A Metamodelling Approach to the Management of Intermodal Transportation Networks

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Abstract. The paper develops a novel and broad metamodel of a generic Intermodal Transportation Network (ITN), devoted to provide a reference model for the real time management and control of such systems. In order to take operational decisions, the presented model describes in detail the ITN structure and dynamic evolution that is updated on the basis of the information obtained in real time by modern information and communication technologies tools. The proposed metamodelling approach consists in employing a top down procedure and is based on the UML formalism, a graphic and textual modelling language intended to describe systems from structural and dynamics viewpoints. Hence, the paper models a generic ITN starting from the network description and shows as an example the metamodel of one of the most important nodes that compose it: the port subsystem. To this aim, we present the main UML diagrams describing the structure and dynamics of a case study.

1 Introduction

An Intermodal Transportation Network (ITN) can be defined as a logistically linked system integrating different transportation modes (rail, ocean vessel, truck etc.) to move freight or people from origin to destination in a timely manner [9]. The 21st century will see a renewed focus on ITN, driven by the necessity of moving ever growing quantities of goods and by the technological evolution each of the transportation modes has recently gone through. However, ITN decision making is a very complex process, due to the dynamical and large scale nature of the ITN, the hierarchical structure of decisions, as well as the randomness of various inputs and operations. Typically, ITN management techniques are based on a three-level hierarchy: strategic, tactical and operational ones. Strategic planning involves ITN design and considers time horizons of a few years. Tactical planning basically refers to the optimization of the flow of goods and services through a given ITN. Finally, operational planning is short-range planning and involves transportation scheduling at all transporters on an hour-to-hour basis, subject to the changing market conditions as well as to unforeseen transportation requests and accidents.

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The related literature has largely addressed the ITN modelling and management problems at strategic and tactical levels. Recently, entrepreneurs and researchers are being attracted by the key problem of using effectively and efficiently the latest developments of ICT (Information and Communication Technologies) for ITN operational management [6], [11], [12], [13]. In fact, since intermodal transportation is more data-intensive than conventional transportation, ICT are considered a primary "enabling tool" for the safe and efficient real time management and operation of ITN. Indeed, today the effective use of the modern ICT tools has made it possible to know the state of the system in real time and therefore manage and change on-line paths, vehicle flows, deliveries and orders. In order to operate such choices, there is a need of dynamic models that can track the state changes of the various system components and determine operation indices typical of the real time management, such as utilization, traffic indices and delivery delays [14]. In the domain of ITN models at the operational level we recall the class of discrete event system models [1], [3], [4] and of the simulation models [13], [14]. However, the above models are designed to describe a particular ITN and do not fully take into account the multiplicity of elements that can influence the ITN dynamics and the corresponding information structure. Since ITN are often complex and distributed systems, they have also been effectively represented by multi-agent techniques. However, this promising approach to transportation and traffic management is still at its early stages [2].

This paper develops a novel metamodel of ITN at the operational level intended for real time management and control of such systems. The metamodel has a general and modular structure and is characterized by high information integration. In order to take operational decisions, the presented model describes in adequate detail the structure and dynamic evolution of the ITN and is updated on the basis of data exchanged by the players in the system and information obtained in real time by using modern ICT tools [7]. The proposed approach consists in applying metamodelling by a top down procedure based on the UML formalism [9], [10], a graphic and textual modelling language intended to understand and describe systems from various viewpoints. Hence, UML enables us to describe the structure and dynamics of a generic ITN starting from the description of the network, until the model of the most important entities that compose it (classes) and their corresponding activities. Moreover, UML unifies the formalism by using appropriate and effective diagrams that can be easily translated into a simulation software. Indeed, the approach to the management and control of ITN is based on the construction of a reference model that simulates the evolution and dynamics of ITN and provides to the control modules the knowledge base necessary for decisions in real time. To this aim, the model reproduces the behaviour of the ITN by storing the real events such as variations in demand and orders, blockages, accidents, breaks and all those occurrences that interact with the flow and management of materials and transporters. Hence, based on the knowledge of the reference model state and the events, decision makers can make the appropriate choices optimizing suitable performance indices. To the best of the authors' knowledge, such a UML based metamodel approach has never before been proposed for ITN.

