table 1, the service lines 3 and 6 must change their path.

Table 2. Some important data for the simulation of the base scenario S0

Data for simulation	
Crane average service time	3 minutes (±60s)
Unitary service rate (μ)	20 vehicles/h
Number of operative cranes	6
Total average service rate	120 vehicles/h
Number of service lines	8
Single arrival rate (λ)	10 vehicles/h
Lines frequency	6 minutes (± 30s)
Documents check (one operation)	100s (± 30s)
Documents check (double operation)	200s (± 30s)
Transshipment operation	180s (± 60s)
Warm up period	20 minutes

3.2. Key performance indicators (KPI)

The railroad combined transport, as well as the railroad terminal, requires a heterogeneous solution which involves several operators. The terminal performance can be evaluated through key performance indicators (KPIs), which may be different according to the stakeholders and their goals. Several indicators are proposed in the literature for evaluating intermodal terminal performance based on economy, quality, and efficiency ((Carboni and Deflorio, 2018), (Martín et al., 2017), (Siciliano et al., 2006), (Morales-Fusco et al., 2017), (OECD, 2002)).

The performance indicators selected for obtaining an overview of terminal performance in different scenarios are the traffic flow in terms of the traffic cumulative curve, total travel time (turnaround time) from check-in to check-out operations, and average delay for all vehicles. The turnaround time is the total time elapsed between the entrance of a truck at the terminal for delivery or pickup of an ITU and its exit from the same; it indicates the degree of utilization and productivity (Carboni and Deflorio, 2018). To focus on the impact of equipment failure on vehicles that should have been served by the broken crane, disaggregated values of the indicators for the involved service line are also provided.

According to the simulated layout, the main effect of the interruption is expected on the operations of crane 1, where the services of crane 2 are also allocated. Therefore, the maximum queue and the average delay indicators observed over the simulation period are useful time-dependent indicators for supporting terminal management. These indicators can also highlight terminal redundancy to tackle critical scenarios, and they can measure the state of traffic at the terminal and consequent security problems. Finally, energy and environmental impacts are also investigated for different scenarios to assess the effect of equipment failure and possible gating strategy solutions. As explained in Carboni and Deflorio (2017), the fuel consumption is estimated from emission data provided by the Panis et al. (2006) model implemented in Aimsun®. In Table 3, the estimated indicators are classified based on different points of view (global for the entire terminal, or for the crane or service line) and their scopes such as safety, environment, efficiency, and resilience.

Table 3. Selected performance indicators and related perspective and scope.

Performance Indicator	Level			Scope			
	Terminal	Crane	Service Line	Safety/security	Environment	Efficiency	Resilience
Traffic flow	√					√	√
Turnaround time	√		√			√	√
Delay	√	√	√			√	√
Max queue		√		√		√	√
Fuel consumption	√		√		√		

4. Results

As a global result, the impact of crane failure can be measured as an approximate 5% reduction of the terminal

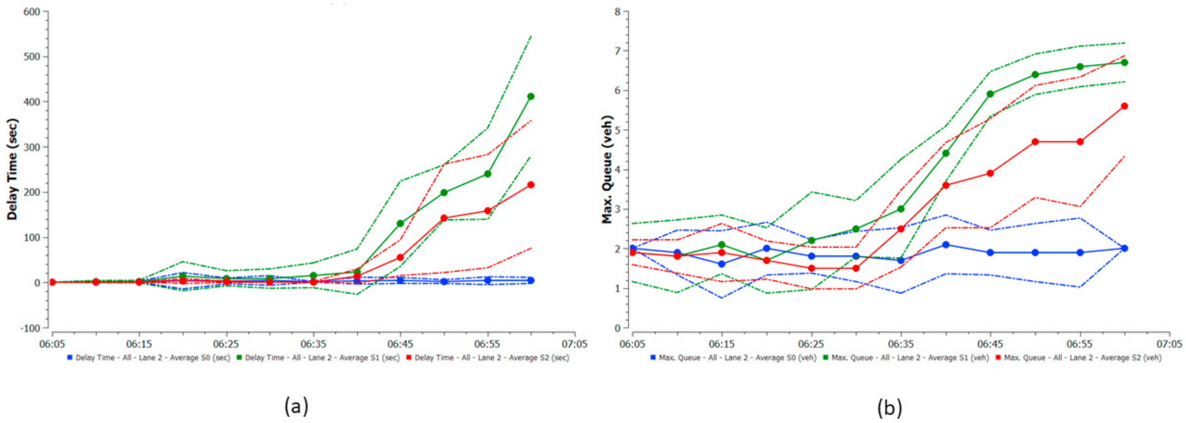
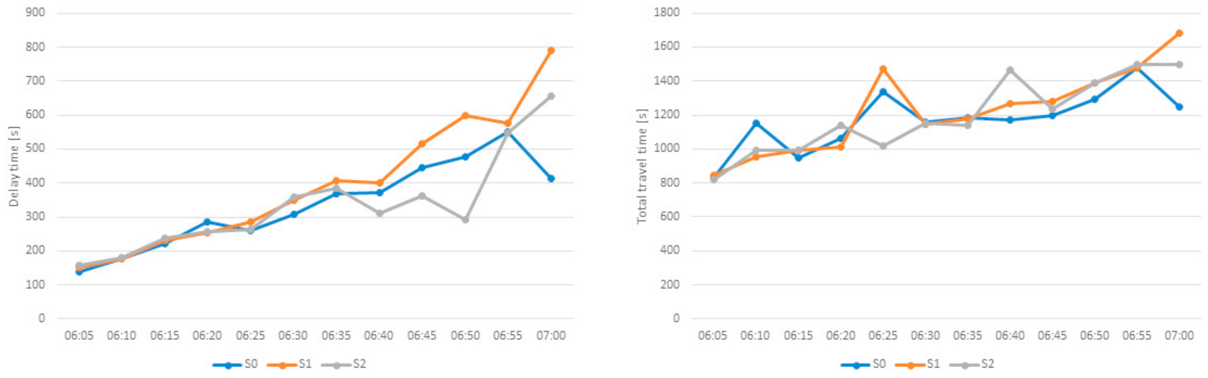


