The Impact of ICT on Intermodal Transportation Systems: a Modelling Approach by Petri Nets

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Abstract
The paper addresses the issues of modelling and managing Intermodal Transportation Systems (ITS) at the operational level, considering the impact of the new Information and Communication Technologies (ICT). ITS are regarded as discrete event systems and are modelled in a timed Petri net framework. In order to show the efficiency of the ITS modelling and controlling technique, the case study of the ferry terminal of Trieste (Italy) is considered. The results show that the approach can be employed to verify the potential of ICT for efficient real time management of ITS, and their impact on the ITS infrastructures.

Keywords — Petri-nets, Transportation, Discrete event systems, Information technology, Simulation.

1. Introduction
Intermodal Transportation Systems (ITS) are logistics networks integrating different transportation services, designed to move goods from origin to destination in a timely
manner and using multiple modes of transportation (Caris, Macharis & Janssens, 2008, Macharis & Bontekoning, 2004). The ITS management and planning are currently relevant subjects of research because ITS allow more efficient, cost effective and sustainable transportation than the traditional transportation systems (Crainic & Kim, 2007, (European Commission Task Force, 1997). However, ITS decision making is a very complex process, due to the dynamical and large scale nature of these systems, the hierarchical structure of decisions, the multiplicity of actors involved, as well as the randomness of various inputs and operations. A systematic way to capture all decisions in the management of ITS typically proposed in the related literature is based on a three-level hierarchy: strategic, tactical and operational ones. Strategic level planning involves ITS design and considers time horizons of a few years, requiring approximate and aggregate data. Tactical level planning basically refers to the optimization of the flow of goods and services through a given logistics network. Finally, operational level management is a short-range planning, involving transportation scheduling of all transporters on an hour-to-hour basis, subject to the changing market conditions as well as to unforeseen transportation requests and accidents.

With the development of Information and Communication Technologies (ICT), operative issues can be dealt in a different way than in the past, taking advantage of the effective impact of these innovative technologies on ITS decision making. Indeed, ICT solutions can increase the data flow and the information quality while allowing real-time data exchange in intelligent transportation systems and traffic networks (Crainic & Kim, 2007, Dotoli & Fanti, 2006, Dotoli, Fanti & Meloni, 2006). As discussed by Giannopoulos (2004), numerous novel applications of ICT to the transportation field are currently in various stages of development, but in the information transfer area the new systems seem to be unimodal. In the application of ICT solutions to multimodal chains, an important and largely unexplored research field is the assessment of the impact of the new ICT tools on management and control of ITS at the operational level before their implementation, by a cost-benefit analysis (Xu & Hancock, 2004, Zografos & Regan, 2004). In particular, an effective ITS model at the operational level should focus on evaluating performance indices.
describing activities, resources (cost, utilization and inventory), output (throughput, lead time) and flexibility (lead-time, lead time variability) (Viswanadham, 1999) by integrating information flows.

In the related literature, simulation has represented an effective and useful instrument to analyze transport logistics and evaluate the impacts of the proposed solutions (Yun & Choi, 1999, Shabayek & Yeung, 2002, Coronado, Coronado & Lalwani, 2009). However, ITS and their decision making processes exhibit a high degree of concurrency and are characterized by resource sharing and conflicts. Hence, ITS systems can be successfully modelled as Discrete Event Systems (DES), whose dynamics depends on the interaction of discrete events, such as demands, departures and arrivals of means of transportation at terminals and acquisitions and releases of resources by vehicles. DES models are widely used to describe decision making and operational processes in logistics systems. In particular, Ramstedt and Woxenius (2006) analyze the literature about the simulation of the decision-making process within a transportation chain and Gambardella et al. (1998) simulate a resource allocation problem in an intermodal container terminal. In a subsequent work, Rizzoli et al. (2002) present a discrete-event simulation model of the flow of intermodal terminal units among and within inland intermodal terminals, serving a user area via a road network and interconnected by rail corridors. Moreover, Legato and Mazza (2001) propose a queuing network model of the logistic activities related to the basic processes of vessels in a container terminal. Also in (Parola & Sciomachen, 2005) a discrete event simulation model is used to analyze in an intermodal container environment the impact of new road and railway networks on the logistics system. In addition, Maione (2008) proposes a multi-agent system architecture for simulation and control of intermodal container terminals. Among the available DES models, Petri Nets (PN) may be selected as a graphical and mathematical technique, suitable to describe concurrency and synchronization (Peterson, 1981). Indeed, processes in intermodal terminals are addressed in (Fischer & Kemper, 2000) with stochastic PN and in (Degano & Di Febbraro, 2001, Di Febbraro, Porta & Sacco, 2006) with Timed Petri Nets (TPN).

This paper addresses the management of ITS at the operational level focusing on the
impact of ICT tools on the management and control of the intermodal chain. In particular, the paper focuses on the application of ICT that allows sharing information among stakeholders on the basis of user friendly technologies. In order to show the modelling and controlling approach, the paper analyzes the ITS that is constituted by the Port of Trieste (Italy) and the Fernetti truck terminal and involving the truck traffic due to the Trieste-Turkey ferry service. More precisely, the ITS is modelled in a TPN framework by applying a top-down approach and employing a modular description of the subsystems composing it.

Consequently, the aim of the paper is twofold. First, with reference to a real situation, it shows how the introduction of simple ICT solutions can noticeably improve the behaviour of the ITS. Second, at a more general methodological level, the paper proposes a modelling technique in the TPN framework that consists in a modular description of the ITS. The resulting model can be easily updated if the system changes and the presented modules can be used to describe subsystems of any generic ITS.

Comparing the TPN framework with other discrete event simulation models, on one hand it is necessary to point out that TPN are not able to describe in detail all the complex operations of an ITS like other simulation tools can operate (such as Arena, Witness, ExtendSim, etc.). On the other hand, more aggregated models such as queuing analysis can be suitable to describe real networks of ITS for their limited computational costs, but they are not capable of providing high resolution. TPN offer intermediate advantages by an appropriate framework that allows employing the two significant advantages of the PN representation: graphical and mathematical. On the one hand, the graphical aspect enables a concise and effective way to design and verify the model. On the other hand, the mathematical representation allows us to easily simulate the system in software environments (i.e., the well known software MATLAB) considering different dynamic conditions characterized by a different level of information shared between terminals and operators. Moreover, on the basis of some theoretical results (Giua, DiCesare & Silva, 1992) the PN mathematical representation allows synthesizing the control laws by monitor places enforcing Generalized Mutual Exclusion Constraints (GMEC). More precisely, the control laws express the exchanges of information allowed by the modern ICT tools and
can be easily realized by GMEC in the TPN framework.