The paper is organized as follows. Section 2 describes the main steps of the ITN metamodel approach. Subsequently, sections 3 and 4 respectively describe the static and dynamic diagrams in the ITN metamodel. A conclusion section closes the paper.

2 The Metamodel of Intermodal Transportation Networks

We consider a generic ITN constituted by a set of terminals (ports, airports, railway stations, etc.), together with the interconnections between them and land infrastructures. Metamodelling is a technique that applies to models [5]. A metamodel provides an accurate description of the constructs and rules needed to obtain semantic models and encapsulates all the concepts that are necessary to describe the structure and dynamics of a particular system.

The metamodelling approach presented in this paper is a top-down approach that decomposes the system to gain insight into its compositional sub-systems. In the top-down approach an overview of the ITN is formulated, specifying any first-level subsystems: ports, airports, railway stations, intermodal terminals, ground, sea and air connections, information systems, carrier and freight forwarder. Subsequently, each subsystem is refined in detail from the structural and dynamical points of view, using suitable UML diagrams, such as class diagrams and activity diagrams. In the following sections we detail the main steps of the proposed ITN metamodelling approach. First, a procedure addressing static models is devised, defining the so-called package diagram and the class diagrams. Subsequently, process flows are considered and dynamic models are obtained, by referring to the so-called activity diagrams.

3 Static Modelling of Intermodal Transportation Networks

3.1 The Package Diagram

The first step of the presented metamodelling approach consists in identifying the main subsystems composing an ITN. These can be divided into structural subsystems (i.e., ports, airports, railway stations, intermodal terminals, ground, sea and air connections, carrier and freight forwarder) and the information system. They represent the generic concepts used within the metamodelling framework and are modelled in UML by *packages*. However, such subsystems are complex nodes that can be considered composed by other generic objects (or classes). Hence, we represent the overall ITN by the UML package diagram [9], [10]. Packages are groups of entities related to each other. Figure 1 depicts the package diagram of a generic ITN. We identify the following seven packages that form the ITN: the port, the airport, the railway station, the ground, sea and air connection, the intermodal terminal, the information system and the carrier and freight forwarder (see Fig. 1). Each package is composed by different classes representing structural basic objects interconnected with each other. Arrows show the cases in which a class in one package needs to use a class in another package. This causes a dependency between packages: for example, the information system is updated on the basis of data obtained in real time using modern ICT tools.
We assume that each package includes an information class representing the informative structure devoted to manage the considered system. However, we consider also the possibility of the existence of a centralized information system that can manage and coordinate different packages. For example, the port package contains an information class that manages the flow of trucks, trains, cranes, etc. On the other hand,

the external and higher level information system can control the interactions between the port and the infrastructures, by receiving data from the port area and the ground, sea, rail and air connections.

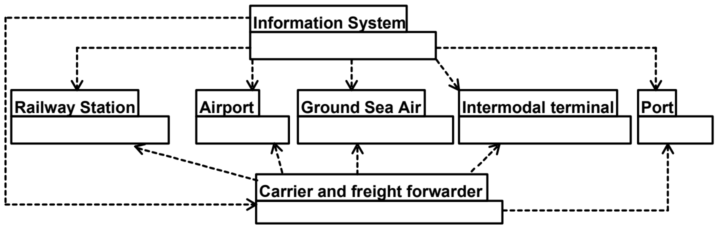


Fig. 1. The package diagram of the ITN: arrows show dependence among packages.

