UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dottorato di Ricerca in
Ingegneria dell'Informazione
XXIV Ciclo

MODELS AND METHODS FOR MULTI-ACTOR SYSTEMS

Settore scientifico-disciplinare:
MAT/09 RICERCA OPERATIVA

Dottoranda:

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Abstract

The study of the models and methods to apply to multi-actor systems is a widely discussed research topic in the related scientific literature. The multi-actor systems are defined as systems that are characterized by the presence of several autonomous elements, of different decision makers and of complex rules that allow the communication, the coordination and the connection of the components of such systems. Commonly, the study of Multi-Actor System, MAS, recalls the well-known issues concerning the multi-agent systems.

The research topic related to the multi-agent system firstly started to appear in scientific literature in 1980s, mainly in relation to the computer science and artificial intelligence. In this dissertation, in particular, the study of the multi-agent systems, and specifically of the multi-actor systems, is taken into account merely in relation to the distinctive features of complexity that characterize such systems and not to the issues concerning the agent-oriented software engineering. Therefore, the research results presented in this thesis are focused on the development and on the realization of innovative models and methodologies to face the management and the decision making mechanisms applied to complex multi-actor systems.

This dissertation especially focuses on two different examples of multi-actor systems in two very diverse perspectives. The former deals with the research problem related to intermodal transportation networks, while the latter with the so called *consensus* problem in distributed networks of agents.

Concerning the research problem related to the intermodal logistic systems, the research activity addresses the management of their more and more increasing complexity by the applications of the modern Information and Communication Technologies (ICT) tools that are key solutions to achieve the efficiency and to enhance logistics competitiveness. The related scientific literature still seems lacking in addressing with adequate attention the impact of these new techniques on the management of these complex systems and, moreover, there is an apparent lack of a systematic and general methodology to describe in detail the multiplicity of elements that can influence the dynamics and the corresponding information and decision making structure of intermodal transportation systems. The innovative results presented in this dissertation are focused on the development of an Integrated System, IS, devoted to manage intermodal transportation networks at the tactical as well as operational decision level to be used by decision makers both in off-line planning and real time management. To specify the Integrated System, a reference model is developed relying on a top-down metamodeling procedure. These innovative research results are a contribution to bridge the gap and to propose not only a systematic modeling approach devoted to describe a generic multi-actor logistic system, but also a management technique based on a closed loop strategy.

The second example of application is focused on a topic that is widely discussed in scientific literature related to the study of the multi-actor collective behaviors in a distributed network. The interaction protocols that allow the agents to reach the convergence to a common value is called *consensus* or agreement problem. This research problem is particularly studied in the context of cooperative control of multi-agent systems because the agents are autonomous, independent and have to interact in a distributed network. The presented research results address the investigation of new and fast alignment protocols that enhance the performances of the standard iteration protocols for particular topologies of digraphs on the basis of a triangular splitting of the standard iteration matrix.

The examined examples, the models and the methodologies applied to analyze them, are very different in the two cases and this testifies the large extent of research problems related to the multi-actor systems.

Keywords: Multi-actor systems, modeling, intermodal logistic systems, distributed sensors networks.

Riassunto espositivo

L'analisi di modelli e metodi da sviluppare e da applicare nel contesto dei sistemi multi-attoriali costituisce un tema molto variegato e discusso nella letteratura scientifica internazionale. I sistemi multi-attoriali sono sistemi che si contraddistinguono per la presenza di molti elementi autonomi diversi tra loro, di molteplici decisori e di complesse regole che determinano la comunicazione, il coordinamento e la connessione all'interno di tali sistemi.

Frequentemente, facendo riferimento a sistemi multi-attoriali, *Multi-Actor Systems*, si richiama il tema molto attuale dei sistemi multi agente, *Multi-Agent Systems.* Diffusisi a partire dal 1980, i sistemi multi agente sono spesso studiati in relazione alle metodologie di sviluppo dell'ingegneria del software. Nel presente lavoro di tesi, il tema dei sistemi multi-agente, ed in particolare di quelli multi-attoriali, non viene analizzato in questo contesto, ma in relazione alle tecniche decisionali da adottare per gestire sistemi caratterizzati da un alto livello di complessità.

In tale ambito, i risultati presentati all'interno di questa dissertazione sono focalizzati sullo sviluppo e sulla realizzazione di nuovi metodi e di nuove metodologie, in grado di affrontare la gestione della complessità dei sistemi multi-attoriali. Vengono in particolare esaminate due diverse problematiche, in due contesti completamente diversi e con tecniche differenti, a testimoniare le vaste applicazioni che riguardano i sistemi multi-attoriali.

I problemi analizzati sono incentrati, in primo luogo, su un'applicazione inerente la gestione di sistemi logistici intermodali ed, in secondo luogo, sullo studio delle regole o protocolli di interazione in una rete distribuita di agenti autonomi.

Per quanto riguarda l'aspetto legato ai sistemi intermodali di trasporto, un tema molto discusso nella letteratura scientifica recente, l'analisi si focalizza sulla gestione della loro sempre crescente complessità, tramite l'utilizzo di sistemi dell'*Information and Communication Technology*, ICT.

Questi strumenti richiedono metodi e modelli che sono innovativi rispetto a quanto è presente nella letteratura scientifica, all'interno della quale è stata riscontrata la mancanza di un approccio sistematico e sufficientemente ad

alto livello per la realizzazione di una metodologia in grado di descrivere allo stesso tempo sia la molteplicità di elementi che influenzano le dinamiche e le informazioni, sia le strutture decisionali dei sistemi intermodali.

L'innovazione dei risultati presentati in questa tesi si focalizza proprio sull'esigenza di proporre un sistema integrato, *Integrated System* (IS), basato su un metamodello delle reti intermodali di trasporto, che fornisca un valido supporto ai decisori sia a livello tattico che operativo.

Il secondo aspetto affrontato in questa tesi riguarda un altro argomento di largo ed attuale interesse nella letteratura scientifica, che viene comunemente chiamato problema del *consenso*. Questo problema affronta lo studio di come diversi agenti autonomi collocati su una rete distribuita siano in grado di comunicare e di accordarsi su un valore comune, senza la presenza di un decisore centrale. A questo scopo ci sono degli algoritmi che specificano le regole o protocolli di interazione tra i diversi agenti.

In tale contesto, i risultati proposti si focalizzano su alcune problematiche rappresentate dal protocollo classico del consenso e soprattutto sulla sua scarsa efficienza in particolari conformazioni delle reti di agenti. Il lavoro di tesi propone, quindi, un approccio di suddivisione, *splitting*, della matrice standard di iterazione, di tipo triangolare, che presenta notevoli vantaggi in termini di *performance* rispetto all'algoritmo classico.

Lo studio di problemi multi-attoriali, pertanto, richiede lo sviluppo di innovative metodologie decisionali e di nuovi metodi di gestione delle comunicazioni, per rispondere al livello sempre crescente di complessità, offrendo in questo modo alcuni spunti molto interessanti per la ricerca.

Parole chiave: Sistemi multi-attoriali, Metodi e Modelli, Sistemi logistici intermodali, Network di sensori.

Dedica

Alle persone nascoste dietro queste pagine
che hanno reso così speciale questo percorso.

A te
che sei la miglior cosa che mi sia mai successa.

Citazioni

Luck is truly where preparation meets opportunity

Randy Pausch

La vita non è uno scherzo.
Prendila sul serio
... che nulla è più bello,
più vero della vita.

Nazim Hikmet

Ringraziamenti

Ringraziamenti

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Valentina Boschian

Trieste, febbraio 2012

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Chapter 1

Introduction

The study of the models and methods to apply to Multi-Actor Systems, MASs, is a widely discussed research topic in the related scientific literature. The MASs are defined as systems that are characterized by the presence of several autonomous elements, of different decision makers and of complex rules that allow the communication, the coordination and the connection of the components of such systems.

This thesis is focused on two main different topics that are analyzed from two different perspectives; nevertheless the examined issues have significant commonalities, because the studied problems are both characterized by a high level of complexity. The addressed topics refer to MASs because they are described as networked systems in which there are several actors and decision makers, with many different ways to interact and with different objectives that often can be partially conflicting. In such complex MASs, it is necessary to consider that the amount of information needed to manage them are always increasing and, it requires new models and methodologies.

In the related scientific literature, [45], [111], [112], [116], [117], the study of such MASs recalls the well-known issues concerning the multi-agent systems. The research topic related to the multi-agent systems firstly started to appear in scientific literature in 1980s, mainly in relation to the computer science and artificial intelligence and many research works are focused on the study of multi-agent systems looking at agents as the key elements of the agent-oriented software engineering, see for instance, [56], [103], [52], [57]. Currently, the related literature regarding the multi-agent systems is very wide and faces a lot of other different topics, such as planning and scheduling in logistics and supply chain management, industrial control systems, simulation modeling, sensor networks.

On the contrary, in this dissertation multi-agent systems are taken into account purely to their distinctive features of complexity and, in particular, because multi-agent systems offer a conceptual approach to include multi-actor decision making into models, [72]. Indeed, the decision making mechanism in MASs is a very complex process, due to the dynamical and large scale nature of the networks, the hierarchical structure of decisions, and the randomness of various inputs and operations.

The multi-agent systems analyzed in this thesis are focused on actors that can be considered agents only in relation to their autonomous, distributed and interaction capabilities. Thus, the actors, or, in the above specified terms, the agents, are taken into account only from an external perspective and not from the internal point of view related, for instance, to the agent-oriented software development methodologies.

This dissertation especially focuses on two different examples of MASs in two very diverse perspectives. The former deals with the research problem related to study of the modeling approaches dedicated to the decision support management techniques for logistics networks, while the latter with the so called *consensus* problem in relation to the identification of the interaction rules that specify the information exchange between an agent and all of its neighbors in a distributed network of agents.

Thus, the research results presented in this thesis are focused on the development and on the realization of innovative models and methodologies to face the management and the decision making mechanisms in complex MASs.

This dissertation firstly analyzes the topic of the management of Intermodal Transportation Networks (ITNs) since modeling, planning, and control activities involving logistic systems are research fields that have received a noteworthy attention by the research community due not only to their economic impact, but also to the complexity of decisional, organizational, and management problems relevant to logistic networks.

Enhanced planning, management procedures and decision technologies are thus required, offering both great opportunities and great challenges in the logistic sector. Indeed, research is required to build up new models concerning the various planning and management problems under intelligent transportation systems and real time information and to develop appropriate solution methods.

In order to be efficient, an intermodal logistic system needs to synchronize the logistics operations and the information exchange among stakeholders. Hence, solutions based on the modern Information and Communication Technologies (ICT) are the key tools to achieve the efficiency and to enhance logistics competitiveness. Today, the effective use of the modern ICT tools allows to know the state of the system in real time and, in order to operate such choices, dynamic models are necessary to provide predictive information about the system state. Analogously to what can be done in other application areas, such as production processes, or passenger transportation systems, it is possible to identify different hierarchical and functional levels also for transportation systems, to which different decisional problems are associated: the strategic, the tactical and the operational level. These decisions, assuming a real time availability of the information regarding the conditions of the network should be taken in a dynamic context.

The related literature still seems lacking in the modeling and management of logistic systems at the operational level and has not yet addressed with adequate attention the impact that the new ICT techniques can have on the management and control of these systems. Moreover, in the related literature there is an apparent lack of a systematic and general methodology to describe in detail the multiplicity of elements that can influence the dynamics and the corresponding information and decision making structure of intermodal systems.

The innovative results presented in this thesis are focused on the development of an Integrated System, IS, devoted to manage ITNs at the tactical as well as operational decisional level. To specify the IS, a reference model is developed relying on a top-down metamodeling procedure. The proposed IS for ITN decision making can work in two alternative ways, respectively devoted to the on-line management and off-line planning of the ITN. First, for the tactical level decisions, the IS bases on the reference model simulation the detection of the anomalies and bottlenecks of the system. Successively, the IS proposes, tests and evaluates some solutions on the basis of the estimation of suitable performance indices. Second, the IS takes real-time operational decisions. In this case, the reference model is updated on the basis of data exchanged by the stakeholders in the system and information obtained in real time by using modern ICT tools. Hence, based on the knowledge of the reference model state and events, decision makers can make appropriate choices optimizing suitable performance indices. The results presented in this chapter are a contribution to bridge the gap and to propose not only a systematic modeling approach devoted to describe a generic multi-actor logistic system, but also a management technique based on a closed loop strategy.

The second example of MASs application, presented in this dissertation, is focused on a topic that is widely discussed in scientific literature related to the study of the multi-agent collective behaviors in a distributed network. The interaction protocols that allow the agents to reach the convergence to a common value is called *consensus* or agreement problem. This research problem is particularly studied in the context of cooperative control of MASs because the agents are autonomous, independent and have to interact in a distributed network. Since the standard iteration protocols exhibit low speed of reaching a consensus for particular topologies of the digraph, the presented research results address the investigation of new and fast alignment protocols that enhance the performances of the standard iteration protocols for particular topologies of digraphs on the basis of a triangular splitting of the standard iteration matrix.

The dissertation is organized as follows: Chapter 2 initially gives an overview of traditional definitions of MASs, their characteristics, benefits, advantages, then explains the important role of MASs in relation to the distributed decision making problems within the Operation Research field and the two topics analyzed in this thesis are outlined in terms of MASs. It is noteworthy to underline that the mentioned applications concern only the MASs in terms of multi-actor and complex systems and not in terms of object-oriented methodologies. Chapter 3 is focused on the research activities related to the development of an Integrated System (IS) based on a metamodel of Intermodal Transportation Networks (ITNs) and in order to show the effectiveness of this approach two real cases are modeled and analyzed. The former case study is related to the modeling procedure to improve and optimize the management at the tactical level of an ITN composed by a port and an inland terminal. While, the latter case study is focused on the improvement of the efficiency of an ITN that involves maritime and road transportation from the point of view of the customs clearance operations. Chapter 4 presents the research results concerning the *consensus* or agreement problem of reaching the convergence to a common value in a distributed network of agents. In particular, the focus is on the investigation of new and fast alignment protocols that enhance the performances of the standard iteration protocols for particular topologies of digraphs on the basis of a triangular splitting of the standard iteration matrix. Finally the Conclusions summarize the main results and highlight how the large extent of research problems related to the MASs can offer valid opportunities for research activities that are novel compared with the ones presented in the related scientific literature.

Chapter 2

Multi-Actor Systems

2.1 Definition of Multi-Actor Systems

This section aims to give a general overview of the multi-agent systems in order to delineate what **multi-agent systems** are and in which terms they area analyzed in this dissertation.