Hence, the considered case study is a means to explain the modelling and controlling technique in the TPN framework. In particular, the presented simulation analysis provides suitable performance indices devoted to evaluate activities, resources (by their utilization) and outputs (by throughputs and lead times) in order to preliminarily foresee the benefits of the integration of the ICT solutions. The system is studied in two operative conditions: the first operative condition (named case as is) describes the current management of the considered ITS, whereas the second operative condition (named case to be) assumes that ICT allow exchanging information among the logistics actors. After a suitable validation of the simulation results, the model is employed to preventively estimate the effective impact of ICT on the ITS infrastructures, carrying out a performance evaluation both in term of utilization of the system resources as well as of system cost indices.

The remainder of the paper is structured as follows. Section 2 presents a brief overview of TPN, while Section 3 describes the case study. Moreover, Section 4 depicts the proposed TPN model and Sections 5 and 6 respectively present the system management and the ITS simulation under two operative conditions (i.e., the current port management and an ICT-integrated solution). Finally, the last Section 7 summarizes the conclusions.

2. Background on Petri nets

2.1 Basics on Petri nets

Petri Nets (PN) are a widely used tool for the description of the structure and dynamics of DES (Cassandras & Lafortune, 2008). This section recalls some basic definitions on PN. For additional details the interested reader is referred to (Peterson, 1981).

A Timed PN (TPN) (Peterson 1981) is a bipartite digraph described by the five-tuple $TPN=(P, T, \textit{Pre}, \textit{Post}, \textit{F})$, where $P$ is a set of places with $|P|=m$, $T$ is a set of transitions with $|T|=n$. Note that symbol $|A|$ denotes the cardinality of the generic set $A$. The set of transitions $T$ is partitioned into the set $T_{i}$ of immediate transitions (represented by bars), the set $T_{E}$ of exponential transitions (represented by boxes) and the set $T_{D}$ of deterministic
timed transitions (represented by black boxes). Matrices $\text{Pre}: P \times T \rightarrow \mathbb{N}^{mn}$ and $\text{Post}: P \times T \rightarrow \mathbb{N}^{mn}$ are the pre- and post-incidence matrices, respectively, that specify the arcs connecting places and transitions. More precisely, for each $p \in P$ and $t \in T$ element $\text{Pre}(p, t)$ ($\text{Post}(p, t)$) is equal to a natural number indicating the arc multiplicity if an arc going from $p$ to $t$ (from $t$ to $p$) exists, and it equals 0 otherwise. Moreover, function $F: T \rightarrow \mathbb{R}^+$ specifies the timing associated to each transition. In particular, for each deterministic timed transition $t_j \in T_D$, function $F$ indicates its (constant) firing delay $\delta_j$, i.e., $F(t_j) = \delta_j$; for each exponentially distributed timed transition $t_j \in T_E$, $F$ specifies the average firing delay, i.e., $F(t_j) = 1/\lambda_j$, where $\lambda_j$ is the parameter of the corresponding exponential distribution; for each immediate $t_j \in T_I$ function $F$ denotes the corresponding zero firing time, i.e., $F(t_j) = 0$. Note that $\mathbb{N}$ is the set of non-negative integer numbers and $\mathbb{R}^+$ is the set of non-negative real numbers.

The $m \times n$ incidence matrix of the net is defined as follows:

$$C = \text{Post} - \text{Pre}. \quad (1)$$

Given a TPN, for each place $p \in P$ the following sets of transitions may be defined: $\bullet p = \{t \in T: \text{Post}(p, t) > 0\}$, named pre-set of $p$; and $p \bullet = \{t \in T: \text{Pre}(p, t) > 0\}$, named post-set of $p$. Analogously, for each transition $t \in T$ the following sets of places may be defined: $\bullet t = \{p \in P: \text{Pre}(p, t) > 0\}$, named pre-set of $t$; and $t \bullet = \{p \in P: \text{Post}(p, t) > 0\}$, named post-set of $t$. Moreover, a transition $t \in T$ is called source transition if it has no input arcs, i.e., it holds $\bullet t = \emptyset$.

The state of a TPN is given by its current marking, which is a mapping $M: P \rightarrow \mathbb{N}^m$, assigning to each place of the net a nonnegative number of tokens. $M$ is described by a $|P|$-vector and the $i$-th component of $M$, indicated with $M(p_i)$, represents the number of tokens in the $i$-th place $p_i \in P$. A TPN system $\langle TPN, M_0 \rangle$ is a TPN with initial marking $M_0$.

A transition $t_j \in T$ is enabled at a marking $M$ if and only if (iff) for each $p \in \bullet t_j$, it holds:

$$M(p) \geq \text{Pre}(p, t_j) \quad (2)$$

and the symbol $M(t_j)$ denotes that $t_j \in T$ is enabled at marking $M$. When fired, $t_j$ produces a
new marking $M'$, denoted by $M(\ell_j)M'$ that is computed by the PN state equation:

$$M' = M + C \tilde{t}_j,$$

(3)

where $\tilde{t}_j$ is the $n$-dimensional firing vector corresponding to the $j$-th canonical basis vector.

Let $\sigma$ be a sequence of transitions (or firing sequence): the notation $M(\sigma)M'$ indicates that the sequence $\sigma$ may fire at $M$ yielding $M'$. Marking $M$ is said reachable from $\langle TPN, M_0 \rangle$ iff there exists a firing sequence $\sigma$ such that $M_0(\sigma)M$. The set of all markings reachable from $M_0$ defines the reachability set of $\langle TPN, M_0 \rangle$ and is denoted by $R(TPN,M_0)=\{M \in \mathbb{N}^{m} | \exists \sigma : M_0(\sigma)M\}$.

2.2 Generalized mutual exclusion constraints

This section recalls the problem of enforcing Generalized Mutual Exclusion Constraints (GMEC) on PN (Giua, DiCesare & Silva, 1992). In synthesis, GMEC enforce limitations on the weighted sum of markings in a place subset, resulting in a PN supervisor that specifies a state feedback control law preventing the net from reaching a given set of forbidden markings from the initial marking. Advantages of representing the controller via GMEC are that the closed loop system can be analyzed as a whole using PN techniques and tools, and that the computation of the control action is fast, since it does not require any separate computation (Wang, Zang & Yan, 2004).