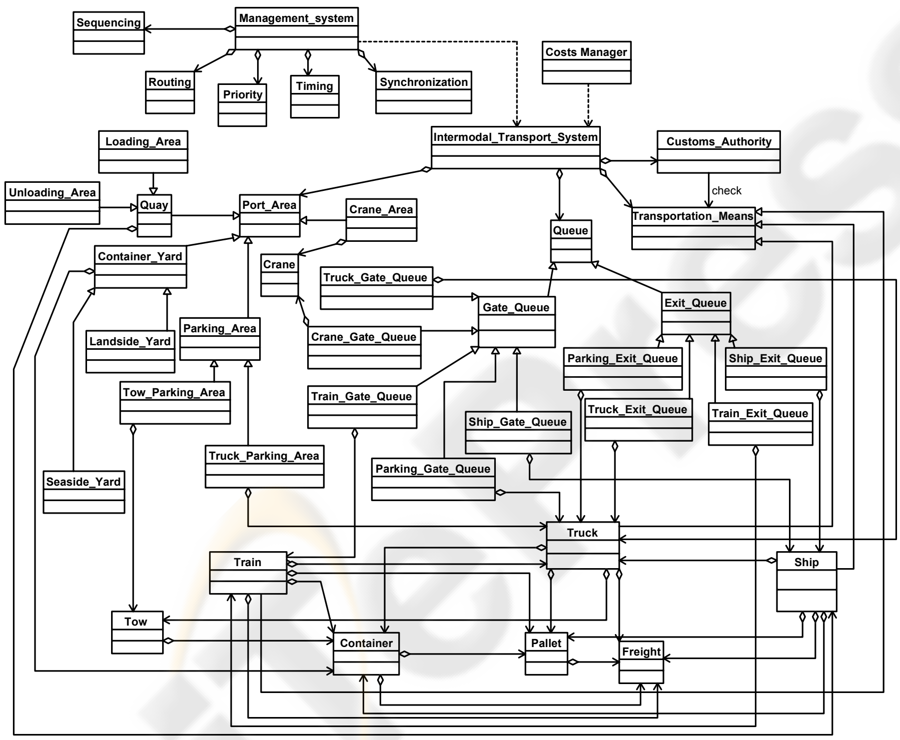


Fig. 2. The port class diagram: connections show relationships among objects in the class.

3.2 The Class Diagrams

The subsequent step of the static modelling consists in setting up the so-called class diagrams, specifying the configuration of the various packages defined in the previously discussed package diagram [9], [10]. A class diagram describes the types of objects in the ITN and the various static relationships between them. These are represented by different pictorial connections and may be relationships of association (solid line), aggregation (solid line with a clear diamond at one end), composition (solid line with a filled diamond at one end), inheritance or generalization (solid line with a clear triangle at one end), realization (dashed line with a clear triangle at one end) and dependency (dashed line with an arrow at one end). Moreover, the class diagram may show the features of a class, i.e. the name, attributes and operations of the class.

As an example, we show in Fig. 2 the class diagram of one of the packages in Fig. 1, namely the Port: for the sake of brevity we omit the class diagrams of the remaining packages in Fig.1, since they may be set-up similarly to the diagram described here. The main classes included in the diagram in Fig. 2 are the Intermodal_Transport_System, the Management_System and the Cost_Manager. In the sequel we briefly describe such classes together with their typical attributes and methods. Obviously, these features may vary depending on the ITN under study [14].

The Intermodal_Transport_System class represents the overall port terminal system. The class attributes are: 1) the dynamic lists of ships, trains and trucks currently in the terminal; 2) the dynamic lists of ships, trains and trucks already served by the operators in the terminal or by the quay cranes, waiting for permission to exit from the terminal; 3) the dynamic lists of ships, trains and trucks queued and waiting for service; 4) the dynamic lists of ships, trains and trucks currently being served; 5) the dynamic lists of ships, trains and trucks currently leaving the terminal; 6) the lists of occupied quay cranes and available ones. The class methods are: 1) the registration of ships, trains and trucks entering the terminal; 2) the extraction from the list of ships, trains and trucks waiting for service; 3) the extraction from the list of available cranes; 4) the assignment of a crane to a specific task of freight loading/unloading; 5) the crane activation; 6) the extraction from the list of ships, trains and trucks exiting from the terminal; 7) the update of the list of served ships, trains and trucks; 8) the update of the list of waiting ships, trains and trucks; 9) the update of the list of ships, trains and trucks exiting the terminal; 10) the update of the list of available cranes. The Intermodal_Transport_System class aggregates the following classes: Port_Area, Queue, Transportation_Means and Customs_Authority.