Agent theory firstly started to appear in scientific literature in 1980s, mainly in relation to the computer science and artificial intelligence (AI) issues as an extension of the objected oriented and distributed AI fields. Despite almost thirty years of history, a definition for the term agent still remains debated [72]. Schleiffer in [96] states that: "intelligent agent technology is the articulation of human decision making behavior in the form of a computer program". However this definition has some drawbacks because it does not explicitly specify the characteristics of an agent. One of the most cited definitions for agents was published by Wooldridge and Jennings [114]: an agent is "a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives".

These first definitions stress the relationship of the agents with computer science development field. While, in this dissertation multi-agent systems are taken into account merely to their distinctive features of complexity in terms of **multi-actor systems**, hereafter **MASs**. Therefore, the following considerations fit better the scope of the thesis in which an agent is mainly considered as an actor in a **complex and distributed system**.

Therefore, a multi-agent system, is defined as a system composed of multiple interacting intelligent agents. By considering these agents as actors, MASs can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve [45]. Intelligence may include some methodological, functional, procedural or algorithmic searching, finding and processing approach. Usually MASs manifest self-organization and complex behaviors even when the individual strategies of all their agents are simple, [53].

Another definition of multi-agent systems is given by [109] that asserts that a multi-agent system "consists of a network of loosely-coupled computational autonomous agents who can perform actions". These agents have resources at their disposal and they possess knowledge, capabilities or skills. They are situated in a common environment and they can interact through a set of rules, namely an interaction protocol.

The single agent-based systems differ from MASs mainly for the following points related to the:

- environment: agents need to take into account others who may interfere with their plans and goals. They need to reach coordination in order to avoid conflicts;
- knowledge/expertise/skills: these are distributed in a MAS;
- design: agents need not be homogeneous and may be designed and implemented using different methodologies and languages;
- interaction: agents interact following rules of interaction, named interaction protocols.

Moreover, [45] proposes this well-recognized definition that states that "an interaction occurs when two or more agents are brought into a dynamic relationship through a set of reciprocal actions". The interactions are developed as a result of a series of actions whose consequences influence the future behavior of agents that can be direct or indirect, intended, or unintended. The interaction assumes that agents that are capable of acting and/or communicating and in the environment there are dynamic elements allowing for local and temporary relationships among agents. The exchange of messages among agents is governed by interaction protocols that are of different types:

- communication protocols that provide rules to structure the transfer of messages and produce meaningful dialogues or conversations;
- cooperation protocols that provide a framework in which each agent can coordinate its actions to achieve a complex task or solve a difficult problem in a cooperative way;
- negotiation protocols that are used in situations where agents have conflicting goals to enable the parties to reach a compromise and resolve conflicts.

2.2 Characteristics of MAS

Following the overview of the definitions of multi-agent systems and MASs presented in literature, this section aims at describing the main characteristics that identify a MAS, underlying the benefits, the advantages and the challenges of this approach.

Generally, complex environments with multiple actors can be organized according to various properties like: accessibility (depending on if it is possible to gather complete information about the environment), determinism (if an action performed in the environment causes a definite effect), dynamics (how many entities influence the environment in the moment), discreteness (whether the number of possible actions in the environment is finite), and dimensionality (whether spatial characteristics are important factors of the environment and the agent considers space in its decision making).

Deeply into details, the main characteristics of a multi-agent system, that fit also a MAS, have been defined by [114], stating the following four distinct characteristics: autonomy, social ability, reactivity, and pro-activeness. These characteristics are widely accepted as they are at the heart of what agents represent. This set of four properties has been expanded on significantly over the years and across multiple fields.

2.2.1 Basic Classification of MASs

In the related literature [114], two different typologies of MASs are commonly presented: the so-called “closed MASs” and “open MASs”.

In the former case, the main feature of the systems is its static design with pre-defined components and functionalities. The properties of the system are known in advance, the actor are cooperative and multiple developers can work towards the development of the system at the same time. The main advantages of this closed MASs are that they are simple and predictable, since the components, interaction language and protocols are known, actors usually are cooperative. While the main disadvantages are that the maintenance costs are high and it is difficult to inter-operate with other systems.

In the latter case, open MASs do not have prior static design and actors are not necessarily aware of others, therefore a mechanism for identifying, searching and locating others is required. Then the actors may be non-cooperative or not trustworthy. The main advantages are that a single actor or groups of actors are designed separately in a modular way, the system is flexible and fault tolerant, easier to maintain and dynamic. While the main disadvantages are that the overall behavior of the system is not predictable and the protocols may vary across actors.

2.2.2 Benefits, Advantages and Challenges of MASs

If a problem domain is particularly complex, large, or unpredictable, MASs are usually addressed because of their modularity. Indeed, they allow each actor of the system to use the most appropriate paradigm for solving its particular problem. When interdependent problems arise, the agents or the actors in the system must coordinate with one another to ensure that interdependencies are properly managed.

Furthermore, in an open MAS, the structure of the system can dynamically change. The characteristics of such a system are that its components are not known in advance, they can change over time and can consist of highly heterogeneous actors implemented by different people, at different times, with different software tools and techniques.

Research in MASs is concerned with the study, behavior, and construction of a collection of possibly pre-existing autonomous actors that interact with each other and their environments.

The motivations for the increasing interest in MAS research include the ability of MASs to solve or offer better solutions in relation to the following points, [101]:

1. to solve problems that are too large to be solved by a centralized actor structure because of its limitations represented by one centralized system;
2. to provide solutions to problems that can naturally be regarded as a society of autonomous interacting components. For example, in air-traffic control problems and multi-agent bargaining for buying and selling goods on the Internet;
3. to provide solutions that efficiently use information sources that are spatially distributed. Examples of such domains include sensor networks and information gathering from the Internet;
4. to provide solutions in situations where expertise is distributed. Examples of such problems include concurrent engineering, health care, and manufacturing.

Therefore, the most important benefit of MASs is their capability. Since they are inherently modular, it should be easier to add new actors to a MAS than it is to add new capabilities to a monolithic system.

Moreover, MASs offer other several advantages such as, their extensibility and flexibility, robustness and reliability, computational efficiency and speed, maintainability and reusability.

On the other hand, there are still several open issues related to MAS in relation to their design and implementation, such as, the efficient and effective interaction protocols to apply, the task and problem formulation, decomposition, task allocation to individual actors and subtask synthesis, the actor identification, search and location in open systems, representation of information about the state of the environment, as well as other actors, their actions and knowledge, efficient planning and learning algorithms.

2.2.3 MASs Applications in literature

As underlined in the previous sections, MASs are particularly suitable for building systems to solve complex problems that cannot be solved by any one agent or actor on its own and for dealing with problems that involve many problem-solving methods, require different types of expertise and knowledge or where there are multiple viewpoints and for creating systems where dynamic reorganization is required.

Application domains that are likely to benefit from multi-agent technology and concepts are domains with the following characteristics [100]:

- interactions are very fast;
- interactions are repeated with either
  - high communication overheads, or
  - a limited domain so that learning by the agent about user behavior is effective;
- each trade is of relatively small value;
- the process is repeated over long periods;
- the product traded is relatively easy to specify.

Therefore, there are several domains, [77], [95], [75], [5], [122], in which the application of MASs is useful such as, automated marketplace trading, defence simulation and training, planning and scheduling in logistics and Supply Chain Management, SCM, industrial control systems, simulation modeling, smart sensor networks, enterprise system integration, and event management systems. The first MAS applications appeared in the mid-1980s and then increasingly covered a variety of domains, [65], [66], [24], ranging from manufacturing to process control, air traffic control, and information management. One of the earliest MAS applications was distributed vehicle monitoring (DVMT) [40], where a set of geographically distributed agents monitor vehicles that pass through their respective areas, attempt to come up with interpretations of which vehicles are passing through the global area, and track vehicle movements. Other systems in this area include those for configuration design of manufacturing products [30] and collaborative design [28].

Other agent-based process-control systems have been written for process control, such as ARCHON, a software platform for building MASs [65], for monitoring and diagnosing faults in nuclear power plants [107], spacecraft control [98], and climate control [62].

In addition, there are a variety of MAS applications in telecommunications. In one such application [108], negotiating agents are used to tackle the feature interaction problem by utilizing negotiating agents to represent the different entities that are interested in the set up of a call. When conflicts are detected, the agents negotiate with one another to resolve them so that an acceptable call configuration can be established. Other problems for which agent-based systems have been constructed include network control, transmission and switching, service management, and network management.

2.3 MAS and Operation Research

In relation to all the considerations made in the previous sections of this chapter, it is noteworthy to point out as Operations Research, OR, may be used to describe centralized or decentralized planning approaches, and as OR terminology may similarly be invoked in describing agents, [72]. In this perspective, an agent or an actor may be viewed as an entity with an objective function that must be met, or equally in the language of agents, with a goal, subject to constraints imposed by the environment. In the language of agents, these constraints may be based on perceptions of the environment and constructed from logic or from pre-established mappings between situations and outcomes. The agents or the actors may achieve their goals thanks to the implementation of optimization techniques that solve a mathematical program in which these goals and environmental constraints are formalized.

Despite being able to describe agents in an OR sense, the agent-based literature tends to be present rather poor optimization procedures and hence important benefits can be gained by the application of concepts of mathematical programming [97]. Therefore, MAS are not only a mechanism by which distributed decision makers, or agents, may communicate, they represent a decision making mechanism worthy of classification, [75].

This dissertation recalls the issues related to the decision making techniques related to MASs and in particular focuses on two different examples of MASs in two very diverse perspectives. The former deals with the research problem related to intermodal transportation networks, and the latter with the so called *consensus* problem in relation to the design of interaction rules that specify the information exchange between an agent and all of its neighbors in a distributed network of agents.

The examined examples, the techniques and the methodologies applied to analyze MASs are very different in the two cases and this testifies the large extent of research problems related to the MASs.

In order to better outline the topic addressed by the present work, the following subsections aim at contextualizing MASs in logistic applications as well as in relation to the consensus problem in distributed network of agents.

2.3.1 MAS in Logistics and Transportation

The most relevant applications of MASs, for this research, are those in the field of logistics and transportation. Fischer et al., [48] and [49], identify four primary reasons why applying MASs to transportation problems:

- problems related to transportation are inherently distributed tasks. Trucks and jobs are not only geographically distributed, but also maintain some level of autonomy in the field;
- vehicle routing performed with any degree of realism must cope with multiple dynamic events;
- traditionally a large amount of information were maintained centrally and this causes serious drawbacks related to the level of synchronization and of the efficiency of the operations. As such, MASs provide an alternative solution method focused only on local information;
- in reality, transportation companies engage in a high-level of negotiation and cooperation in performing their daily transport tasks. MASs have the capability to include such cooperative behaviors that optimization based algorithms do not have.

Several other reports focus on interesting applications of agents in transportation. For example, Davidsson and Henesey, in [31], address the applicability of agent technology to strategic decision-making within transportation logistics and state that agent systems fit the needs of transport logistics, because they closely match an ideal agent technology application. Davidsson and Henesey, in [31], provide also a survey of existing research on agent-based approaches to transportation and traffic management.

Moreover, Caridi and Cavalieri, in [19], explain some basic strengths of multi-agent systems for logistic applications: (i) modularity; (ii) decentralization, reducing impact of local modifications on other system modules (replanning, etc.); (iii) embedding multiobjective functions; (iv) effectively modeling time-varying physical systems.

The logistic problem discussed in the dissertation analyzes the MASs in a completly different perspective from the previous examples taken from literature. Indeed, since intermodal logistic systems are characterized by a multiplicity of actors and decision makers, with several interactions rules, with different objectives and needs to obtain information in real-time, the problem is studied as a MAS in relation to its complex decision making strategies. From this point of view, the focus of the research is on the realization of an Integrated System (IS) used by decision makers both in off-line planning and real time management. To specify the IS, a reference model is developed to represent the IS knowledge-base relying on a top-down metamodeling procedure.

As a result, in order to describe a generic Intermodal Transportation Network in the presented IS framework, the reference model has to be broad, systematic, modular and easy to update. To this aim, the proposed metamodeling approach foresees the description of the structure and the behavior of a particular system.

2.3.2 MAS in distributed networks

The research related to the topic of networked systems has widely increased during the last years attracting the attention of researchers from different fields such as mathematicians, computer scientists and engineers (see, for instance, [50], [51], [82], [85], [93]). This is due to the recent technological advances in communication and computation following the miniaturization of electronic components which have allowed the realization of large groups of embedded systems, such as sensors and robotic networks.

The global knowledge and global control of a distributed network of agents cause problems related to potential inconsistencies in agents goals, plans, knowledge and results. To achieve coherent problem solving, these inconsistencies must be recognized and resolved. Solving this problem by making an agent omniscient so it can see the states of all agents and determine where the disparities lie and how to resolve them is a limiting approach because it makes this agent a bottleneck and a single point of failure. To detect and correct conflicts using only local perspective is very difficult. To facilitate detection and resolution of conflicts, agents can rely on models of the world and other agents. Disparity resolution can be influenced by the organizational structure of the agent network, the kinds of models an agent has, and the agent's reasoning algorithms.

Within this framework, the consensus problem addressed in this dissertation is analyzed. In particular, the focus of the research is on the investigation of new and fast alignment protocols that can be applied to the discrete time model of distributed networks of agents to specify the interaction rules that regulate the information exchange between an agent and its neighbors. To this aim a class of consensus algorithms that are based on the positive splitting of the standard iteration matrix is proposed and discussed.

Chapter 3

A MAS Model for the Intermodal Transportation Systems

3.1 Introduction

The main topic addressed and discussed in the present chapter deals with the study of the **impact of Information and Communication Technology, ICT, in intermodal transportation systems**. These logistic systems are characterized by the presence of several actors and decision makers, with many ways to interact, with different objectives that often are also contrasting. In such complex MASs, it is necessary to take into account that the amount of information needed to manage these systems are always increasing and therefore it is necessary to develop new models and methodologies.

In the related literature there is an apparent lack of a systematic and general methodology to describe in detail the multiplicity of elements that can influence the dynamics and the corresponding information and decision making structure of intermodal systems.

The results presented in this chapter are a contribution to bridge the gap and to propose not only a **systematic modeling approach** devoted to describe a generic **multi-actor logistic system**, but also a **management technique** based on a closed loop strategy.

The research problem, addressed in this chapter, faces the study of the intermodal logistic complex and multi-actor networks under the perspective of developing a **methodological approach** to support the several decision makers involved in analyzed transportation systems at **different decisional levels**.