Let $\langle TPN, M_0 \rangle$ be a TPN system, whose set of reachable markings is $R(TPN,M_0)$. Assume that a set of legal markings $\mathbb{L}_M \subseteq \mathbb{N}^{m}$ are given and consider the basic control problem of designing a supervisor that restricts the reachability set of the closed loop system to $\mathbb{L}_M \cap R(TPN,M_0)$. The legal marking set $\mathbb{L}_M$ is expressed by a set of $n_c$ GMECs. In particular, a GMEC is a couple $(L, H)$ where $L: P \rightarrow \mathbb{Z}$ is a $1 \times m$ weight vector, $H \in \mathbb{Z}$ and $\mathbb{Z}$ is the set of integer numbers. A set of GMEC $(L, H)$, with $L=[l_1^T l_2^T \ldots l_{n_c}^T]^T$ and $H=[H_1 H_2 \ldots H_{n_c}]^T$, defines the legal marking set $\mathbb{M}(L,H)=\{M \in \mathbb{N}^{m} | LM \leq H\}$. The support of $L$ is the set $Q_L = \{p \in P | L(.,p) \neq 0\}$. A controlling agent, called supervisor,
must ensure that the forbidden markings will not be reached, then the set of legal markings under control is $\mathbb{M}_C(L,H) = \mathbb{M}(L,H) \cap R(TPN,M_0)$.

When modelling a supervisory control problem using PN, a transition may be either controllable or uncontrollable: a controllable transition may be disabled by the supervisor. As shown in (Giua, DiCesare & Silva, 1992), if all transitions are controllable then the TPN controller enforcing $(L,H)$ has incidence matrix $C_c \in \mathbb{Z}^{n_c \times n}$ given by

$$C_c = -LC$$

and the initial marking of the controller $M_{c0} \in \mathbb{N}^{n_c}$ is given by

$$M_{c0} = H - LM_0.$$ (5)

The controller exists iff the initial marking is legal, i.e., $H - LM_0 \succeq 0$. The controller so constructed is maximally permissive, i.e., it prevents only transition firings that yield forbidden markings. The control net has $n_c$ control places, called monitor places and no transition is added to the controlled net.

3. Description of the case study

This section analyzes a real case study describing an ITS including the port of Trieste, (Italy), the Fernetti truck terminal, the roads and highways connecting them. In particular, the truck traffic due to the Trieste-Turkey ferry service between the port and the truck terminal is considered. Moreover, the current management of the logistics system is considered and a possible ITS modification due to the integration of ICT tools into the system.

A schematic map of the road connections with the road lengths between the two terminals is presented in Fig. 1. Trucks heading to Turkey enter the system from the so-called Lisert tollbooth with different daily arrival rates. In particular, two types of trucks are considered in the system: straight trucks and semi-trailer trucks: straight trucks (also called box trucks) are single-unit vehicles with the cargo body and towing engine mounted on the same chassis, while semi-trailer trucks (also called articulated trucks) are articulated
vehicles consisting of a towing engine (usually called tractor) and a semi-trailer that carries the freight. Moreover, Fig. 1 shows that some additional box trucks enter the ITS daily on board of dedicated trains arriving to Trieste from Salzburg to be loaded on the ship to Turkey. In particular, in the port there is a daily service of roll-on/roll-off ferries between Trieste and Turkey. The ship can embark about $C_b=235$ vehicles without distinction. The port queuing area has a capacity of $C_{PC}=40$ straight trucks and $C_{PT}=450$ semi-trailer trucks, hence the logistics management is different for the two categories of transportation means. More in detail, straight trucks are embarked as such, whereas semi-trailer trucks arriving in port from Lisert are first disassembled, so that their unhooked semi-trailer is embarked, while tractors wait in a dedicated parking area for the arrival of other semi-trailers carrying further freight on board of the next ship. Moreover, note that semi-trailer trucks coming from the Lisert tollbooth to be embarked can go directly to the port parking area to wait for their turn. On the contrary, if a straight truck coming from Lisert has to be embarked, it has to first go to the Fernetti truck terminal to wait for its turn. The Fernetti terminal can accommodate at most $C_F=150$ trucks. Table 1 summarizes the capacities of the ITS resources.

The ferry to Turkey sails every day at 6.00 p.m., and embarkation begins at noon stopping at 5.30 p.m. Trucks waiting in Fernetti can go to the port only during the embarkation period, hence, considering the distance between the two terminals, they can leave Fernetti from 11.00 a.m. till 5.00 p.m. only. The Lisert tollbooth, the Fernetti terminal and the port are connected by highways whose names and length are depicted in Fig. 1. Moreover, trains arrive in port (see Fig. 1) every day at 11.00 a.m., 01.00 p.m. and (with the exception of Tuesdays and Fridays) at 03.00 p.m.

There is currently no information flow between the logistic system terminals. Hence, in the sequel the authors investigate the integration into the ITS of ICT tools that can inform trucks coming from the Lisert tollbooth and vehicles waiting at the Fernetti terminal on the unused capacity of the port area. More precisely, the management system enables straight trucks entering the ITS to directly head to the port when the system resources are available and prevents vehicles from heading to the port when it is saturated.
4. The Timed Petri Net Model

This section presents the TPN modelling technique that can be used to describe an ITS by considering the travel of trucks through the roads to arrive to the port and the ship. In particular, the TPN system \(\langle TPN, M_0 \rangle\) of Fig. 2 with \(TPN=(P, T, Pre, Post, F)\) models the structure and the dynamic evolution of the ITS described in Section 2 under the current management that is here called case as is.

The structure of the model is modular and built by a top-down approach. Indeed, the TPN system in Fig. 2 has a structure that closely depicts the ITS configuration shown in Fig. 1, so that the modelling procedure could be applied to a generic ITS with few modifications. In particular, the tollbooth subsystem, the highways, the truck terminal subsystem, the rail...
 subsystem, the port sub-system, and the ship sub-system are singled out in a generic and modular approach. Note that such systems are typically included in ITS, therefore this may be viewed as a representative case study for showing the effectiveness and efficiency of the presented modelling and controlling technique.

The TPN digraph elements are specified as follows. The place set is $P = P_R \cup P_C \cup P_F$: set $P_R$ models the system resources (i.e., tollbooth, highways, rail, port, Fernetti terminal and ferry); set $P_C$ models the available capacities of the resources; set $P_F$ collects places devoted to model conditions in order to prioritize and synchronize the main events of the logistics chain (time of day or day of the week, opening/availability and closure/unavailability of resources, etc.). In the TPN model a token in a place $p_i \in P_R$ represents a truck, semi-trailer or train in the system, a token in a place $p_i \in P_C$ is an available position in a resource and a token in a place $p_i \in P_F$ represents a condition that is verified.