The Port_Area class represents the physical port area, modelled generalizing the following classes: Quay, where the ship loading/unloading processes take place, Container_Yard, representing the freight stock area, Crane_Area, describing the crane pick up and delivery point and Parking_Area, representing the zones where vehicles are parked. Hence, all these classes inherit the properties and basic services of their parent class, i.e. the Port_Area. This has the following attributes: 1) dimensions; 2) list of occupied locations; 3) list of unoccupied locations; 4) opening time; 5) closing time; 6) number of operators. Its methods are: 1) the extraction from a list of locations in the port area; 2) the access control; 3) the assignment of a location to an entity (ship, train, truck); 4) the clearing of a location upon the leaving of an entity. The Container_Yard class defines the storage area where freight is stored and waits for being delivered to their destination. The Quay class models the quay where ships are loaded/unloaded. Hence, the Quay class aggregates the Ship class, while it generalizes the Loading_Area and Unloading_Area classes. The Crane class attributes are: 1) the crane type (quay crane loading/unloading freight onto/from the ship, stacker crane retrieving/storing freight from the Container_Yard, automated guided vehicle or tractor moving freight from the quay area to the container yard area, etc.); 2) the crane identification number. The Loading_Area class models the ship loading area, while, the Unloading_Area class represents the ships unloading area. The Parking_Area class is the area where trucks wait either to be loaded or to be embarked. The class also includes means of transportation waiting for any reason. The Parking_Area class obviously includes the Truck class and generalizes the Truck_Parking_Area and Tow_Parking_Area classes. The Container_Yard class includes the Container class and generalizes the Seaside_Yard and Landside_Yard classes. The Seaside_Yard (Landside_Yard) class represents the warehouse area where containers, freight, tow or pallets to load on trains or trucks destined to the inland (to be shipped) are stored.

The Queue class enables the management of queues and the computation of waiting times and hence of costs. The attributes of this class are: 1) the maximum number of entities a queue may have; 2) the queue management policy; 3) the velocity of queue management; 4) the costs associated to the waiting time in queue of a user; 5) the queue identification number; 6) the current number of users in a queue; 7) a Boolean flag indicating whether the queue is full. Its methods are: 1) the inclusion of an entity in the queue; 2) the cancellation of an entity from the queue; 3) the queue management; 4) the queue cost computation. Its children classes are called Gate_Queue and Exit_Queue, respectively representing the input and output queues in all the port, e.g. queues in parking area, in crane area, etc. The Gate_Queue and Exit_Queue both have as children classes those representing the truck, train, ship, parking and crane queues. For instance, the Parking_Gate_Queue and the Parking_Exit_Queue classes respectively represent the input and output truck queues in the parking area.

The Transportation_Means class represents the transportation means circulating in the port, i.e., trucks, trains and ships. Hence it generalizes the Truck, Train and Ship classes and is associated to the Customs_Authority class. Indeed, customs have the task of controlling the arriving transportation means and applying the corresponding taxes. The Transportation_Means class exhibits the attributes: 1) the transportation means identification number; 2) the transportation means dimensions; 3) the carrier name; 4) the category of transported goods (e.g., hazmat); 5) the goods place of origin; 6) the goods destination; 7) the goods weight; 8) the identification number of the carried tows, containers, freight or pallet; 9) a Boolean flag indicating full load; 10) the current waiting time for the unload and load operation. The class methods are as follows: 1) the load/unload operation; 2) the waiting time computation. Note that the class diagram shows that the Truck class is included in the Train and Ship classes, while it aggregates the Tow, Container, Freight and Pallet classes. The Container class includes the Freight and Pallet classes, which in turn includes the Freight class. Note that both the Tow and Container class have one attribute, the identification number. On the contrary, the Pallet class attributes are the identification number and its capacity, while the Freight class attributes are the identification number and dimension. The Train class represents trains moving freight entering or exiting from the port. Such a class includes the Container class and makes use of the Intermodal_Transport_System class, so that trains remain in the railway as minimum time as possible. The Ship class models ships berthed at the port. This class includes the Container and Truck classes.