Fig.3. Crane 1 - (a) average delay time per vehicle; (b) max queue in three scenarios.

throughput, from 60 ITUs per hour in S0 to 57 ITUs per hour in S1. The difference between the input flow (approximately 80 ITUs/h) and the number of units leaving the terminal, which means approximately twenty vehicles inside the system at the end of the simulation, is caused by the near-capacity scenario and the variability of arrival and service rates. The time series for the performance indicators focused on crane 1 are shown in Fig.3.

The impact of equipment failure in the disruption scenario (S1) is evident. The graphs report the average value (thick lines) and variation of parameters such as operation duration and vehicle feature due to random phenomena, which are observed while generating the replications.

Over the simulation period, the number of vehicles waiting to be served by crane 1 increases up to seven, which can cause security problems in the lane due to space and clearance needs for ITU movements within the terminal, and the local accumulated delay can be perceived as a problem by truck drivers. The critical scenario, simulated in S1, impacts the terminal performance, and the crane redundancy only partially mitigates the problem. A third scenario (S2) is then introduced to simulate a simple and intuitive gating strategy for controlling the traffic and avoiding security and safety problems in the crane areas. The results confirm the same throughput value as obtained in S1 (57 ITUs/h), which is, therefore, not reduced by the control strategy; it is also confirmed the improvement of the terminal performance in reducing the delay and the maximum queue for crane 1 (Fig.3). Positive impacts can also be observed on the affected service line. In that regard, Fig. 4 reports the average delay time per vehicle and turnaround time for line 3. The gating strategy in S2 clearly contributes to holding the delays caused by the crane failure in the final part of the simulation period. Finally, considering the impact on the energy consumed by the trucks in the terminal, the tested traffic control solution reduces the total fuel consumption by approximately 4% with respect to S1.



(a)

(b)

Fig. 4. Line 3 – (a) average delay time per vehicle; (b) total travel time in three scenarios.

5. Conclusion

This paper presents a micro-simulation approach to provide a tool for the evaluation of resilience of typical railroad terminals in a critical scenario such as the temporary unavailability of a gantry crane. The terminal equipment can indeed be critical because as their number is often not designed according a high level of redundancy to reduce the cost of the logistics infrastructure.

Three main scenarios are investigated in a simulation environment. Starting from the baseline scenario (S0), a crane disruption is simulated in scenario S1, the effects of which have been mitigated in scenario S2 by applying a traffic control strategy. The evaluation was carried out with the support of typical performance indicators quantified in the simulation from the crane, service line or terminal perspective. Moreover, monitoring queue and delay values can support terminal management, even in cases that use the traffic control strategies proposed in this study. A gating strategy was tested under the assumption that vehicles could be lightly delayed in advance at a parking area far from the cranes when the maximum queue at a crane exceeds an established threshold. The simulation results show that the proposed control method can reduce delays and queues in the most congested zone without any drawbacks on the saturation condition at the entrance parking area or the waiting times for trucks. In fact, positive impacts are observed on the delay times estimated for vehicles operating on the service line affected by a crane failure.

All the data used in simulation experiments describe realistic scenarios and are assumed based on practical experience, mainly to test process operations under typical conditions. Further research can be carried out to apply the simulation model and investigate further critical scenarios for intermodal terminals or for other logistic facilities, and evaluate similar control strategies for improving terminal resilience.

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