The transition set is $T = T_E \cup T_D \cup T_I$. The exponential stochastic transitions belonging to $T_E$ model the input of vehicles into the ITS, their flows and activities (such as the travel along the roads, the entering into the port, the embarkation, etc.). Moreover, the set $T_D$ of deterministic timed transitions models the occurrence of deterministic events at particular times of the day, i.e., the Fernetti terminal opening (transition $t_{65}$) and closing events ($t_{64}$), the arrival ($t_{67}$) and the departure ($t_{66}$) of the ferry, the embarkation start ($t_{71}$) and closure ($t_{70}$), the trains arrivals ($t_{74}$ to $t_{80}$), etc. Set $T_I$ collects the TPN immediate transitions, i.e., $t_{48}$ modelling the ferry sailing, $t_{52}$ modelling the disembarked semi-trailers that do not leave the port within the end of the day, $t_{22}$ and $t_{23}$ modelling the trucks arrival from the A-North highway.

Matrices $Pre$ and $Post$ and the initial marking $M_0$ of the TPN system in Fig. 2 can be deduced from the edges and the token distribution shown in the figure. In particular, each place $p_i \in P_R$ can accommodate vehicles and, assuming that the system is empty at the initial marking, it holds $M_0(p_i)=0$ for each $p_i \in P_R$. On the other hand, the initial marking of each $p_i \in P_C$ is set equal to the corresponding resource capacity.

In the following sections the TPN model of the ITS case study is described in detail.
Table 2.

Meaning and firing times of some transitions in the TPN of Fig. 2 and 3.

<table>
<thead>
<tr>
<th>Transitions</th>
<th>Event description</th>
<th>Firing time F(t_i) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_i with i=1,…,7</td>
<td>Deterministic time delay</td>
<td>24</td>
</tr>
<tr>
<td>t_8 (t_6)</td>
<td>Arrival of semi-trailer (straight) trucks in port on Mondays</td>
<td>0.29 (0.57)</td>
</tr>
<tr>
<td>t_10 (t_8)</td>
<td>Arrival of semi-trailer (straight) trucks in port on Tuesdays</td>
<td>0.29 (0.59)</td>
</tr>
<tr>
<td>t_12 (t_10)</td>
<td>Arrival of semi-trailer (straight) trucks in port on Wednesdays</td>
<td>0.21 (0.41)</td>
</tr>
<tr>
<td>t_14 (t_12)</td>
<td>Arrival of semi-trailer (straight) trucks in port on Thursdays</td>
<td>0.15 (0.29)</td>
</tr>
<tr>
<td>t_16 (t_14)</td>
<td>Arrival of semi-trailer (straight) trucks in port on Fridays</td>
<td>0.14 (0.27)</td>
</tr>
<tr>
<td>t_18 (t_16)</td>
<td>Arrival of semi-trailer (straight) trucks in port on Saturdays</td>
<td>0.14 (0.29)</td>
</tr>
<tr>
<td>t_20 (t_18)</td>
<td>Arrival of semi-trailer (straight) trucks in the port on Sundays</td>
<td>0.83 (1.71)</td>
</tr>
<tr>
<td>t_24 (t_22)</td>
<td>Output of the D-North (D-South) road</td>
<td>0.03 (0.03)</td>
</tr>
<tr>
<td>t_26 (t_24)</td>
<td>Output of the C-North (C-South) road</td>
<td>0.07 (0.07)</td>
</tr>
<tr>
<td>t_i with i=24,…,31, 33,…,42,55,…,63</td>
<td>Output of A-North, A-South, B-North and B-South highways</td>
<td>0.17</td>
</tr>
<tr>
<td>t_i with i=74,…,80</td>
<td>Daily train arrival</td>
<td>2</td>
</tr>
<tr>
<td>t_i with i=81,85,87,91,93</td>
<td>Deterministic time delays</td>
<td>7</td>
</tr>
<tr>
<td>t_i with i=83,89</td>
<td>Delay time between train arrival</td>
<td>5</td>
</tr>
<tr>
<td>t_i with i=82,86,88,92,94</td>
<td>Deterministic time delays</td>
<td>17</td>
</tr>
<tr>
<td>t_i with i=84,90</td>
<td>Deterministic time delay</td>
<td>19</td>
</tr>
</tbody>
</table>

Fig. 2. The TPN system \(\langle TPN, M_\delta \rangle\) modelling the case as is.
4.1 The tollbooth subsystem

The Lisert tollbooth is represented in Fig. 2 by a sub-net in which places $p_8, p_9 \in P_R$ model the system resources for straight and semi-trailer trucks, respectively, so that a token in such places represents a truck of either type. Since the system dynamics is significantly affected by the particular timing of the ITS, an in-depth study has been performed about the truck arrival rates in the different days of the week. Hence, a suitable subnet is devoted to model the truck arrival rates in the different days of the week. More precisely, places $p_i \in P_F$ with $i=1,\ldots,7$ model the week days, while transitions $t_i \in T_D$ with $i=1,\ldots,7$ model the flow of time from day to day. In Fig. 2 it holds $M_0(p_1)=1$ and $M_0(p_i)=0$ with $i=2,\ldots,7$, i.e., the depicted situation corresponds to the Lisert tollbooth on Mondays. In addition, the transitions $t_i \in T_E$ with $i=8,\ldots,21$ model the input of trucks into the ITS from Lisert on the different days of the week, differentiating the input flows for straight and semi-trailer trucks. Table 2 shows the average firing times of the exponential transitions that model the inputs of trucks and are obtained on the basis of the real weekly data: for instance, on Mondays 83 semi-trailer trucks arrive on average in the port, hence it holds $F(t_8)=24/83$ h.