In particular, these research activities are focused on the development of an **Integrated System (IS)** based on a **metamodel of Intermodal Transportation Networks (ITN)** and intended to be used by decision makers that have to take operational as well as tactical decisions in large and complex ITN and may rely on information based services.

The related literature still seems lacking in the modeling and management of logistic systems at the operational level and has not yet addressed with adequate attention the impact that the new ICT techniques can have on the management and control of these systems [119].

Indeed, the proposed approach to the management and planning of ITN is based on the construction of a **reference model** that is the core of the decision making procedure. The model describes systematically and in detail the generic ITN, providing the system states to the simulation module that foresees the evolution and dynamics of the ITN. In order to obtain a generic model describing a nonspecific ITN, a metamodeling technique is proposed in order to provide an accurate description of the construct and rules needed to obtain semantic models while encapsulating all concepts necessary to describe the structure and the behavior of a particular system [58].

In the domain of ITN models, the class of discrete event system models [29], [38], [47] and of the simulation models [119], [120] are typically considered in order to address the management of ITN at the tactical level as well as at the operational one. However, the cited models are designed to describe a particular ITN and in the related literature there does not exist any methodology able to thoroughly and systematically take into account the multiplicity of elements that can influence the ITN dynamics and the corresponding information structure.

More in detail, the considered metamodeling technique is a top down procedure based on the Unified Modeling Language (UML) formalism, [6], [81], a graphic and textual modeling language intended to understand and describe systems from various viewpoints. Moreover, UML unifies the formalism by using appropriate and effective diagrams that can be easily translated into any simulation software.

The proposed IS for ITN decision making can work in two alternative ways, respectively devoted to the on-line management and off-line planning of the ITN. First, for the tactical level decisions, the IS bases on the reference model simulation the detection of the anomalies and bottlenecks of the system. Successively, the IS proposes, tests and evaluates some solutions on the basis of the estimation of suitable performance indices. Second, the IS takes real-time operational decisions. In this case, the reference model is updated on the basis of data exchanged by the stakeholders in the system and information obtained in real time by using modern ICT tools. Hence, based on the knowledge of the reference model state and events, decision makers can make appropriate choices optimizing suitable performance indices.

In order to show the effectiveness of the application of the presented IS, within the research activities two real cases involving an ITN are modeled and analyzed. The former case study is related to the modeling procedure to improve and optimize the management at the tactical level of an ITN system composed by a port and an inland terminal. While, the latter case study is focused on the improvement of the efficiency of an ITN that involves maritime and road transportation from the point of view of the customs clearance operations.

The results presented in this chapter are based on following the author's publications in international journals, [7], [8], [9], and in the proceedings of international conferences,[10], [11], [12], [13], [14], [15], [3].

The Chapter is structured as follows: firstly an overview of the main scientific work about the topic of intermodal transportation is presented, then the methodology based on the IS and on the specification of the reference metamodel is detailed. Finally, the two case studies are presented and analyzed.

3.2 A review of the scientific literature on intermodal transportation systems

An Intermodal Transportation Network (ITN) is 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 [27], [37].

Intermodal transportation is growing and will continue to increase in the foreseeable future [27] and the 21st century will see a renewed focus on ITNs, 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.

The ITN management and planning are currently relevant subjects of research because ITN allows more efficient, cost effective and sustainable transportation than the traditional transportation systems [27].

In order to be efficient and competitive, an ITN needs to plan and synchronize the logistics operations and the information exchanged among stakeholders [44]. The problems related to the planning and management of logistic systems have been studied by researchers of different scientific fields [20], [76].

Indeed, ITN decision making is a very complex process, due to the dynamical and large scale nature of the intermodal transportation chain, the hierarchical structure of decisions, as well as the randomness of various inputs and operations. Analogously to what is done in other application areas (e.g., production processes), it is possible to identify different hierarchical/functional levels also for transportation systems to which different decisional problems are associated [38]:

- the **strategic level**, related to the long-term definition of the transportation network, to the selection of the different transportation modes and to the evaluation of the feasible flows (capacities of the nodes and of the arcs);
- the **tactical level**, related (on a middle-short term) to the management of logistic flows connected to the information flow and to the transportation network that is topologically and dimensionally defined at the higher (strategic) level;
- the **operational level** which includes real-time decisional processes, where decisions concern the resource assignment, the vehicle routing definition, and so on. In particular, assuming a real time availability

of the information regarding the conditions of the network (like unexpected requests of transportation, variations in the availability of the transportation system, road conditions and traffic flows), operational decisions should be taken in a dynamic context.

Recently, practitioners and researchers are attracted by the key problem of using effectively and efficiently the latest developments of Information and Communication Technology, ICT, tools for ITN tactical and operational management [59], [92], [105], [119]. Since intermodal transportation is more data-intensive than conventional transportation, ICT are considered a primary "enabling tool" for the safe and efficient management and planning of ITNs at the tactical and operational levels.

In particular, the modern ICT tools help to produce, manipulate, store, communicate, and disseminate information and make possible to know the state of the system in real time and therefore manage and change on-line paths, vehicle flows, orders and deliveries. In order to operate such choices, there is a need of suitable decision modules based on detailed models that can track the state changes of the various system components and determine performance indices typical of the tactical and real time management, such as utilization, traffic indices and delivery delays, [106].

In particular, with the development of 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 ITN 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 [27], [37], [39].

Hence, solutions based on the modern ICT are the key tools to achieve the efficiency [59] and to enhance logistics competitiveness. Today, the effective use of the modern ICT tools makes it possible to know the state of the system in real time and in order to operate such choices, dynamic models are necessary that can provide predictive information about the system state.

Moreover, the increasing complexity of ITNs and the availability of ICT, for the interaction among the decision makers and the acquisition of information, require the development of models and lead to the definition of novel problems with respect to the related literature [26], [59]. Enhanced planning, management procedures and decision technologies are thus required, offering both great opportunities and great challenges in the logistic sector [27]. Research is thus required to build up new models concerning the various planning and management problems under intelligent transportation systems and real time information and to develop appropriate solution methods. The related literature still seems lacking in the modelling and management of logistic systems at the operational level and has not yet addressed with adequate attention the impact that the new ICT techniques can have on the management and control of these systems [119].

Planning and management problems in ITNs have received an increased attention mainly in the field of strategic and tactical design [20], [4] and other few contributions face the problem of the evaluation of the ICT solutions on the real transportation systems. In this field, simulation is considered as an effective and useful instrument to analyze transport logistics and evaluate the impact of the proposed choices and management solutions. In particular, Xu and Hancock [119] present a prototype system that integrates logistic decision-making, freight-traffic operations, and real-time information. A freight movement simulation reproduces the traffic flows under various scenarios for the study of comprehensive freight decision making processes and operations. However, the authors do not give line guides to model the intermodal systems and, as they point out, the integrated system has to be further enhanced by formulating a more general or "real" logistic decision-making process.

Moreover the bulk of the literature on computer based simulations of multimodal freight transportation systems refers to studies carried out on scales that are usually not sufficiently wide to fully capture system level interactions, especially in areas around multimodal system. These earlier studies have often simulated isolated areas of the system and range in scope from maritime terminal simulations [2], [121], [79] to rail network simulations [34], [74], [25], [22], [69], and inland terminal simulations [94], [54]. Other studies have also focused on projections for container shipments [110] and container scheduling [70].

The review of the main scientific contributions in this research field is detailed focusing on two different main topics: the models related to the **intermodal transportation system** in general and then the models focused on **port terminal problems**. The two cases analyzed in this dissertation addresses the aspects related to maritime transportation and for this reason it is noteworthy to analyse the related scientific literature.

3.2.1 Intermodal transportation system models

The intermodal transportation systems represent a first step for the definition of systems able to describe a whole ITN, as these systems are related to the carriage of goods in a timely manner by at least two modes of transport in the same loading unit without stripping operations when the transportation modes change. This subsection analyzes some scientific contributions concerning this topic.

ITNs can be successfully modeled as Discrete Event Systems, DESs, 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. Furthermore DESs are able to exhibit a high degree of concurrency and are characterized by resource sharing and conflicts. DES models are widely used to describe decision making and operational processes in logistics systems. In particular, paper [89] analyses the literature about the simulation of the decision-making process within a transportation chain and paper [55] simulates a source allocation problem in an intermodal container terminal.

Gambardella et al. [54] propose a simulation model facing a resource allocation problem in an intermodal container terminal. In a subsequent work [94], a DES is presented addressing the study 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. Also in [89], a DES is used to analyze in an intermodal container environment, the impact of new road and railway networks on the logistics system. An object oriented approach is used in [120] in order to simulate container terminal operations.

Moreover, paper [36] proposes a queuing network model of the logistic activities related to the basic processes of vessels in a container terminal. Also in [76] a DES is used to analyse in an intermodal container environment the impact of new road and railway networks on the logistics system. In addition, [23] proposes a multi-agent system architecture for simulation and control of intermodal container terminals. Among the available DES models, Petri Nets (PNs) are selected as a graphical and mathematical technique, suitable to describe concurrency and synchronization [91]. Indeed, processes in intermodal terminals are addressed in [47] with stochastic PNs and in [32] and [37] with timed PNs. However, the cited models are designed to describe a particular ITN. An effort to propose a methodology able to thoroughly and systematically model a generic ITN is performed by [39] that use a modular modeling approach in a timed PNs framework to describe and simulate the ITN behaviour.

In the related literature there is an apparent lack of a systematic and general methodology to describe in detail the multiplicity of elements that can influence the ITN dynamics and the corresponding information and decision making structure.

A big effort in this way has been conduct in recent years by [39] and [7]. In particular, they propose two different approaches in order to model an ITN system: the first one describes the system by Timed Petri Nets (TPNs) and simulates it in MATLAB environment; the second one adopts the UML language to describe the system and ARENA Rockwell for simulation.

In the first contribution, [39] address the management of ITN at the operational level focusing on the impact of ICT tools on the management and control of the intermodal chain. In particular, they focus on the application of ICT that allows sharing information among stakeholders on the basis of user friendly technologies. In order to show the modeling and controlling approach, they analyse 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 modeled in a TPN framework by applying a top-down approach and employing a modular description of the subsystems composing it.

Consequently, the aim of paper [39] 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 modeling 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 DESs, 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 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 [36] 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 case study described in [39] allows to explain the modeling 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 describes the current management of the considered ITS, whereas the second operative condition 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 infrastructures, carrying out a performance evaluation both in term of utilization of the system resources as well as of system cost indices.

3.2.2 Port terminal models

In the field of port terminal models, some studies face the problem of the impact of arrival processes on the efficiency of the loading and unloading process for ships [2]. More precisely, the study applies three arrival processes; stock controlled, equidistant, and uncontrolled to ships docking at a chemical plant in the port of Rotterdam.

The term stock-controlled arrivals means that ships are scheduled such that a minimum base stock is maintained in the tanks, equidistant arrivals means that ships arrive at regular intervals spread throughout the year, and uncontrolled arrivals was modeled with a Poisson distribution. For container terminals, a stock-controlled arrival may not be applicable; however, the results showed that an equidistant arrival distribution may provide a more efficient loading and unloading process for ships than a Poisson arrival distribution. Multimodal freight terminals can be either a maritime or inland terminal. Inland terminals can be distinguished first of all by the fact that they are "inland and are nodes in a tightly interconnected network, composed of rail and road networks", [94]. They may also require different loading/unloading and yard operations because their Intermodal Terminal Units, ITUs, can be a mixture of maritime containers, semi-trailers, and swap bodies.

Maritime containers are stackable while semi-trailers and swap bodies are not [22]. However, they are similarities which facilitate the exchange of simulation modeling concepts between these two types of terminals. For example, both terminals have yard storage of ITUs, resource (e.g. gantry cranes and forklifts) sharing and allocation challenges, and gates where ITUs enter/depart terminal and their destinations are decided. Also, in both cases a terminal can be viewed as a network for routing ITUs to and from directly incompatible transportation systems.

Simulation modeling research in multimodal terminals has been dominated by inland terminals, with a focus on terminal performance. However, good terminal performance hinges on efficient storing of containers in the yard, scheduling of loading and unloading operations, and allocation of terminal resources. In the study [94] the researchers identified the main modeling requirements as the loading/unloading of ITUs onto/from trains, storage of ITUs on the yard, and the arrival/departure of ITUs by truck. Both manual and automatic scheduling approaches have been used to model train and truck arrival at terminals. Manual approaches usually use a fixed timetable which can be developed from fixed travel times plus some stochastic delay value or from previously recorded train or truck events at the gates. On the other hand, the automatic approach uses algorithms to generate stochastic arrivals based on some statistical distribution. For example, in the simulation study [94] of a terminal, the researchers used an algorithm to generate their truck arrivals from traffic rates obtained from an external road network model.

The allocation of resources and scheduling of loading/unloading operations was the focus of a case study [121] of the La Spezia Container Terminal (LSCT) located in the Tyrrhenian Sea in Italy. The researchers in this study developed three connected modules a simulation model of the terminal, a forecasting model which predicts expected container traffic by analyzing historical data, and a planning model to efficiently allocate resources and schedule loading/unloading operations. Their planning model uses a complex mixed-integer linear program to find the best combination of resources that minimizes costs, and then uses a Flexible Job Shop (FJS) model to prepare schedule lists for loading/unloading operations. These outputs are treated as management policies and provided as input data for the terminal simulation model. Their computer generated resource allocation and loading/unloading policies were able to achieve 30% savings on the net profit from terminal operations.

Simulation models that integrate all phases of intermodal transportation over spatially wide scales can also serve as important tools in the socioeconomic evaluation of alternative management strategies adopted by various actors in the freight distribution chain. European researchers have developed such an evaluation methodology [54] for the PLATFORM project. Their methodology uses a Cost Benefit Analysis (CBA) for commercial entities such as terminal managers, forwarders, and rail operators whose main goal is to increase profits while minimizing costs. However, the methodology uses a Multi Criteria Analysis (MCA) technique to evaluate decisions by actors in the policy arena whose concern is with the community welfare and other non-monetary impacts.

Finally, the literature review shows that discrete-event simulation is the most preferred modeling technique for the components of the intermodal transportations system.

3.3 The Integrated System Structure to manage multi-actor ITNs

This section presents the Integrated System (IS) structure devoted to manage a MAS characterized as an ITN at the tactical or operational decision level to be used by decision makers both in ITN off-line planning and real time management. To specify the IS, a reference model is developed to represent the IS knowledge base and relying on a top-down metamodeling procedure.