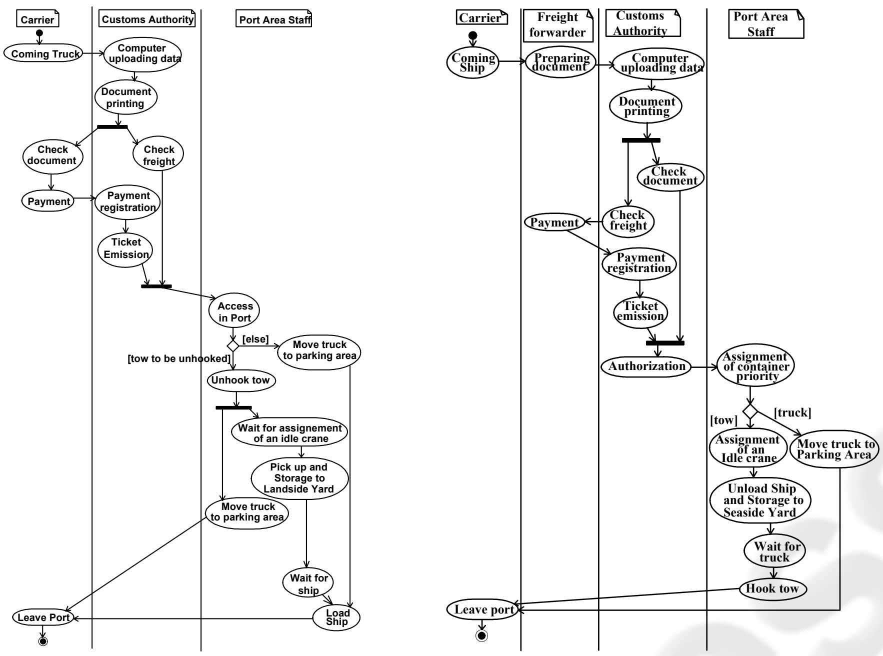
The Customs_Authority class represents the customs and their tasks of controlling all transportation means and their freight and applying taxes. It is therefore connected to the Transportation_Means class by an association function named “check”. Its attributes are: 1) the opening and closing times; 2) the control time of goods; 3) the number of customs operators. Its methods are: 1) the freight control; 2) the tax assignment.

The Management_System class is devoted to managing the whole Intermodal_Transport_System class. This class provides the rules to perform choices and decisions in the ITN. Hence, it *uses* the database provided by the Intermodal_Transport_System class to elaborate the decisions. It *aggregates* the following classes: the Synchronization class, introduced to minimize operation delays in the intermodal terminal so as to maximize synchronization of operations; the Priority class, which deals with the assignment of priorities to the transportation means (e.g., trucks transporting hazmat are assigned priority or a FIFO logic may be considered); the Routing class, which describes the operation path that has to be followed; the Sequencing class, assigning the subsequent operation that the system has to execute; the Timing class, which determines the timing of the next operation.

Finally, the diagram in Fig. 2 includes the Costs_Manager class that computes the managing costs of the container terminal. Hence, this class uses data stored in the Intermodal_Transport_System and exhibits the cost calculation operations.

4 Dynamic Modelling of Intermodal Transportation Networks

In this section we employ activity diagrams to provide a "dynamic view" of the system. Activity diagrams aim to describe the logic of the involved processes and the workflow [9], [10]. They are similar to flowcharts, but they allow representations of parallel elaborations in order to explain the critical points in the processes and workflow of the whole system by pointing out all the possible paths, parallel activities and their subdivisions. The main elements of these diagrams are: the initial activity (denoted by a solid circle); the final activity (denoted by a bull's eye symbol); activities, represented by a rectangle with rounded edges; arcs, representing flows, connecting activities; forks and joins, depicted by a horizontal split, used for representing concurrent activities and actions respectively beginning and ending at the same time; decisions, representing alternative flows and depicted by a diamond, with options written on either sides of the arrows emerging from the diamond; swim lanes, highlighting responsibilities; signals representing activities sending or receiving a message, which can be of two types: input signals (message receiving activities), shown by a concave polygon, and output signals (message sending activities), shown by a convex polygon. Moreover, activities may involve different participants in a system. Hence, partitions are used to show which actor is responsible for which actions and divide the diagram into columns or swim lanes.



(a) (b)

Fig. 3. The activity diagrams of the ship loading (a) and unloading (b) processes.