4.2 The highways

The ITS depicted in Fig. 1 comprises several highways that straight or semi-trailer trucks pass through to reach the port or the truck terminal. As it is well known, the models available in the related literature to describe traffic networks can be divided in microscopic and macroscopic models. Microscopic models describe system entity interactions with a high level of detail: the resulting software are costly to develop and execute (Gabard, 1991). On the other hand, macroscopic models represent the traffic streams in an aggregate manner: these models are less costly to develop but their representation may be inaccurate and not valid. Recently, different contributions describe the traffic networks by discrete event system models that exhibit intermediate characteristics between microscopic and macroscopic models. Thanks to the well known ability of PN to capture concurrency and asynchrony, PN based models have been suitably derived for traffic systems, see for instance (Tzes, Kim & McShane, 1996, Gallego, Farges & Henry, 1996, Di Febbraro,
Following the mentioned approaches, highways are here modelled by the TPN in Fig. 2 that includes several subnets modelling the roads, eventually divided in subsections describing portions of the street. Each subsection is modelled as a resource by two places: a place $p_i \in P_R$ describing the number of vehicles in the considered portion of street and a place $p_j \in P_C$ representing the available capacity. For instance, the short C-South highway, which is dedicated to straight trucks leaving Fernetti and heading south to the port, is simply modelled by $p_{45} \in P_R$ and its available capacity $p_{46} \in P_C$. Hence, a token in $p_{45}$ represents a straight truck travelling in the C-south highway, while a token in $p_{46}$ represents the number of such vehicles that the highway can still accommodate. In Fig. 2 it holds $M_0(p_{46})=66$, i.e., the road is initially empty and the available free space is of 66 box trucks, computed based on the C-South road length of 2 km and on the average overall occupied space of 30 m per truck (which includes the truck actual length and the safe following distance). Longer highways are modelled by multiple analogous sub-sections, e.g., the 20 km long A-South highway is modelled by four successive subnets, with a resource capacity of 660 trucks, without distinction between straight and semi-trailer trucks. Since straight and semi-trailer trucks are managed with different rules when they are directed to the port, it is necessary to differentiate between straight and semi-trailer trucks to model A-North and B-South highways.

As regards the exponential transitions describing the flow of tokens (trucks) through the different sections of the roads in the ITS, their firing times are assigned by verifying that the trucks average speed equals 30 km/h, so that for instance transitions $t_{44}$ and $t_{46}$, respectively output of the D-North and D-South roads that are 1 km long, both have a firing time $F(t_{44})=F(t_{46})=1/30$ h.

### 4.3 The truck terminal subsystem

The Fernetti terminal is represented in Fig. 2 by a subnet in which places $p_{41} \in P_R$ and $p_{42} \in P_C$ respectively represent the terminal resource accommodating straight trucks and the
corresponding available capacity. In addition, places $p_{78}, p_{77} \in P_F$ respectively model the opening and closing conditions of the terminal for outbound vehicles, while transitions $t_{64}, t_{65} \in P_D$ model the terminal closure and opening for such vehicles. Hence, considering that trucks can exit the terminal from 11.00 a.m. till 5.00 p.m., the corresponding transitions firing times are $F(t_{64})=18 \text{ h}$ and $F(t_{65})=6 \text{ h}$. Moreover, considering that about 40 trucks per hour exit on average the Fernetti terminal (when open), it holds $F(t_{43})=1/40 \text{ h}$.

4.4 The rail subsystem

The additional straight trucks entering the ITS on board of the dedicated trains arriving from Salzburg (Austria) (see Fig. 1) are represented by the subnet called Rail in Fig. 2. An average of 12 additional box trucks leaving for Turkey reach the Trieste port on each train entering the ITS. Each day of the week is modelled in Fig. 2 by two places $p_i \in P_F$ and $p_{i+1} \in P_F$ with $i=87, 89, \ldots, 99$, where the first place is marked when train is in port and the second one is marked when no train is in port. Moreover, the transitions $t_i \in T_D$ with $i=74, \ldots, 94$ model the timing of the train arrivals during the day and the corresponding time delays are reported in Table 2. In addition, place $p_{101} \in P_R$ represents a dedicated queuing area for straight trucks arriving by train. Since each train accommodates 12 straight trucks, it holds $Post(p_{101}, t_i)=12$ with $i=74, \ldots, 80$. Finally, the exponential transition $t_{95}$ models the entrance of these vehicles in the port and, since on average 9 straight trucks (when present) coming from Salzburg enter the port queuing area every hour, it holds $F(t_{95})=1/9 \text{ h}$.

4.5 The port subsystem

The port is represented in Fig. 2 by a subnet comprising different elements for the two types of considered vehicles, i.e., straight and semi-trailer trucks. In particular, places $p_{47} \in P_R$ and $p_{48} \in P_C$ respectively represent the port parking area for straight trucks and the corresponding remaining available capacity. Note that the straight trucks can enter the port area both from the B-South highway and on board of trains. In addition, transition $t_{47} \in T_E$ models the straight trucks embarkation on the ship and the contemporary disembarkation of box trucks from the ferry heading to the B-North highway via $p_{49} \in P_R$ and $t_{54} \in T_E$. It holds
\( F(t_{47}) = 1/60 \text{ h} \), since every minute on average a straight truck is embarked and an additional vehicle is disembarked. Moreover, every 6 minutes on average a truck exits the port via the B-North highway, hence it holds \( F(t_{54}) = 1/10 \text{ h} \).

As regards the semi-trailer trucks coming from the B-South highway (see Fig. 1), after entering the port each semi-trailer is unhooked from its tractor, which is then parked in a dedicated area, while the semi-trailer is queued in a queuing area to be embarked. Accordingly, places \( p_{52}, p_{53} \in P_R \) respectively represent the semi-trailers queuing area and tractors parking area outside the port. Moreover, since during the embarkations there are simultaneously the semi-trailers that are disembarked from the ship, places \( p_{54}, p_{55} \in P_R \) respectively represent the two areas dedicated to the disembarked and embarked semi-trailers and the corresponding available capacity is modelled by \( p_{56} \in P_C \). In order to obtain the port utilization, the equal markings \( M(p_{55}) \) and \( M(p_{56}) \) keep memory of the occupation of the two areas. In addition, the transition \( t_{50} \in T_E \) models the simultaneous embarkations and disembarkations with a firing time \( F(t_{50}) = 0.22 \text{ h} \). Moreover, since semi-trailers can be embarked/disembarked in groups of 70 units, in order to have about 70 tokens in \( p_{54} \) and \( p_{55} \) and based on the value assigned to \( F(t_{50}) \), transition \( t_{49} \in T_E \) modelling the time for a semi-trailer to be disembarked has a firing time \( F(t_{49}) = 0.001 \text{ h} \). The disembarked semi-trailers are parked in an area modelled by place \( p_{57} \in P_R \), where they are hooked to the tractors waiting in place \( p_{53} \in P_R \) and subsequently enter the B-North highway. The port outlet is modelled by transition \( t_{51} \in T_E \) with \( F(t_{51}) = 0.67 \text{ h} \). However, only about 25\% of the semi-trailer trucks are able to exit the port the same day of the freight arrival. Hence, place \( p_{86} \in P_F \) (\( p_{85} \in P_F \)) enables (inhibits) the freight to leave the port on the arrival day. Accordingly, transitions \( t_{72} \in T_E \) and \( t_{73} \in T_E \) model the delay times with \( F(t_{72}) = 23.5 \text{ h} \) and \( F(t_{73}) = 0.9 \text{ h} \). Hence, place \( p_{88} \in P_R \) models the parking of semi-trailers exiting the port the next day, transition \( t_{53} \in T_E \) with \( F(t_{53}) = 0.21 \text{ h} \) models the exit of one vehicle every 12.5 minutes from the port the next day of the arrival through the B-North highway. In addition, in order to manage the embarkation timings, place \( p_{82} \in P_F \) enables the condition of embarkation/disembarkation and places \( p_{83}, p_{84} \in P_F \) disable the embarkation if they are marked. Accordingly, transitions \( t_{70} \in T_E \) and \( t_{71} \in T_E \) with \( F(t_{70}) = 5.5 \text{ h} \) and \( F(t_{71}) = 18.5 \text{ h} \).
model the fact that the ship is berthed in the port for 10 hours, 7 of which are dedicated to embarking/disembarking operations. Moreover, transition $t_{69} \in T_D$ with $F(t_{69})=1h$ creates a displacement of $1h$ between the start of the embarkation and the Fernetti opening and it is enabled only at the initial marking of the simulation by place $p_{83} \in P_F$.