The IS provides the ITN designers with important key features. First, the reference model exhibits easy implementation in engineering software packages. Second, the IS can detect the bottlenecks of the system and evaluate the performance of alternative middle term solutions. Third, based on modern ICT tools, the IS enables the decision makers to update some operational design parameters in a real time closed loop strategy.

The IS is composed of three fundamental modules:

1. the **reference model**,
2. the **simulation module** and
3. the **comparing module**.

As depicted in Figure 3.1, the reference model receives the rules of the ITN behavior from the Decision Making System (DMS) and returns the model state to it. Moreover, the reference model communicates the state and the rules to the simulation module that evaluates the system performances. In addition, the simulation module sends the estimated performances to the comparing module that compares the obtained performance indices with the established system objectives. Hence, the comparison results are sent to the DMS that transmits the commands through the Information and Communication System (ICS) to the real ITN.

In particular, Figure 3.1 concisely describes the structure of the IS for the operational level application and the corresponding decision procedure. In this case the IS works on-line and takes decisions in real time in order to choose the right paths, sequencing, timing and priorities of the operations, as well as all the remaining operational choices.

At the operational level, the behavior of the considered decision making process is the following. By means of the ICT tools belonging to the ICS, the ITN detects the events occurring in the system and sends the related information messages via the ICS to the DMS that drives the events to the reference model. In turn, the reference model stores the events and accordingly updates its state. In consequence of the detected events and

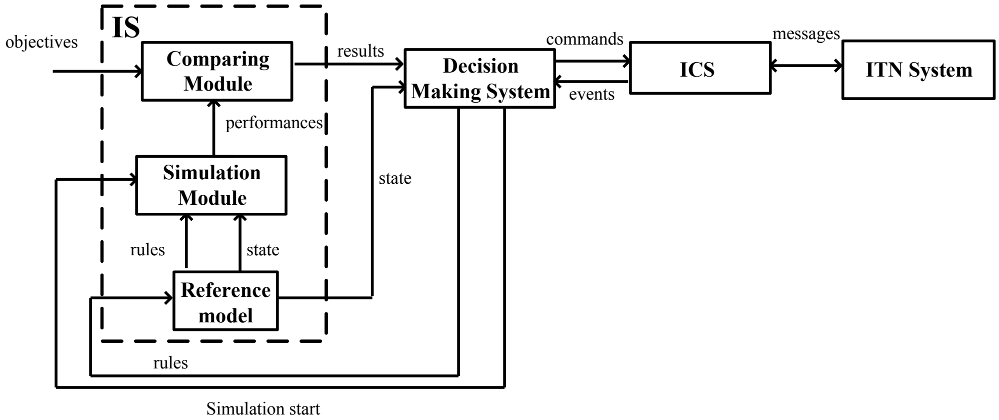

Figure 3.1: The IS structure at the operational level

the model state knowledge, the DMS decides to trigger the simulation and, on the basis of the obtained results, it modifies and tunes the rules. More precisely, the reasons that can determine the start of the simulation are the unpredictable event occurrences as well as the model state that can exhibit queues, blockages, breaks and all those occurrences that interact with the flow and management of materials and transporters. The DMS can be composed of distributed software modules as well as by teams of expert practitioners that specify the decision strategies. Such decision strategies are the rules, the functions, and the optimization formulations that allow taking decisions.

Nevertheless, it is important to remark that specifying the DMS activities is not the aim of the paper. In addition, the simulation provides the performance indices to the comparing module that evaluates the impact of the decision policies on the future system performances. On the basis of this closed loop evaluation of the choices proposed by the DMS, the commands are transmitted to the ICS that sends the corresponding messages to the ITN. Moreover, it is apparent the crucial role of the reference model that can be considered, using a well-known automatic control concept, as a kind of observer that is able to estimate the state of the system on the basis of the knowledge of the occurred events.

At the tactical level, the decision making procedure based on the proposed IS is shown in Figure 3.2. It is evident that the roles of the simulation module and the reference model are essentially unchanged but in this case the IS works off-line. Indeed, the considered ITN performance indices are the ones typical of the tactical level and do not depend on the real time events occurring in the system. Hence, the simulation module applies the decision rules and foresees the performances by evaluating the impact of the

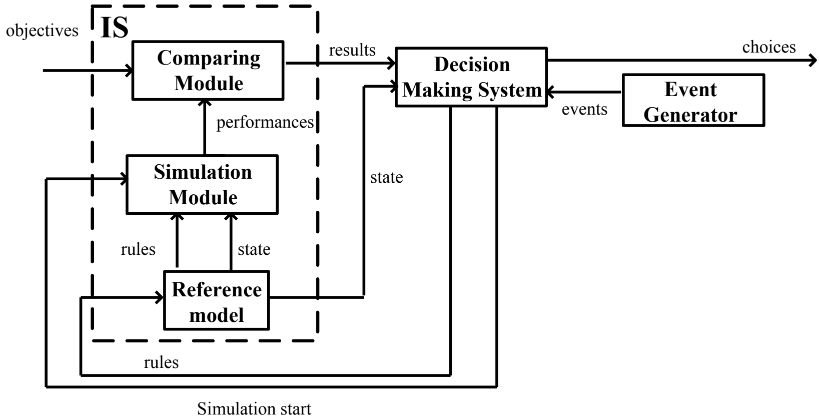

Figure 3.2: The IS structure at the tactical level

decisions. Moreover, the comparing module compares the obtained results with the system objectives. On the basis of the obtained results, the DMS decides whether it has to modify some decision strategies. To this aim, the DMS triggers the simulation start and may propose different scenarios in order to optimize the ITN performances. Even in this case the roles of the reference model and the simulation module are enabling the application of a feedback on the system behavior in a closed loop mode.

3.4 The Reference Model specification in the UML framework

Section 3.3 points out that a basic component of the IS is the reference model that describes in detail the ITN and the related information structure. This Section is focused on the reference model specification.

Hence, in order to describe a generic ITN, the reference model has to be broad, systematic, modular and easy to update. To this aim, a metamodeling approach is proposed and it is an accurate description of the construct and rules needed to obtain models encapsulating all concepts necessary to describe the structure and the behavior of a particular system. This section presents a top-down systematic methodology that builds the metamodel in the Unified Modeling Language (UML) framework [6], [81] that is a graphic and textual modeling language intended to understand and describe systems from various viewpoints. Hence, UML enables us to describe the structure and the behavior of a generic ITN starting from the description of the network, until the model of the most important entities that compose it, called classes, and their corresponding activities.. Indeed, UML unifies the formalism by using appropriate and effective diagrams that can be easily translated into any simulation software in an object oriented approach.

From the structural point of view, a system is made up of a collection of pieces often referred to as objects and described by classes. Hence, in the UML environment the system structure is described by class diagrams that illustrate the different types of objects that the system can have and their relationships. Each class is represented by a rectangular box divided into compartments. The first compartment holds the class name, the second holds attributes and the last holds operations. More precisely, attributes are qualities and named property values that describe the characteristics of a class. In addition, operations are features that specify the class behavior. Moreover, classes can exhibit relationships that are represented by different graphic connections:

- 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).

In addition, labels on the lines may express how many instances of a particular class are involved in a relationship:

1. if no value is specified a multiplicity of 1 is assumed;
2. to show a different value, simply the multiplicity specification near the owned class is placed;
3. to specify a range of values two integers are separated by two dots and an infinite upper bound can be represented by symbol "*";
4. the only symbol "*" means zero or more.

From the behavioral point of view, a system can be described in UML by the activity diagrams that show high-level actions chained together to represent a process occurring in the system. 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);
- other 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; signals representing activities sending or receiving a message.

Such messages 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 or swim lanes are used to show which actor is responsible for which actions and divide the diagram into columns or swim lanes.

Class and activity diagrams can be collected into logically related groups that in UML are modeled with packages. In particular, package diagrams are often used to view dependencies among packages that are represented by complex nodes composed of other generic communicating objects. Hence, arrows show the cases in which a class in one package needs to use a class in another package and causes a dependency between packages.

The following sections aim at presenting the top down procedure that addresses the structural model by using the UML package diagrams and class diagrams to specify the sub-system structure. Moreover, the behavior model is described by the UML activity diagrams that aim at illustrating the logic of the involved processes and the workflows.

3.4.1 The ITN Structural Model: The Package Diagram

The first step of the described metamodeling approach consists of identifying the main subsystems composing an ITN.

Indeed, the ITN can be divided into structural subsystems (i.e., inland terminals, ports, airports, railway stations, and ground, sea and air connections), logistic operators and the information system. They represent the generic concepts used within the metamodeling framework and are modeled by the UML package diagram of Figure 3.3. The following seven packages that compose the ITN are identified: Port, Airport, Railway Station, Inland Terminal, Ground, Sea and Air connection, Information and Management System (IMS) and the Logistic Operator and Customs Authority (LOCA). The arrows show the dependence between packages and exhibit that the information system is updated on the basis of data obtained in real time using ICT tools.

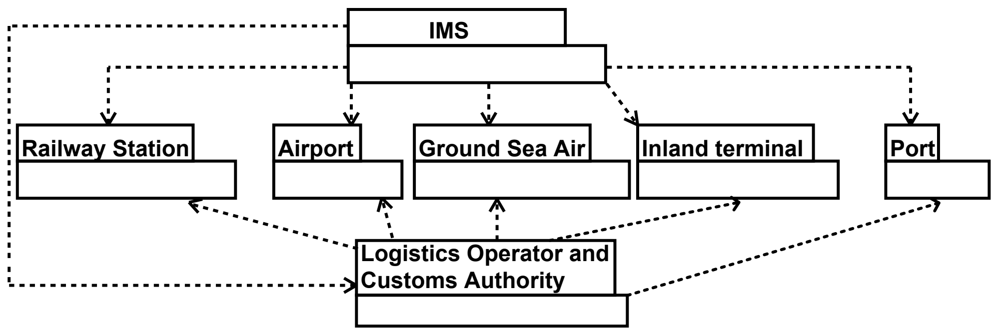

Figure 3.3: The ITN package diagram

For the sake of generality, in the model it is assumed that each package includes an information class representing the informative structure devoted to manage the considered sub-system. However, a centralized information system managing and coordinating different packages is also considered by the inclusion of the IMS package in the model. For instance, the Port package contains an information class that manages the flow of trucks, trains, cranes, etc. On the other hand, the external and high level information system modeled by the IMS package 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.

3.4.2 The ITN Structural Model: The Class Diagrams

The second step of the structural modeling procedure consists of setting up the class diagrams, specifying the configuration of the various packages defined in the package diagram. As an example, Figure 3.4 and Figure 3.5 show the class diagram of two packages shown in Figure 3.3, namely the IMS and the Port: for the sake of brevity the class diagrams of the other packages in Figure 3.3 are not detailed, since they are set up similarly to the diagram described here.

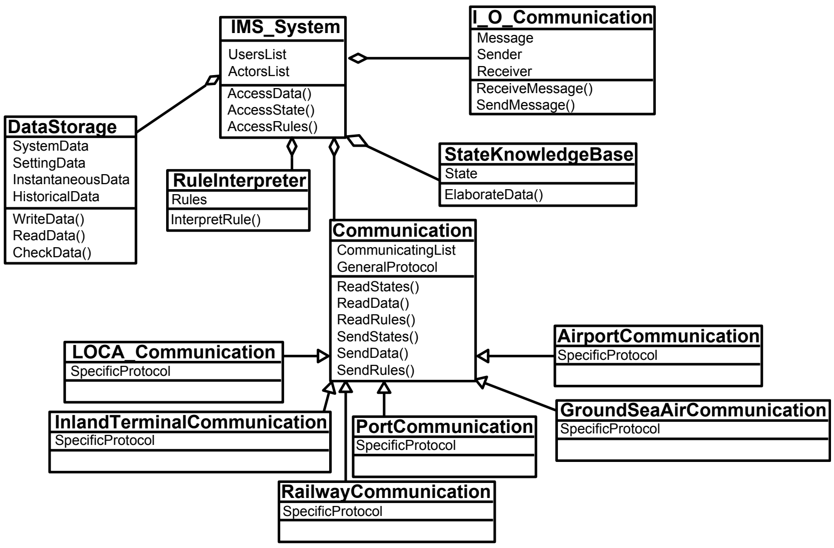

Figure 3.4: The class diagram of the IMS package

The IMS is the subsystem that has the task of enabling the communications among the reference model, the DMS, and the simulation module. Consequently, the IMS class diagram in Figure 3.4 includes the input/output communication class that enables the "talking" with the environment. The remaining classes in Figure 3.4 describe the attributes and the operations of the communications among the main ITN packages. In particular, the IMS class diagram points out the data storage, the rule interpreter and the state knowledge base classes that implement the decision rules transmitted by the DMS. Moreover, the communication class has in charge the message transmission among the structural ITN packages, i.e., the LOCA, the inland terminal, the port, the airport, the ground, sea, air connections, and the railway station.

Attributes and operations are very similar for all the classes of the IMS class diagram: the attributes are the list of actors the class has to communicate with; the operations are the protocols to receive and/or transmit the management rules, states, and data.