In the following we describe the activity diagrams of two basic port operations: the ship loading and unloading processes. Note that, in order to illustrate in detail the workflow of these processes, we refer to the case study of the Trieste port (Italy) [1].

4.1 The Activity Diagram of the Ship Loading Process

The logic flow associated to the ship loading operations of the port of Trieste [1] is described by the activity diagram depicted in Fig. 3a. The actors of these activities are the carrier (included in the Carrier and Freight Forwarder package, see Fig. 1), the customs authority (represented by the corresponding Customs_Authority class in the class diagram of Fig. 2) and the port area staff (operators that are attributes of the Port_area class). When trucks arrive at the port area, the loading documents are prepared by the carrier. They contain data about the freight producer (e.g., company name, country of origin etc.), the transported goods (e.g., quality, quantity etc.) and the vehicle (e.g., nationality, number plate etc.). These documents are uploaded in electronic form and printed by the customs authority. The printed documents are checked by the carrier and the freight is checked by the customs authority. Shipping tariffs are paid by the carrier. Subsequently, the payment is registered and the ticket is printed by the customs authority.

After the ticket emission and freight check, the port area staff has to manage the access of trucks into the port. We enlighten that in the considered port terminal the trucks arriving at the port can either be loaded into the ship with their tow or the tow can be unhooked and successively it is loaded into the ship [1]. At this point, on the basis of suitable priority rules that are established by the management system, either a complete truck can be loaded into the ship or a tow is unhooked and waits for the assignment of an idle crane. More precisely, trucks move to the parking area and can subsequently be loaded onto the ship. Alternatively, after the unhooking process, tows are loaded on a crane and are stored in the landside yard were they wait for the ship loading. Finally, tows are loaded by the quay crane on the ship.

We remark that the described logic flows may be significantly improved by suitable arrangements employing modern ICT tools, e.g. setting up a truck tracking device, an electronic transportation document system, etc. Obviously, the corresponding activity diagram can be obtained by suitably updating the ship loading process depicted in the diagram of Fig. 3a.

4.2 The Activity Diagram of the Ship Unloading Process

The logic flow associated to the ship unloading operations is similar to the previously analyzed loading phase and is described as follows (see Fig. 3b). The ship enters the port and the freight forwarder prepares the documents to unload vehicles and goods. These documents are uploaded in electronic form and printed by the customs authority. Data contained in the documents and freight are checked. Tariffs to unload the ship are then paid by the freight forwarder, successively the payment is registered and the ticket is printed. When the documents are checked and the tickets are ready, the authorization is issued. Hence, the port area staff, on the basis of the priority assigned by the management system class either enables the exit of trucks or assigns an idle crane to tows. In the latter case the tows are parked in the seaside yard, where they wait for trucks. Finally, trucks hook the tows and leave the port.

Similarly to the activity diagram of the ship loading process, also the activity diagram of the unloading process may be significantly improved by modern ICT tools.

5 Conclusions

The paper presents a novel top down procedure to develop a metamodel of Intermodal Transportation Networks (ITN), devoted to real time management and control at the operational level. To this aim, the model describes in detail the structure and dynamic evolution of the ITN so that it can be updated in real time using information from the real system obtained by modern information and communication technologies tools. The proposed metamodelling procedure is based on the UML formalism, a graphic and textual language able to describe systems from structural and dynamics viewpoints. To show the proposed model effectiveness, the paper focuses on a particular node of the ITN, i.e. the port, with particular reference to the port of Trieste (Italy). The detailed description of the main system components and of two basic processes of the port show how the UML diagrams can effectively depict the structure and activities of such complex and large systems. Hence, the proposed metamodelling approach and the used UML formalism provide a reference model that closely simulates the evolution of the ITN. This feature of the reference model is crucial and can be effectively employed in order to supply the control modules with the knowledge base necessary for decisions in real time. Future research will address the model of all the nodes of the ITN and the specification of the decision and control modules. In addition, we plan to apply and validate the proposed approach to a real case study. To this aim, preliminary studies are being carried out with several European ports and authorities in the framework of a research project funded by the European Commission. Finally, further studies could be developed to support learning from data in the provided model, e.g. adding decision support and control modules based for instance on agent techniques.

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