4.6 The ship subsystem

The ship is modelled in Fig. 2 by a subnet in which places $p_{50} \in P_R$ and $p_{51} \in P_C$ respectively represent the ship resource for trucks or semi-trailers (without distinction) and the corresponding available capacity. In addition, places $p_{79}$, $p_{80}$, $p_{81} \in P_F$ respectively model the conditions of ship in port about to sail, ship not in port and ship in port (and embarking/disembarking freight). Accordingly, deterministic transitions $t_{66}$, $t_{67}$ and $t_{68}$ with firing times $F(t_{66})=0.5h$, $F(t_{67})=17h$ and $F(t_{68})=6.5h$ model the time necessary for the ferry to sail, to arrive in port and the time in which the ferry is berthed.

5. The system management

5.1 Case as is

The TPN shown in Fig. 2 models the travel of the trucks, semi-trailers and trains entering the ITS and reaching the port under the current management policy (case as is). In this operating condition straight and semi-trailer trucks (tokens) enter the system and flow through the roads and terminals constrained by the capacity places. Hence, the dynamics of the TPN is easy to explain. For example, a straight truck enters the ITS from the Lisert tollbooth (token in $p_8$), goes through A-North, C-North and D-North and arrives to the truck terminal ($p_{41}$) where it waits for its turn to be embarked. Successively, the straight truck goes through D-South, C-South and B-South to the port of Trieste to be embarked in the ship (place $p_{50}$).

Note that in the TPN of Fig. 2 the timed exponential transitions $t_{96}$ (modelling the heading of trucks from A-North to the port) and $t_{90}$ (modelling the heading of trucks from A-North to the Fernetti terminal) are in conflict. To model the fact that in case as is straight
trucks go directly to the Fernetti terminal before heading to the port, the conflict is solved assigning priorities (David and Alla, 2005): hence, priority is given to $t_{30}$ over $t_{96}$.

Moreover, a token in $p_{101}$ (a straight truck enters the ITS on board of a train arriving from Salzburg) can directly go into $p_{47}$ (port of Trieste) to be embarked in the ship (place $p_{50}$). On the other hand, a token in $p_{9}$ (a semi-trailer truck enters the ITS) goes through A-North and B-South directly in port where it is disassembled into tractor (in $p_{53}$) and semi-trailer ($p_{52}$), the last of which is subsequently queued to other semi-trailers (place $p_{54}$) and embarked in the ship (place $p_{50}$).

It is interesting to remark that in case as is the ship booking and shipping charges payment for straight trucks entering the ITS from the tollbooth are performed in the Fernetti terminal. Hence, all these box trucks have first to go to Fernetti and, only when the ferry is ready, they subsequently head to the port.

5.2 Case to be

A second management policy (called to be) is here considered, supposing that ICT tools allow exchanging information among the logistics actors. Hence, it is assumed that by a suitable information the straight trucks entering from Lisert can go directly to the port if the ferry is ready and parking is available. More precisely, the straight trucks entering the ITS from the Lisert tollbooth receive the information that the port parking is available and the A-North and B-South roads are under-saturated. In such a case, box trucks can go directly to the port without reaching the Fernetti terminal, thus limiting pollution, decreasing travel costs and increasing the road safety. In order to specify the control law, the TPN system $\langle TPN, M_0 \rangle$ of Fig. 2 is considered: the straight trucks entering the ITS from the Lisert tollbooth go straight to the port when they receive the suitable information. Hence, the ITS control law is realized by preventing the TPN from evolving towards forbidden states, i.e., port saturated and roads to port saturated. Since these restrictions on the system behaviour are logical predicates that do not depend on the time evolution, the control problem can be formulated using GMEC, i.e., constraining the weighted sum of markings in a place subset, as follows:
\[
\begin{align*}
M(p_{22}) + M(p_{25}) + M(p_{28}) + M(p_{31}) + M(p_{34}) + M(p_{40}) + M(p_{43}) + M(p_{45}) + M(p_{47}) &\leq C_{PB}, \\
M(p_{10}) + M(p_{13}) + M(p_{16}) + M(p_{19}) + M(p_{37}) + M(p_{39}) + M(p_{41}) &\leq C_{F} + C_{PB} \\
-M(p_{22}) - M(p_{25}) - M(p_{28}) - M(p_{31}) - M(p_{34}) - M(p_{40}) - M(p_{43}) - M(p_{45}) - M(p_{47})
\end{align*}
\] (6)

In particular, the first constraint in (6) imposes that the number of straight trucks in the roads from Lisert to the port and in the port itself cannot exceed \(C_{PB}\). On the other hand, the second constraint of (6) imposes that the sub-system including the roads from Lisert to Fernetti and the terminal itself is under-saturated with respect to straight trucks. Hence, the number of such vehicles in the sub-system cannot overcome the summation of capacity \(C_{F}\) plus the remaining capacity of the subsequent road and the port capacity. Hence,

\[
H = \begin{bmatrix} C_{PB} \\ C_{F} + C_{PB} \end{bmatrix}
\]

is defined and the vector \(L \in \mathbb{Z}^{2 \times 101}\) is derived from constraints (6), so that the GMEC \((L, H)\) defines the legal marking set \(\mathbb{M}(L, H) = \{ M \in \mathbb{N}^{101} \mid LM \leq H \}\). The controller enforcing the GMEC is realized by adding to the set of places \(P\) two monitor places \(p_{c1}\) and \(p_{c2}\) with the associated incidence matrix \(C_{c} = -LC\) and initial marking \(M_{c0} = H - LM_0 = \begin{bmatrix} C_{PB} \\ C_{PB} + C_{F} \end{bmatrix} = \begin{bmatrix} 40 \\ 190 \end{bmatrix}\). Since \(M_{c0} \geq 0\), the controller exists.