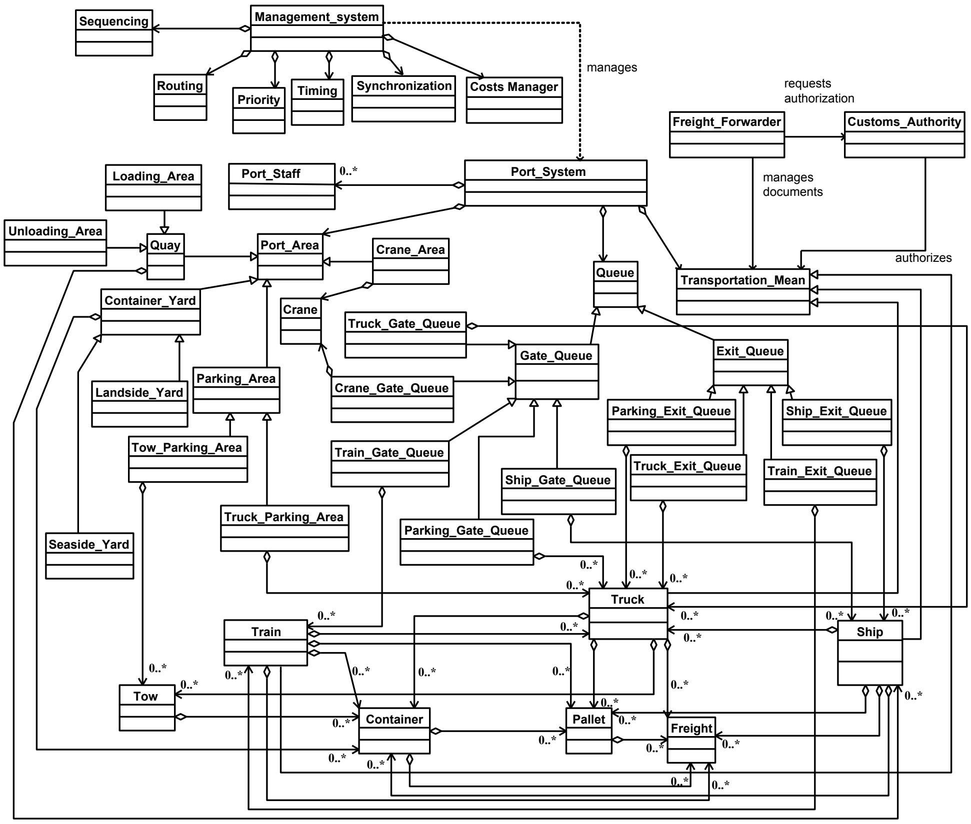

Figure 3.5: The class diagram of the Port package

The main classes of the diagram depicted in Figure 3.5 are the *Port_System*, the *Management_System*, the *Freight_Forwarder* and the *Customs_Authority*. The class diagram of Figure 3.5 shows the different types of relationships among the classes of the Port package and a more detailed description can be found in [11]. Moreover, for the sake of clarity, Tables 3.1, 3.2, 3.3, 3.4 and 3.5 list in detail the attributes and the operations respectively of the *Port_System* class, the *Port_Area* class, the *Queue* class, the *Transportation_Means* class and the *Customs_Autority* class.

It is noteworthy to remark that the system dynamics is described by the evolution of the class attributes that can change at each event occurrence. Hence, the state provided by the model is described by the attributes of the classes composing the system.

Class Attributes	**Class Operation**
1) Dynamic lists of ships, trains and trucks that are currently in the terminal	1) Registration of ships, trains and trucks entering the terminal
2) Dynamic lists of ships, trains and trucks already served by the operators in the terminal or by the quay cranes and waiting for permission to exit from the terminal	2) Extraction from the list of ships, trains and trucks waiting for service
3) Dynamic lists of ships, trains and trucks that are queued and wait for service	3) Extraction from the list of available cranes
4) Dynamic lists of ships, trains and trucks currently being served	4) Assignment of a crane to a specific task of freight loading/unloading
5) Dynamic lists of ships, trains and trucks currently leaving the terminal	5) Crane activation
6) Lists of occupied quay cranes and available ones	6) Extraction from the list of ships, trains and trucks leaving the terminal
	7) Update of the list of served ships, trains and trucks
	8) Update of the list of waiting ships, trains and trucks
	9) Update of the list of ships, trains and trucks exiting the terminal
	10) Update of the list of available cranes

Table 3.1: The *Port_System* class attributes and operations

Class Attributes	**Class Operation**
1) Dimensions	1) Extraction from a list of locations in the port area
2) List of occupied locations	2) Access control
3) List of unoccupied locations	3) Assignment of a location to an entity (ship, train, truck)
4) Opening time	4) Releasing a location upon the leaving of an entity
5) Closing time	
6) Number of operators	

Table 3.2: The *Port_Area* class attributes and operations

Class Attributes	**Class Operation**
1) Maximum number of entities in a queue	1) Inclusion of an entity in the queue
2) Queue management policy	2) Cancellation of an entity from the queue
3) Speed of queue management	3) Queue management
4) Costs associated to waiting time in queue of a user	4) Queue cost computation
5) Queue identification number	
6) Current number of users in a queue	
7) Boolean flag indicating whether the queue is full	

Table 3.3: The *Queue* class attributes and operations

Class Attributes	**Class Operation**
1) Transportation means identification number	1) Load/unload operation
2) Transportation means dimensions	2) Waiting time computation
3) Carrier name	
4) Freight category	
5) Freight place of origin	
6) Freight destination	
7) Freight weight	
8) Identification number of carried tows, containers, freight or pallet	
9) Boolean flag indicating full load	
10) Current waiting time for unload/load operation	

Table 3.4: the *Transportation_Means* class attributes and operations

Class Attributes	**Class Operation**
1) Opening and closing times	1) Freight control
2) Freight control time	2) Tax assignment
3) Customs operators number	

Table 3.5: the *Transportation_Means* class attributes and operations

3.4.3 The ITN Behavioral Model: The Activity Diagrams

In this section an ITN activity diagram is reported to show how the model provides an overview of the system behavior. As an example, Figure 3.6 depicts the activity diagram of a basic port operation, i.e., the ship loading process. Note that, in order to illustrate in detail the process workflow, the reference case study of the Trieste port (Italy) is considered. In particular, the diagram specifies the actions of the actors involved in the work process: the logistic operator (in the LOCA package), the Customs authority (in the *Customs_Authority* class) and the port area staff (an attribute of the *Port_Area* class).

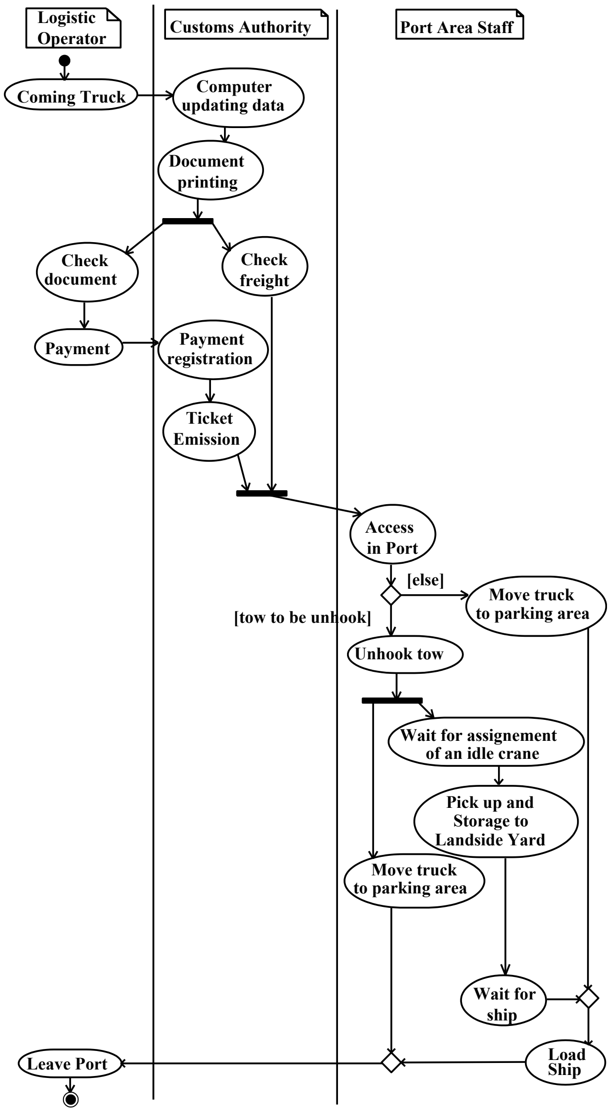

Figure 3.6: The activity diagram of the ship loading process

3.5 The IS specification for two ITN case studies

To show the effectiveness of the proposed management approach, the IS is specified and analyzed in relation to two different case studies.

On one side, an ITN characterized by a port and an inland terminal is studied. This ITN is composed by the port of Trieste (Italy) and the SDAG inland terminal located in Gorizia (Italy). More precisely, the UML reference model describing the transport of glass sheets coming from China and arriving to the Port of Trieste and the inland terminal is detailed. The case study is analyzed in the framework of the EURIDICE Integrated Project, sponsored by the European Commission under the 7th Framework Program [88]. The metamodeling approach allows to describe in detail the ITN and the behavior of the system focusing on the relation between the freight transportation and the transport-related information. A first simulation study based on the translation of the reference model in the Arena software environment [67] gives the elements to detect the anomalies and bottlenecks of the current organization. Hence, considering an ICT solution proposed by the DMS, the IS models and analyzes the ITN under the new management policy.

On the other side, the focus is on the study of ICT based solutions to speed up the transit of goods at international borders and to increase security levels. A discrete event simulation study shows that the suitable application of the modern ICT based solutions has a huge potential for efficient real time management of customs operations, drastically reducing the lead times in the port. Moreover, the simulation results allow proposing a reorganization of the workflow in order to suitably utilize human resources in the context of the new proposed ICT management.

3.5.1 The common approach to analyze the case studies

The two case studies are analyzed following the same approach that is based on the following main points. First, the case study is delineated by describing the different phases and operations that characterize the current situation, called *as is*. Then, the UML metamodel, detailed in Section 3.4, is defined referring to the analyzed case study and the new proposed ICT solution, called *to be*, is described taking into account the different phases previously explained. In order to evaluate the benefits of the *to be* solution, the simulation module is specified.

In particular, the case study reference model is translated into a simulation model, whose dynamics depends on the interaction of discrete events, such as demands, departures and arrivals of transporters at facilities, acquisitions and releases of resources by vehicles, blockages of operations. In particular, the presented model described in the UML framework is implemented in the Arena environment [67], [68] that is discrete event simulation software particularly suited for dealing with large-scale and modular systems. Indeed, the activity diagrams can be easily used to generate the Arena simulation model that can be straightforwardly implemented by the following three steps [102]:

1. the Arena modules are associated with the UML activity diagram elements, by establishing a kind of mapping between each Arena module and the UML graphical element of the activity diagrams. Indeed, even if the Arena software is not able to read UML diagrams, the activity diagrams can be quite directly translated into such a computer program;

2. the simulation parameters are included in the Arena environment, i.e., the activity times, the process probabilities, the resource capacities, and the average input rates are assigned. Nevertheless, these specifications can be modified in every simulation and enable the choice of the scenarios in the case study implementation and management;

3. the simulation run of the experiments is singled out and the performance indices are determined and evaluated by means of suitable statistics functions.

To analyze the ITN case study behavior, the some performance indices are selected [106]:

- the **system throughput, T**: it is defined as the average number of containers delivered per time unit (t.u.);

- the **lead time, LT**: it is a measure of the time spent during the different processes of the flow of goods. Different LTs are defined: the total average lead time (LT) and partial lead time specifically defined for certain phases of the flow;

- the **average percentage utilization of the resources**;

- **average Labor Time, LB**: it isdefined as the total average time spent by an employee (man-hour) per month to fulfill the described phases. Different LBs are defined: the total average labor time (LB) and partial labor time specifically defined for certain phases of the flow.

The arrival time instants of containers are randomly generated by an exponential distribution and the processing times of the activities have a triangular distribution. These two distributions are chosen for the following reasons [67]: the exponential distribution is often used to model inter-event times in random arrival and breakdown processes, but it is generally inappropriate for modeling process delay times. On the other hand, the triangular distribution is commonly used in situations in which the exact form of the distribution is not known, but estimates of the minimum, maximum, and most likely values are available.

This modeling methodology applied to the case study highlights the main features of the proposed model: the modularity and the high level of detail. Indeed, to broaden the model it is necessary simply adding other class diagrams in an object oriented approach. On the other hand, it is easy to model more in detail the system or change the ITN management rules respectively updating the attributes and the operations of the classes and substituting the activity diagrams.

Moreover, the application of this management approach to the case studies shows how to improve the ITN performance by the detection of bottlenecks and system anomalies. In addition, the availability of new ICT solutions for evaluating the ITN performance enables a quantitative assessment of the management strategies. Indeed, it is apparent that ICT have a huge potential for efficient ITN real time management and operation, drastically reducing the lead times in the port and in the inland terminal.

3.5.2 The port and inland terminal case study

This subsection specifies an IS that is devoted to manage at the tactical level the flow of goods and information of a real ITN. The considered case study is composed of a port, an inland terminal and the ground connection. In particular, the ITN refers to the flow of freight (that are sheets of glass used to produce solar panels) arriving from a Chinese port to the port of Trieste (Italy), and subsequently to the so called SDAG inland terminal of Gorizia (Italy) via the ground connection between them. Figure 3.7 schematically shows the flow of goods and information for the considered ITN.

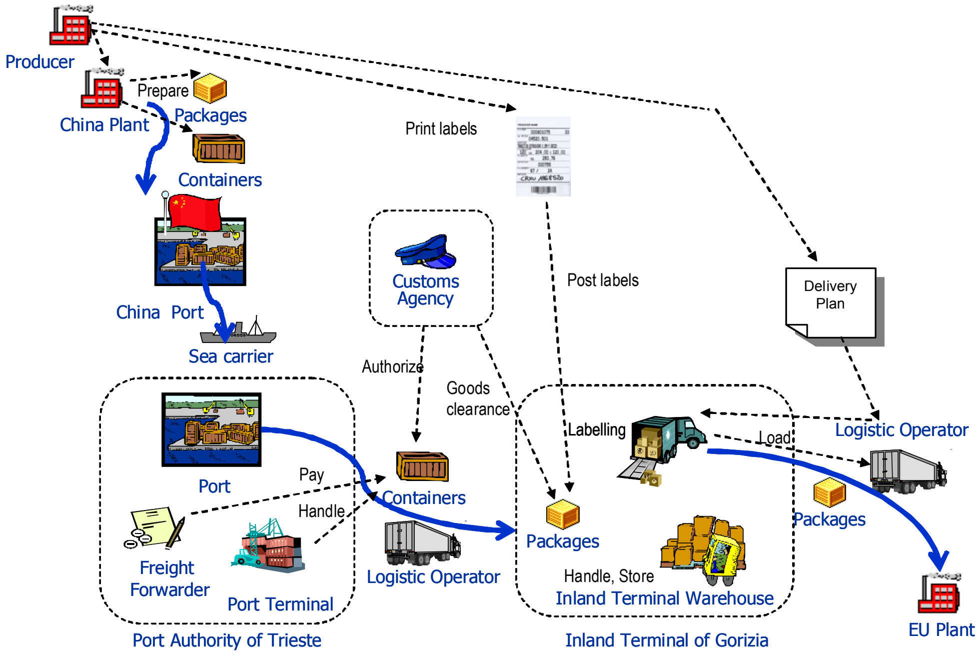

Figure 3.7: The flow of goods and information of the ITN case study

Moreover, in order to show the proposed decision making procedure, the presented case study focuses on the management of the good and information flows during the unloading, Customs clearance and warehousing processes in the port and in the inland terminal. Hence, it is shown how the IS analyzes and highlights, by the model specification and the simulation, the bottlenecks of the actual ITN, the case *as is*. Subsequently, the DMS proposes the ICT based solutions and the IS applies and evaluates the new management policies by simulating the ITN in the new case, the case *to be*.