Choosing \(Post_{c}\) and \(Pre_{c}\) such that \(Post_{c} - Pre_{c} = C_{c}\) and \(Post_{c}(p_{ci,t}) - Pre_{c}(p_{ci,t}) = 0\) for \(i=1,2\) and for each \(t \in T\), the closed loop TPN system is shown in Fig. 3, where the edges associated to the matrices \(Post_{c}\) and \(Pre_{c}\) are depicted by bold lines.

Note that if the monitor place \(p_{c1}\) enables transition \(t_{06}\) in Fig. 3, connecting the A-North and B-South highways TPN subnets, such a timed exponential transition is in conflict with transition \(t_{30}\), modelling the heading of trucks from A-North to the Fernetti terminal. Since in case to be the straight trucks have to go directly to the port if this is not saturated, the conflict is solved assigning priority to \(t_{06}\) over \(t_{30}\).
6. The case study simulation

6.1 The simulation specification

The system dynamics is analyzed via numerical simulation using the data reported in Table 1 and 2 and in Section 5. The aim is studying the impact of the ICT integration and information among the logistics actors. More precisely, the benefits generated by the introduction of an ICT solution (case to be) into the current ITS layout (case as is) are pointed out.

In order to analyze the system behaviour, the following performance indices are defined (Viswanadham 1999):

1) the average utilization of the port ($U_p$) and the Fernetti terminal ($U_f$) evaluating the average number of straight trucks respectively in the port and in the Fernetti terminal (note that the number of semi-trailer trucks occupying the port is not affected by the ICT integration);

2) the average utilization of the last five kilometres of B-South road ($U_B$) evaluating the average number of straight and semi-trailer trucks in the B-South road;

3) the average throughput $TR(t_i)$ [$\text{h}^{-1}$] of a transition $t_i \in T_E$, i.e., the average number of
fires of $t_i$ per time unit;

4) the average lead time $LT$, i.e., the average value of time spent by the straight trucks to arrive to the port, defined as follows:

$$LT = \sum_{p_j \in P_L} SI(p_j) / TR(t_{41}) \ [h], \tag{7}$$

where $SI(p_j)$ is the average number of straight trucks in $p_j \in P_L$ with $P_L = \{p_{10}, p_{13}, p_{16}, p_{19}, p_{22}, p_{25}, p_{28}, p_{31}, p_{34}, p_{37}, p_{39}, p_{41}, p_{43}, p_{45}\} \subseteq P_R$.

5) the average traffic cost index $C$, assessing the straight truck traffic level and defined as follows:

$$C = \sum_{t_i \in T_H} TR(t_i) \cdot L(t_i) \cdot A \cdot S \ [€/year], \tag{8}$$

where the set $T_H \subseteq T_E$ is a transition subset varying with the operative condition and modelling the paths of trucks. In particular, in case as is it holds $T_H = \{t_{24}, t_{26}, t_{28}, t_{30}, t_{32}, t_{33}, t_{35}, t_{37}, t_{39}, t_{41}, t_{43}, t_{44}, t_{45}, t_{46}\}$, while in case to be $T_H = \{t_{24}, t_{26}, t_{28}, t_{30}, t_{32}, t_{33}, t_{35}, t_{37}, t_{39}, t_{41}, t_{43}, t_{44}, t_{45}, t_{46}, t_{96}\}$. In addition, to each $t_i \in T_H$ is associated the length $L(t_i)$ of the corresponding road modelled by the transition (expressed in km): for instance, since $t_{24}$ models a straight truck that travels for five kilometres along A-North, it holds $L(t_{24}) = 5 \text{ km}$ (see Fig. 2). Finally, $A = 8760 \text{ h/years}$ is the number of hours in one year, while $S$ is the cost in €/km of one truck. In the sequel a cost parameter $S = 1 \text{ €}$ is assumed.

The simulation is performed on the basis of the enabling memory assumption (David and Alla, 2005), i.e., each timed transition keeps memory of the current enabling conditions only. Furthermore, after a firing, a time to firing is drawn for each new enabling of timed exponential transitions while the others do not change. Moreover, if some immediate or deterministic timed (with the same firing time) transitions are in conflict then one of them is randomly chosen for firing. In addition, to solve the conflict among exponential enabled transitions, the transition with shorter firing delay is chosen for firing. The only exception is the conflict between transitions $t_{30}$ and $t_{96}$ (see Fig. 3), i.e., the routing choice of a truck in the A-North highway between heading to the port ($t_{96}$ firing) and heading to the Fernetti.
terminal ($t_{30}$ firing), which is solved by the priority rules specified in sections 5.1 and 5.2.

The TPN model of the case study is simulated in the well known MATLAB software environment: such a matrix-based engineering software appears particularly appropriate for simulating the dynamics of TPN based on the matrix formulation of the marking update, as well as to describe and simulate PN systems with a large number of places and transitions.

The defined performance indices are evaluated by a simulation run of 8760 time units, so that the run time equals one year if one time unit is associated to one hour. The performance indices are deduced by 100 independent replications with a 95% confidence interval. Besides, the half width of the confidence interval is about 1.2% in the worst case, confirming the sufficient accuracy of the performance indices estimation. Finally, considering that the average CPU time for a simulation run is about 408 seconds on a PC equipped with a 1.73 GHz processor and 1 GB RAM, the presented modelling and simulation approach can be applied to large and complex systems.

6.2 The model validation

Validation is concerned with determining how closely the simulation model represents the actual system and it is here performed by the procedure proposed in (Law, 2007) by applying the well known single mean test. In particular, the model assumptions and data are reviewed by the commercial and ICT managers of the Samer & Co. Shipping Company which operates the ferry lines Trieste-Turkey at the Riva Traina in Trieste. Table 3 reports the performance indices obtained by the simulation with the relative half width of the confidence interval and the corresponding values computed by historical data provided by the Samer & Co. Shipping Company. Hence, denoting by $PI$ the generic performance index provided by the simulation, $RPI$ the corresponding performance index obtained by real data and $\rho$ the half width of the corresponding confidence interval, Table 3 shows that for each considered performance index it holds:

$$PI - \rho \leq RPI \leq PI + \rho.$$  \hfill (9)

Applying the single mean test, the results prove that the simulation closely represents the actual system.
Table 3.
Simulation results and performances based on historical system data.

<table>
<thead>
<tr>
<th>Performance index</th>
<th>Meaning</th>
<th>Simulation Value</th>
<th>ρ</th>
<th>Real Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TR(t_{44})$</td>
<td>Throughput of Fernetti terminal input (trucks)</td>
<td>2.43 trucks</td>
<td>0.020</td>
<td>2.43 trucks</td>
</tr>
<tr>
<td>$TR(t_{44})$</td>
<td>Throughput of port input (trucks)</td>
<td>4.90 trucks/h</td>
<td>0.030</td>
<td>4.89 trucks/h</td>
</tr>
<tr>
<td>$TR(t_{47})$</td>
<td>Throughput of port input (straight trucks)</td>
<td>2.43 trucks/h</td>
<td>0.020</td>
<td>2.43 trucks/h</td>
</tr>
<tr>
<td>$TR(t_{47})$</td>
<td>Throughput of ship input (straight trucks)</td>
<td>4.89 trucks/h</td>
<td>0.030</td>
<td>4.89 trucks/h</td>
</tr>
<tr>
<td>$TR(t_{49})$</td>
<td>Throughput of ship input (semi-trailer trucks)</td>
<td>3.81 trucks/h</td>
<td>0.020</td>
<td>3.79 trucks/h</td>
</tr>
</tbody>
</table>

Fig. 4. Average utilization of port, Fernetti terminal and B-South road in case as is and case to be.

Fig. 5. The marking evolution of place $p_{47}$: (a) in case as is; (b) in case to be.
6.3 Simulation results

The simulation results are depicted in Figs. 4 to 6 and in Table 4. Fig. 4 reports the average port utilization, showing that the change from case *as is* to case *to be* leads to a noteworthy increase (equal to +47%) in the average number of straight trucks parked in the port. Nevertheless, it is interesting to note that the Fernetti terminal average utilization decreases from case *as is* to case *to be* (the decrease is -20%), and the last five kilometres of B-South road are extremely less congested in case *to be* (with a -76% reduction), even if the port utilization is augmented and throughput of $t_{41}$, $t_{42}$ and $t_{47}$ are unchanged in case *as is* and case *to be*.

These results are due to the fact that the straight trucks can go directly to the port only when parking is available and that the number of such vehicles in the sub-system including the roads from Lisert to Fernetti and the terminal itself cannot overcome the summation of capacity $C_F=150$ plus the remaining capacity of the subsequent road and the port capacity. Hence, integrating ICT into the system leads to a remarkable increase in the port utilization and a decrease in the Fernetti utilization. Moreover, it is of basic importance that a significant decrease of the road congestion is obtained with the consequent decrease of pollution and traffic costs.

The decrease in the ITS congestion is evident observing the results reported in Table 4. Indeed, the $LT$ value significantly decreases from case *as is* to case *to be* (the reduction equals -31%).

**Table 4.** Performance indices C [€] and LT [h] in case *as is* and case *to be*.

<table>
<thead>
<tr>
<th>Index</th>
<th>Case <em>as is</em></th>
<th>Case <em>to be</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>C [€]</td>
<td>4.27</td>
<td>2.10</td>
</tr>
<tr>
<td>LT [h]</td>
<td>10.37</td>
<td>7.15</td>
</tr>
</tbody>
</table>
Indeed, in case as is the straight trucks wait about 3 hours more than trucks in case to be before entering the port. Table 4 also reports the yearly traffic cost index $C$, showing that in case to be the cost index decreases about of the 51%. This is due to the fact that the straight trucks entering the ITS from Lisert can directly go to the port when the resource availabilities are suitable, reducing the length of their travel.

In addition, Figs. 5 and 6 depict the evolution in a central month in the year long simulation of the marking of places $p_{47}$ (port) and the sum of markings $p_{34}$ and $p_{35}$ (utilization of the last 5 km of B-south road by straight and semi-trailer trucks), respectively in case as is and case to be. In these figures it is interesting to observe the peaks of the single evolutions, an information that cannot be contained in the average utilization showed in Fig. 4. In particular, Fig. 5 shows that the number of straight trucks in the port is more often equal to 40 units in case to be than in case as is, confirming the increase of the port utilization. Moreover, Fig. 6 shows that the peak values of the trucks in the B-south road decrease in case to be in comparison to case as is. Hence, the maximum number of trucks contemporarily present in the B-South road decreases using ICT.

Summing up, the simulation results show that ICT have a huge potential for efficient real time management and operation of ITS, as well as an effective impact on the infrastructures, reducing both the utilization of the system resources as well as the cost performance indices.

7. Conclusion

This paper presents a generic, modular, and top-down approach for modelling and controlling Intermodal Transportation Systems (ITS) at the operational level and focuses on the impact of ICT application on the management of the intermodal chains. In particular, the contribution of the paper is twofold. First, it proposes a top-down modelling technique in a Timed Petri Nets (TPN) framework that allows synthesizing by monitor places the control laws employing the modern ICT tools. Second, in order to show the efficiency of the modelling and controlling approaches, the ITS constituted by the Port of Trieste (Italy) and the Fernetti truck terminal and involving the truck traffic due to the Trieste-Turkey ferry service is modelled and analyzed. Moreover, the TPN model is simulated in a well known software environments considering different dynamic conditions characterized by a diverse level of information shared between terminals and operators. The
obtained performance indices allow quantitatively foreseeing the benefits of the integration of ICT into the logistics system. Indeed, the discrete event simulation results illustrate that integrating ICT into the ITS leads to a more efficient system management, in terms of system resources utilization and overall cost index. Moreover, the obtained results point out that the introduction of a simple and low cost ICT application can improve the utilization of roads with apparent benefits for limiting traffic, pollution and costs.

Future research will address further generalizing the proposed Petri net formalism for modelling and management of more complex ITS, eventually investigating on powerful simulation models in order to describe large ITS and composite ITS solutions.

Acknowledgements
The authors are grateful to the Samer & Co. Shipping Company and, in particular, the Samer’s commercial chair Mr. Richard de Felice and the Samer’s ICT manager Mr. Furio Bressanutti, for their valuable and precious collaboration in describing and analyzing the presented case study.

8. References