3.5.2.1 The Reference Model Specification

Starting from the ITN metamodel defined in 3.3, this sub-section builds the IS reference model for the ITN case study, including the system structure and the activities of the involved stakeholders.

<u>The Structural Model</u>

The ITN structure is described by two class diagrams shown in Figures 3.8 and 3.9 that respectively illustrate the main elements characterizing the port of Trieste and the inland terminal of Gorizia. Obviously, the class diagrams of Figure 3.8 are an instance of the generic port class diagram depicted in Figure 3.4. Moreover, with the exception of few elements, Figure 3.9 is similar to Figure 3.8 and the main differences concern the descriptions of the *Port_Area*, *Queues*, *Warehouse* and *Transportation_Means* classes.

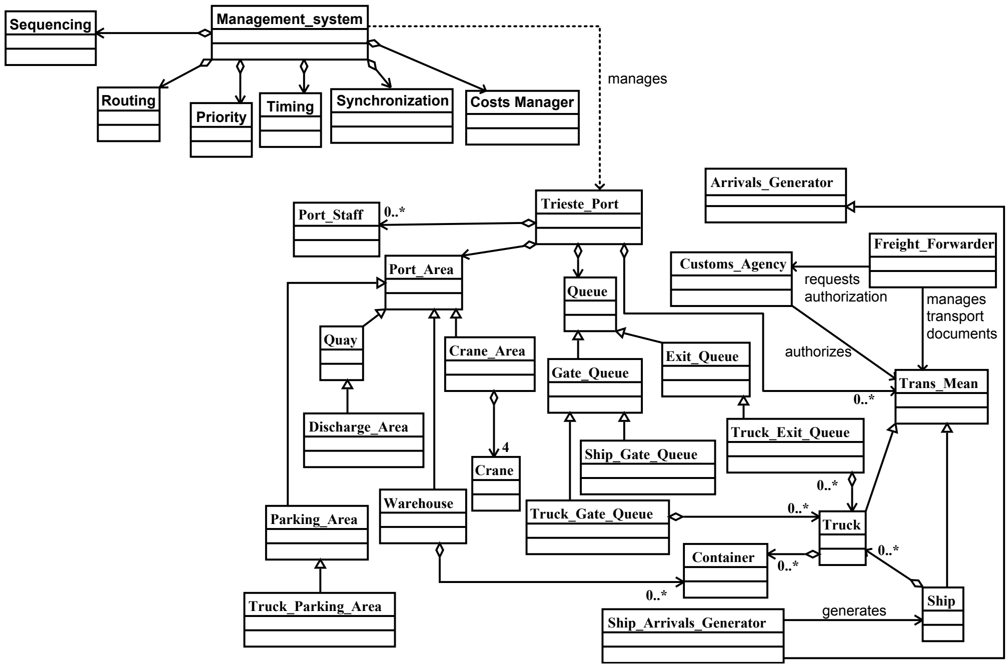

Figure 3.8: The class diagram of the port of Trieste

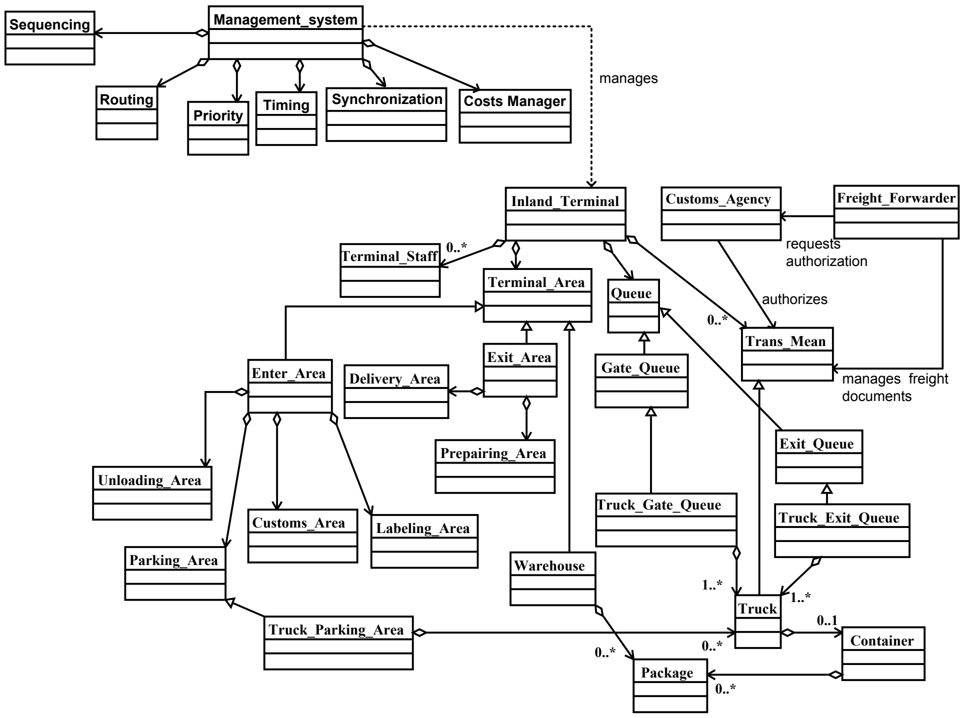

Figure 3.9: The class diagram of the SDAG intermodal terminal of Gorizia

For the sake of simplicity, the figures do not show attributes and operations that are similar to the ones that are detailed in Tables 3.1, 3.2, 3.3, 3.4 and 3.5.

The Behavioral Model

The management of the good and information flows during the unloading, Customs clearance and warehousing procedures in the case *as is* is described by the following phases that are detailed in the activity diagram of Figure 3.10.

1.a Production phase: goods are produced in China. The produced sheets, collected in loading units, are sent to a Chinese port.

2.a Shipping phase: during this phase, a set of documents is prepared, e.g., the packing list for loading called "manifest". This document is transferred to customs and contains information about all the goods in the ship.

3.a Unloading phase in the port: the load arrives to the port of Trieste, where it is unloaded by the terminal operator.

4.a Payment phase: the freight forwarder receives the information regarding units and packages inside them. When the container is released by the terminal operator, shipping tariffs are paid in relation to the quality and quantity of the goods.

5.a Authorization phase: the freight forwarder and the customs authority prepare the transportation documents to authorize the exit of the containers from the port area.

6.a Transportation phase: the goods are loaded on the trucks and transported by the carrier to the inland terminal of Gorizia.

7.a Unloading phase in the inland terminal: the containers arrive to the terminal parking area where they are unloaded and wait for the authorization to enter the inland terminal.

8.a Customs clearance phase: depending on the quality and quantity of the goods, customs tariffs are paid. Customs clearance operations are slow to execute and they are carried out by the freight forwarder that prepares the customs duty bill.

9.a Warehousing phase: goods are managed in the inland terminal. The SDAG staff sticks on the packages the labels that are produced by the freight forwarder and are sent by ordinary mail before the goods arrival.

10.a Loading phase in the inland terminal: the carrier company communicates to SDAG the delivery plan and SDAG operators load the goods on trucks on the basis of the packing list.

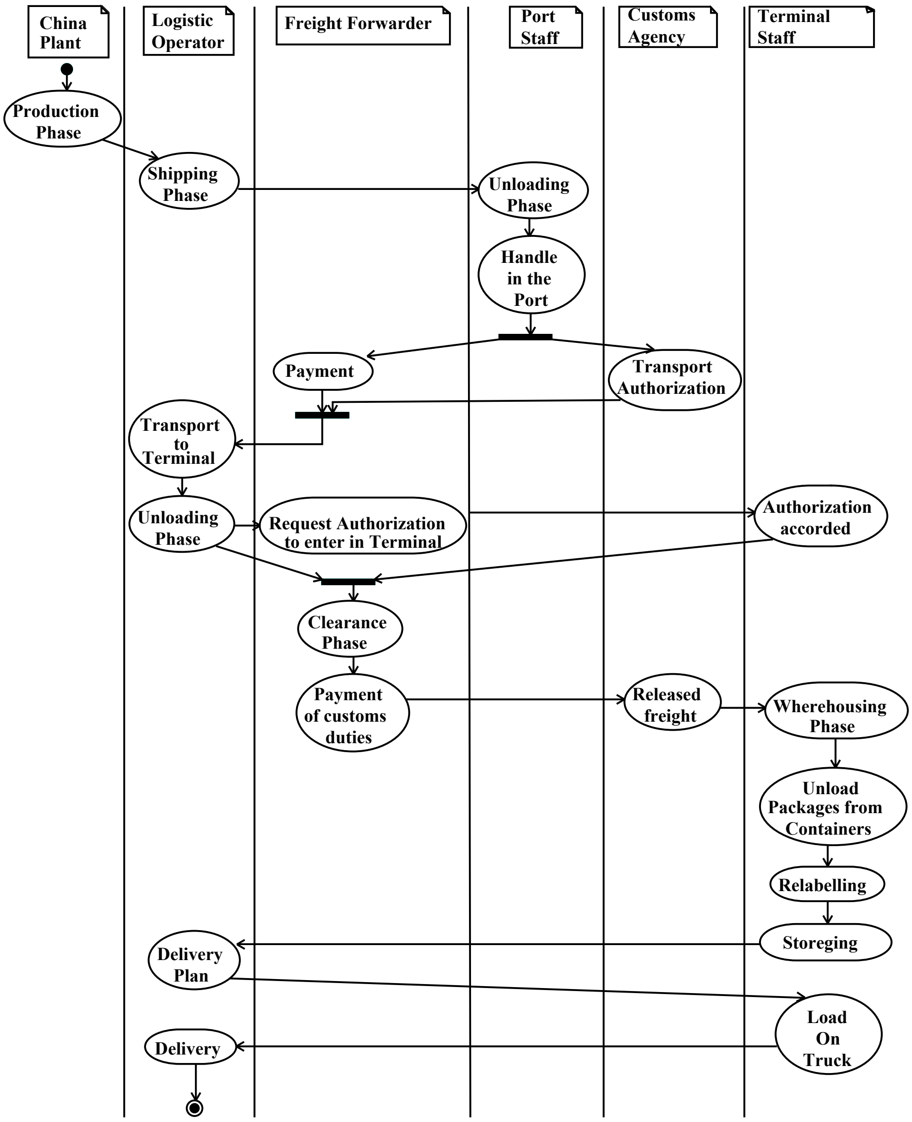

Figure 3.10: The activity diagram of the case study (case *as is*)

3.5.2.2 The Simulation Module Specification

This subsection specifies the simulation module that in the considered case study aims at investigating and comparing the flow of goods and information in the ITN during the unloading and warehousing procedures. In particular, the simulation starts from the beginning of phase 3.a (unloading in port) and ends with phase 9.a (warehousing).

To analyze the ITN case study behavior, the following performance indices are selected from the list presented in the subsection 3.5.1:

- **T**: the average number of containers delivered per time unit (t.u.) by the inland terminal;
- **LT1**: the average time interval elapsed from the unloading in the port (phase 3) till the authorization (phase 4);
- **LT2**:the average time interval elapsed from the unloading in the inland terminal (phase 6) till the warehousing (phase 8);
- **LT**: the average time elapsed from the unloading in the port (phase 2) till the inland terminal warehousing (phase 8);
- **average percentage utilization of the resources**.

The model assumptions and data are gathered from the historical data provided and reviewed by the Port Authority of Trieste and the forwarder staff. In particular, the analysis considers the flow of 1600 containers/month between the port and SDAG. However, the case study simulation focuses on the flow of containers that are managed by a specific freight forwarder: the flow of 20 containers/month of glasses from China, each container has 36 packages inside and each pallet contains about 120 sheets of glass. The arrival time instants of containers are randomly generated by an exponential distribution of mean 0.90 t.u., where the hour is considered as t.u. In addition, the processing times (in hours) of the activities described in Figure 3.10 have a triangular distribution, specified in Table 3.6. In particular, the second column of Table 3.6 reports the modal values δ of the processing time distributions of the case *as is*, the third and fourth columns show the maximum and minimum values of the range in which the firing delay varies, denoted respectively by Dδ and dδ, and the last column reports the number of infrastructure operators, denoted by *Op*, that are necessary to perform the corresponding operation.

To evaluate how the exchanges between customs and freight forwarder affect the system behavior, the decision making system proposes three different scenarios S1, S2 and S3 specified in Table 3.7. More precisely, case S1 considers the operators that currently manage the flow of containers. Scenarios S2 and S3 are chosen to single out the bottlenecks in the full process, focusing on the forwarders and customs operations, respectively: in S2 the number of forwarders in SDAG and in the port area is increased, in S3 the number of customs operators both in port and in SDAG is increased.

Operations	**(t.u.) case *as is***	D_δ **case *as is***	d_δ **case *as is***	**(t.u.) case *to be***	**Op**
Unloading (phase 1)	0.50	3.00	0.42		2
Handling in port	0.33	0.37	0.30		1
Payment	0.25	0.50	0.20	0.00	1
Transport authorization	0.25	2.00	0.20	0.05	1
Transport to SDAG	2.00	2.40	1.60		1
Unloading (phase 2)	0.50	2.00	0.42		2
Request authorization	0.17	1.00	0.13	0.00	1
Acceptance	0.50	2.00	0.42	0.05	1
Clearance	0.25	0.50	0.20	0.00	1
Duties payment	0.25	0.50	0.20	0.00	1
Freight release	0.50	3.00	0.42	0.05	1
Unloading (phase 7)	0.50	2.00	0.42		2
Re-labeling	0.50	0.67	0.40		1
Storage	2.00	2.40	1.60		1

Table 3.6: Distribution specification of processing times and number of operators per operation

Resources	S1	S2	S3
Forwarders in SDAG	3	5	3
Customs staff in port	2	2	4
Port area staff	4	4	4
Customs staff in SDAG	2	2	4
Area staff in port	10	10	10
Forwarders in port	6	8	8
Trucks for transport	8	8	8

Table 3.7: Number of resources per operation in each scenario

The performance indices are evaluated by a long simulation run of 9360 t.u. with a transient period of 720 t.u.. In particular, the estimates of the performance indices are deduced by 50 independent replications with a 95% confidence interval. Besides, the percentage value is evaluated as 1.5% of the confidence interval on the throughput evaluation to assess the accuracy of the indices estimation.

Finally, considering that the average CPU time for a simulation run is about 120 seconds on a PC equipped with a 1.83 GHz processor and 1GB RAM, the presented modeling and simulation approach can be applied to large and complex systems.

3.5.2.3 The Comparing Module for the Case *As Is*

The simulation results are depicted in Figures 3.11, 3.12, 3.13, reporting respectively the system throughputs, the lead times, and the average percentage utilization of the ITN operators.

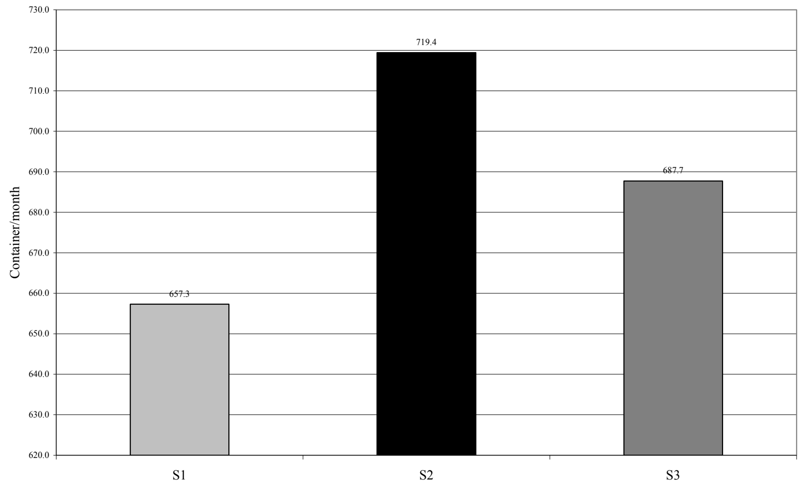

Figure 3.11: The average system throughput for each scenario

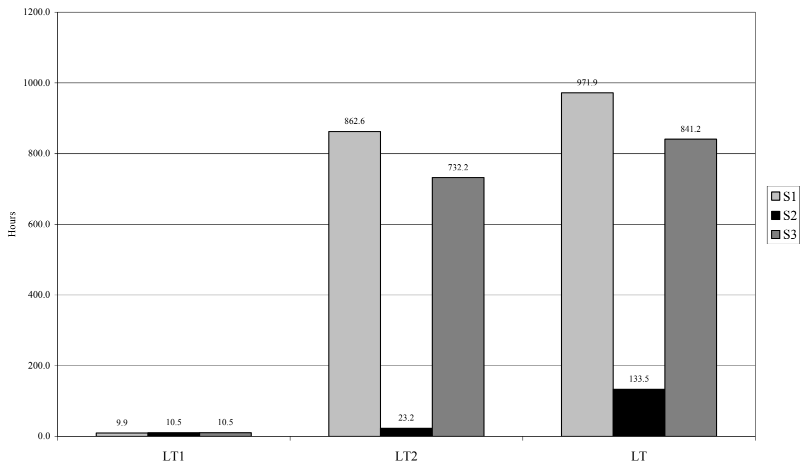

Figure 3.12: The lead times for each scenario)

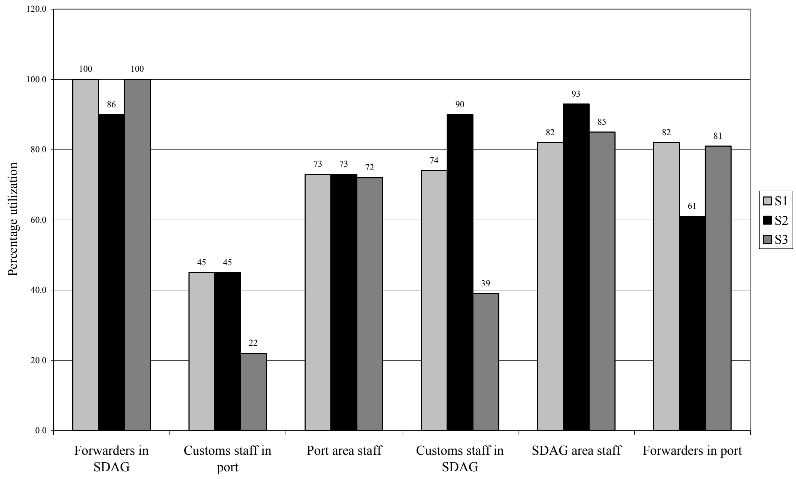

Figure 3.13: The average utilization of resources for each scenario

In particular, Figure 3.11 shows that the throughput in scenarios S2 and S3 raises as expected. However, in S3, where Customs operators are doubled both in the port and in SDAG with respect to S1, the throughput increases only of 5% with respect to S1. Instead, in S2, the increase of forwarders staff both in the port and in SDAG leads to a remarkable 10% increase of the ITN throughput with respect to S1 (see Figure 3.11). Moreover, Figure 3.15 shows that increasing the number of operators in port and in SDAG the average lead times decrease except for the LT1 quota that is minimally increased in S2 and S3 with respect to S1 due to the increased queues in the system. In particular, Figure 3.12 shows that increasing the available forwarders in S2 with respect to S1 leads to a noteworthy -86% decrease of the overall lead time LT due to the drastic reduction of LT2, i.e., the wait between the freight unloading in the inland terminal and the warehousing. On the other hand, under S3 the LT index decreases only of about -13%.

Furthermore, Figure 3.13 shows that under S2 the utilization of the forwarders (in SDAG and in port) remarkably decreases as expected, with a basically unchanged utilization for the other operators in the ITN. Similarly, under S3 the utilization of the customs staff decreases (in SDAG and in port). In addition, the Figure 3.13shows that increasing forwarders and Customs staff slightly impacts the port staff utilization.

Consequently, the simulation enlightens that enhancing the resources used by the freight forwarder allows a better utilization of the whole ITN and at the same time increasing the system productivity and responsiveness. Summing up, the IS reference model points out via the simulation that the role of the freight forwarders has a crucial importance in the management of the freight transportation and suggests to investigate on new management strategies for freight forwarder operations.

Finally, to validate the simulation and determine how closely the simulation model represents the real system, here the procedure proposed in [71] is applied by the well-known single mean test. In particular, the model assumptions and data are reviewed by experts that provided the average Real LT (RLT) values computed by historical data, against the simulated LT values and the half width of the corresponding confidence interval under scenario S1 (that mimics the current ITN situation). Taking into account the values in Table 3.8 of LT, RLT and the half width of the corresponding confidence interval (denoted by), it holds: $LT - \rho \leq RLT \leq LT + \rho$. Applying the single mean test, the results prove that the simulation closely represents the actual system.

Performance index	**Simulated vale LT [h]**	**Real value RLT [h]**	**Confidence Interval half width ρ [h]**
LT1	9.90	10.00	0.70
LT2	862.60	960.00	97.40

Table 3.8: Validation of the lead time under scenario S1

3.5.2.4 The New Rules Proposed by the DMS

This subsection shows how the DMS on the basis of the reference model and the simulation module analysis can propose and evaluate new ICT integrated solutions for freight forwarder operations. More precisely, the new solution is based on the integration of ICT tools including technology components and basic informative services that give the possibility to store and access the identity, context, and location of freight as well as the related up-to-date information. To this aim, an intelligent cargo concept is introduced and by the application of smart tags on containers and packages, a unique identification code allows avoiding duplication of information and accessing weight, quality, quantity and origin of goods. These data can be obtained anywhere along the flow of goods in the ITN to support automated certification and fulfill payments of fixed and variable costs, such as customs, shipping tariffs, and terminal services. The smart device communicates directly with a hosted service that performs several operations, like unambiguous identification of the cargo items, owner and position.

Following the approach shown in Section 3.4, the DMS proposes the solution to the reference model that formalizes the new ITN behavior by the activity diagram. Moreover, the DMS triggers the simulation and specifies suitable scenarios in order to evaluate the impact of ICT on the ITN dynamics. In the following, the changes obtained with the to be solution in the phases listed in Section 3.5.2.1 are highlighted. In particular, the differences only regard the information flow, while the flow of goods is unchanged.

1.b Production phase: goods are produced in China and the hosted service platform is prepared to follow the cargo during the whole flow. Smart tags are created for containers and packages and are directly linked to objects in the platform.

2.b Shipping phase: the "manifest" is prepared in order to allow unloading goods in the port of Trieste. This document is generated directly via cargo-ship interaction, possibly using satellite communications.

3.b Unloading phase in the port: the cargo is unloaded and communicates with the infrastructure in order to recognize its current conditions, invoke services and start processes.

4.b Payment phase: shipping tariffs are automatically paid by the direct interaction on the hosted service platform with the banking system.

5.b Authorization phase: thanks to the cargo intelligence and the hosted services, all the data for creating the authorization documents are in the platform and the process is automatically performed.

6.b Transportation phase: after the execution of the port procedures, the cargo updates its status to leave the Trieste port.

7.b Unloading phase in the inland terminal: the containers arrive to the terminal parking area of SDAG, but they do not wait for the authorization to enter the terminal, because their status is already known and updated.

8.b Customs clearance phase: goods are automatically cleared by communicating with the platform and the custom authority system.

9.b Warehousing phase: containers are opened by SDAG staff and packages are managed in the warehouse. Packages are already labeled and a hierarchy between packages has previously been created.

10.b Loading phase in SDAG: the delivery plan is in the platform and available to all the stakeholders, so that goods can be transported to destination.

Obviously, the structure of the ITN is not changed with respect to the case as is. On the contrary, the behavioral model is modified as reported by the activity diagram of Figure 3.14.

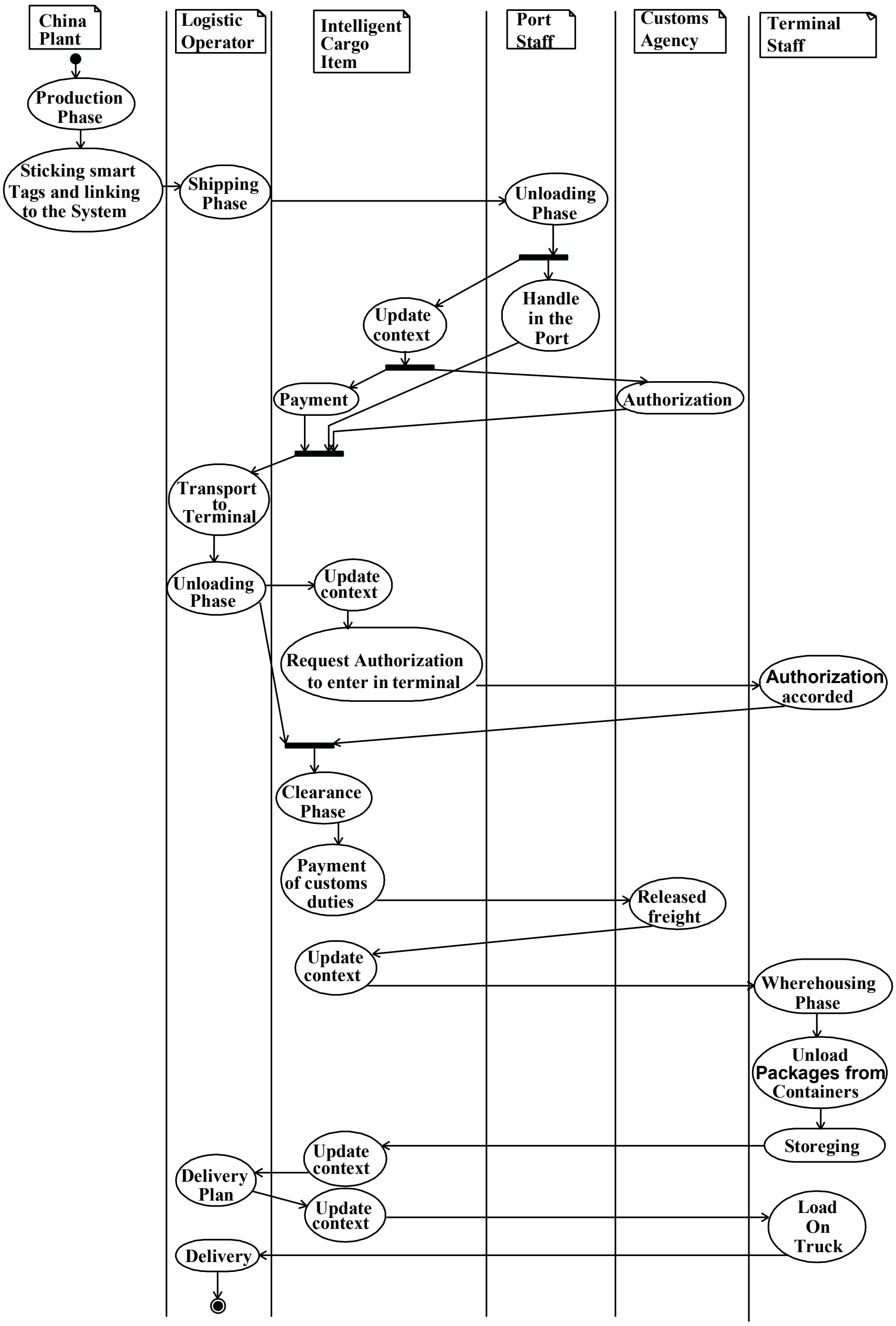

Figure 3.14: The activity diagram of the case study (case to be)

3.5.2.5 The Comparing Module in the Case To Be

The proposed DMS solution is simulated in the ARENA environment by the simulation module that foresees the new scenario to be. In particular, the simulation describes the system behavior starting from the beginning of phase 3.b (unloading phase in the port) and ending with phase 9.b (warehousing phase).

In the case to be the processing times of the phases have a triangular distribution and are reported in the fifth column of Table I that shows the modal values δ of the processing times, assuming that in such case $D\delta=1,2\delta$ and $d\delta=0.8\delta$. An important aspect to be remarked is that some operations are either not present in the case to be or automatically performed (i.e., the associated processing time is zero).

It is noteworthy to remark that the to be scenario affects the management of the containers handled by one specific forwarder in SDAG, i.e., the flow of 20 containers/month. In order to compare the two management policies, the lead times LT, LT1 and LT2 are considered that, as in the case as is, are evaluated by a long simulation run of 9360 t.u. with a transient period of 720 t.u.. Moreover, the estimates of the lead time values are deduced by 50 independent replications with a 95% confidence interval that is evaluated as 1.5% of the confidence interval width to assess the accuracy of the total lead time estimation.

The simulation results are depicted in Figure 3.15 that compares the average lead times in the as is case of the scenario S1 and in the to be management. The results show that the change from the as is to the to be case leads to a noteworthy decrease (equal to about -73%) of the LT1, i.e, the lead time referring to the unloading phases in the port. Moreover, the LT2 decrease equals about -99%. Nevertheless, the average throughput is almost unchanged with respect to scenario S1 and is about 724 containers per month in the to be case. This is due to the fact that only a subset of the containers is managed by the new ICT solution, consequently the benefit of the case to be implementation is limited.

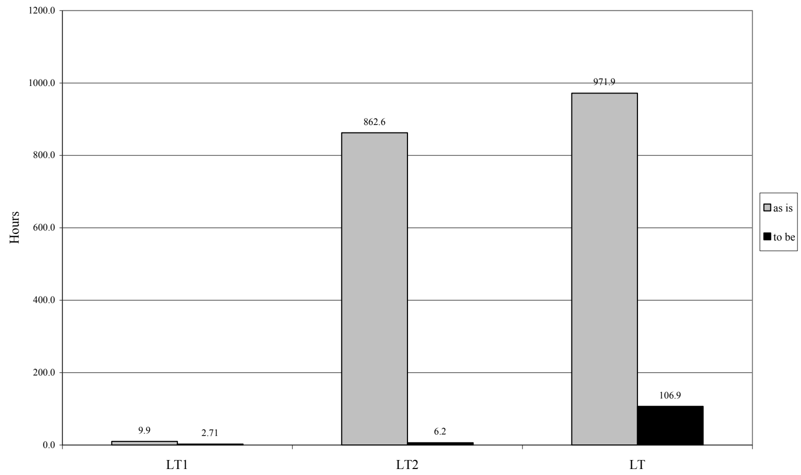

Figure 3.15: The average lead times in the two cases: *as is* and *to be*

3.5.3 The customs clearance case study

This case study analyses a crucial problem in the international freight management and assesses the application of an innovative solution based on ICT tools. In order to improve the customs clearance procedures, the main anomalies and bottlenecks related to international freight management are analyzed by modeling the customs clearance activities in UML. Similarly to the previous case study in Section 3.5.2, some novel ICT based solutions are proposed in order to optimize suited performance indices. The flow of goods and information involved in the case study is simulated in different scenarios in order to highlight the improvements reached by using ICT solutions. The simulation results point out the huge impact of ICT on customs clearance operations.

3.5.3.1 The scientific problem in literature

For the sake of completeness and to clarify the problem addressed by this case study, some other references from the literature, beyond the ones presented in 3.2 are considered, focusing in particular, on the problem of improving the efficiency of an intermodal logistic system that involves maritime and road transportation from the point of view of the processes, and, in particular, the customs clearance operations.

In the related literature several studies addressed the topic of the improvement of efficiency in intermodal logistic systems but they are mainly focused on the configuration of the different components of the systems [27]. As stated in [35], ICT is not just an enabler, but it is fundamental to the future of customs administrations [41]. Moreover, it is important to underline that some actions have been started for introducing technological tools in the customs procedure, such as the CARGO project and the Italian AIDA initiative [1]. The objectives of these projects consist in integrating the customs agency in the logistic chain to overcome the fragmentation of the current processes. Such actions aim to define a procedural, logistics, organizational and technological model which can be implemented to re-launch the national port system. Therefore, the results are focused on local improvements that do not eliminate the human support and the paper based procedures.

In recognition of the pivotal role that ICT plays in modern customs administration, the contribution of this paper consists in proposing an innovative ICT based solution that takes into account the high priority on the selection and implementation of appropriate and effective technological solutions for customs and security operations [35]. Nonetheless, the fundamental and distinctive assumption of this work is that the introduction of new technology without a paradigm change does not completely solve the system anomalies and bottlenecks of the current situation.

Indeed, the procedures related to customs activities have a strong impact on the overall logistic chain because they affect the performance of the whole systems in terms of efficiency and time-spending. Currently, ICT is a critical strategic measure for modern customs organizations to manage the complexities that are implicit in todays global trading environment [73]. Moreover, customs automation is one of the most powerful tools to increase customs efficiency [123].

Moreover, the costs associated with inefficient procedures and systems for the customs operations can be enormous: for instance, the expense of supplying the required customs documents or the surcharges arising from procedural delays when importing goods could total as much as 15% of the value of the goods [83], [84]. Hence, the proposed innovative ICT solution applied to an intermodal logistic system will produce benefits that may radically affect the performances of transport systems [123] from the regulatory point of view.

3.5.3.2 Description of the Case Study

This subsection describes the case study that is devoted to evaluate the proposed ICT solution in order to enhance the efficiency of the overall intermodal logistic system in relation to the customs operations. The case study considers the flow of trucks arriving from Turkey at the Port of Trieste (Italy) transporting hazelnuts and the related CC operations.

Currently, the traffic of ships arriving at the terminal is 14 ships/week and each ship contains about 240 trucks. The considered trucks transporting hazelnuts sacks are in average four or five for each ship. The total percentage of security check controls is about 4-5% considering the whole traffic that involves the terminal. Looking at the hazelnut traffic during a week, there is an average of 56-70 vehicles arriving at the Port of Trieste. Usually the percentage of the goods cleared in the port area depends on the market demand of the period, and the average values of this percentage of 20% of the goods cleared in the port area and 80% cleared outside the port are considered.

<u>**The Current Flow of Goods**</u>

The following phases describe the sequence of the operations in the current case, called case *as is* and explain the main details that characterize the flow of goods and information of the presented case study.

1. **Loading phase**. The hazelnuts sacks are ready to be loaded on trucks to be transported to Europe by ferry. There are not any means of traceability applied to the goods during the production and the loading phase.

2. **Shipping and data collection phase**. The trucks are loaded and the ship is coming to the Port of Trieste. The shipping agent, on behalf of the ship-owner, that is responsible for goods, collects and translates all the information to prepare the pre-arrival document and the "manifest" to authorize the arrival of the ship (so called MMA document). The freight forwarder inserts the information contained in the "manifest" document, such as the TARIC (Integrated Tariff of the European Communities) code, the weight of goods, etc. in the Customs Authority System. The Customs Authority System is centralized at European level and calculates the risk rate associated to the transported goods.

3. **Unloading phase**. The goods arrive at the Port of Trieste, the freight forwarder goes to the Customs Authority office in order to perform all the port unloading operations related to the foreseen documents. The freight forwarder presents a paper document to confirm that the goods are arrived at the Port of Trieste and obtains the MRN (Movement Reference Number) code.

4. **Security notification phase**. The Customs Authority Central System, called NCTS (New Computerized Transit System), decides by an elaboration of data about goods if the freight needs a security check control. The freight forwarder is informed of such a decision by verbal communication and there are two possibilities:

   (a) the freight has to be checked and the freight forwarder communicates to the truck driver the necessity to move the truck into a special area for the security check operations;

   (b) the freight is allowed to exit the port area without any security checks.

5. **Payment phase**. Before exiting the terminal area, the shipping tariffs have to be paid by the freight forwarder in order to perform the unloading operations. When the freight is authorized to leave the port area, it is stopped by an officer of the Port Authority in order to register the date and time of its passage. Moreover, the Port Authority checks whether the freight has been security checked or if it has the transport document to authorize its exit.

6. **Customs clearance phase**. The freight forwarder decides where the goods have to be cleared. The decisions can be of two types:
   (a) goods cleared in port area. The document to perform the customs clearing operations have to be prepared and the tariffs to be paid are calculated;
   (b) goods cleared outside the port area. The documents to authorize the transportation of the goods, that are not yet cleared, have to be prepared. There are two types of transportation documents: the T1 transportation document or the Carnet TIR document. The document prepared for this business case is the Carnet TIR.

   In the two cases, the CC procedures deal with the payments of the Value Added Tax (VAT) and the customs duties by the freight forwarder to the Customs Authority.

7. **Delivery phase**. The goods, not already cleared, arrive to the warehouse area and, when it exits the warehouse, it is ready to be delivered to the consignee.

Main Anomalies and Bottlenecks

By analyzing the current situation described in Section 3.5.3.2, it is possible to point out the following critical issues that affect the efficiency of the considered intermodal logistic system:

- the **lack of synchronization** between the physical and information flow, e.g., the documents such as the "manifest" are sent by plane to the Port of Trieste;
- the **redundancy** in the information exchanges;
- the **increase of unnecessary works** for the shipping agent and the freight forwarder.

Going deeply in the details, there are many activities still manually done, such as the operations to obtain the MRN code and the data collection. In this context the main existing problems are related to the following points:

- the errors in the registered data can be very serious and in the worst case can stop definitively the flow of goods;
- the current means of communications are not suitable, i.e., some data are reported by voice communication by the freight forwarder operator;

- the paper based documents are all the documents concerning the payments of the Customs duties and the fulfillment of the clearing and transport authorization procedures are paper based;
- communication of the fulfillment of the operations are not present, i.e., the payment of the shipping duties are performed also after the exit of the terminal area and there is not a notification in relation to the payments.

3.5.3.3 The Proposed Solution

This subsection describes the proposed ICT based solution to solve the main drawbacks of the phases described in Section 3.5.3.2. The new automated solution is called case *to be*.

The proposed ICT based solution aims to eliminate the current critical issues and the lack of synchronization by electronically associating the information and data about goods with the freight itself. This ICT application addresses the topic concerning the automation of the CC procedures and of the payment of shipping and customs duties. The proposed solution speeds up payments and authorization procedures, such as CC and security control checks. Moreover, it limits delays and errors thanks to the provision of electronic information, updated in real-time on the goods status. Finally, the ICT application progresses the port operations: the arriving at the port, the exiting the terminal area, the exiting the port, the entering and the exiting the warehouse area.

In particular, the utilization of Radio Frequency IDentification (RFID) based technology foresees important changes in the processes of the flow of goods and in the workflow organization. Indeed, RFID tags introduce a univocal code of identification that allows avoiding duplication of data traveling with goods. From the ICT infrastructure point of view, the freight communicates with the ICT system through smart devices, such as gates, located along the wharf, at the exiting point of the terminal area, at the exiting point of the port area and at the entrance of the warehouse. In these points the freight is able to communicate with the ICT infrastructure, updates in real-time its status, in terms of presence, identity and data of the goods. Moreover, the freight can detect its context, i.e., the involved actors, goods position and status.

In the following, the sequence of the operations under the proposed ICT solution is described. To this aim the phases listed in Section 3.5.3.2 are revisited in the following new steps.

1. **Loading phase**. The hazelnuts sacks are ready to be loaded on trucks to be transported to Europe by ferry. The goods loaded on a truck are identified as single freight with an identifier based on the RFID technology in order to trace them throughout the whole flow.

2. **Shipping and data collection phase**. The Turkish shipper, once the trucks are loaded and the ship is coming to the Port of Trieste, links the tags to the data about goods and uploads the data about goods that are related to the Customs clearing procedures. The data are registered in the so called pre-arrival and MMA document. Such documents are automatically communicated to the Customs Authority System that sends back to the freight forwarder the risk rate associated to the freight.

3. **Unloading phase**. The goods arrive at the Port of Trieste and update their status about date, place and time arrival. The freight exchanges information with the Customs Authority. It notifies its arrival and receives back the MRN code and the necessity of security check controls.

4. **Automated security notification phase**. The freight automatically recognizes if it is authorized to exit the port area or if it has to be checked. In the second case, the necessity to stop is communicated to the freight by a traffic light that is positioned at the terminal exit.

5. **Automated payment phase**. The freight arrives to the Port of Trieste and communicates with the bank in order to fulfill the payment of the shipping duties.

6. **Automated customs clearance phase**. The freight forwarder decides when goods have to be cleared and the status of the freight is uploaded on the basis of this decision. There are two possibilities:

   (a) goods cleared in port area. While the goods are exiting the terminal area, it updates its status and recognizes that it has to fulfill customs clearance procedures. The customs duties (e.g., the VAT) are automatically calculated by the ICT infrastructure on the basis of the information communicated by the freight itself. Once all the customs clearance procedures are performed, the status of the freight is updated thanks to a direct communication with the Customs Authority system;

   (b) goods cleared outside the port area. To exit the port area, authorization documents are needed in relation to the MRN code.

The Carnet TIR document and its number are automatically registered. Then the goods are transported to the warehouse where the hazelnuts are stored. In such a case, CC operations are automatically performed in the warehouse area.

7. **Delivery phase**. Finally, the goods exit the warehouse to be delivered to the consignee.

3.5.3.4 The UML Model

In this subsection the model of the considered case study is described including the system physical structure and the activities of the involved actors. In particular, the system is modeled as a Discrete Event System [21]. Referring to the metamodel described in Section 3.4, the main subsystems that compose the logistic network are identified and, in particular, this case study addresses the structural subsystem related to the LOCA UML package, Figure 3.16.

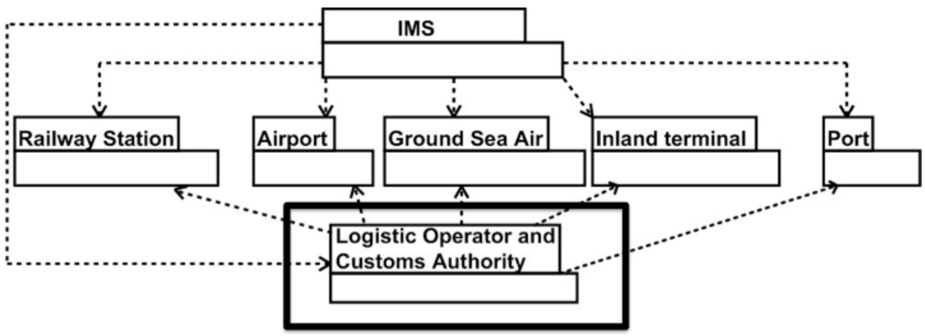

Figure 3.16: The package diagram of the Intermodal Logistic Network

In order to achieve an overall improvement of the logistic system, it is necessary to focus not only on the configuration of the different structural components but also on the management and administrative operations. For this reason, the focus of this case study is on a specific part of the logistic network, analyzing how the utilization of ICT tools impacts on the overall logistic performances. Looking at the effect of ICT on customs administration and security operations, the study particularly addresses the dynamic part related to the information exchanges related to the resources present in the port and involving, in particular, the authorities. Therefore, the focus of this analysis is not on the static component of the system, but above all on the dynamic description of the different operations. Indeed, the considered package has several dependencies with other packages, because of its crucial role.

The Operation Description by the Activity Diagrams

In order to describe the management processes relative to the flow of goods and of information, the UML activity diagrams are utilized. Figure 3.17 shows the activity diagram of the current flow of good for the considered case study.

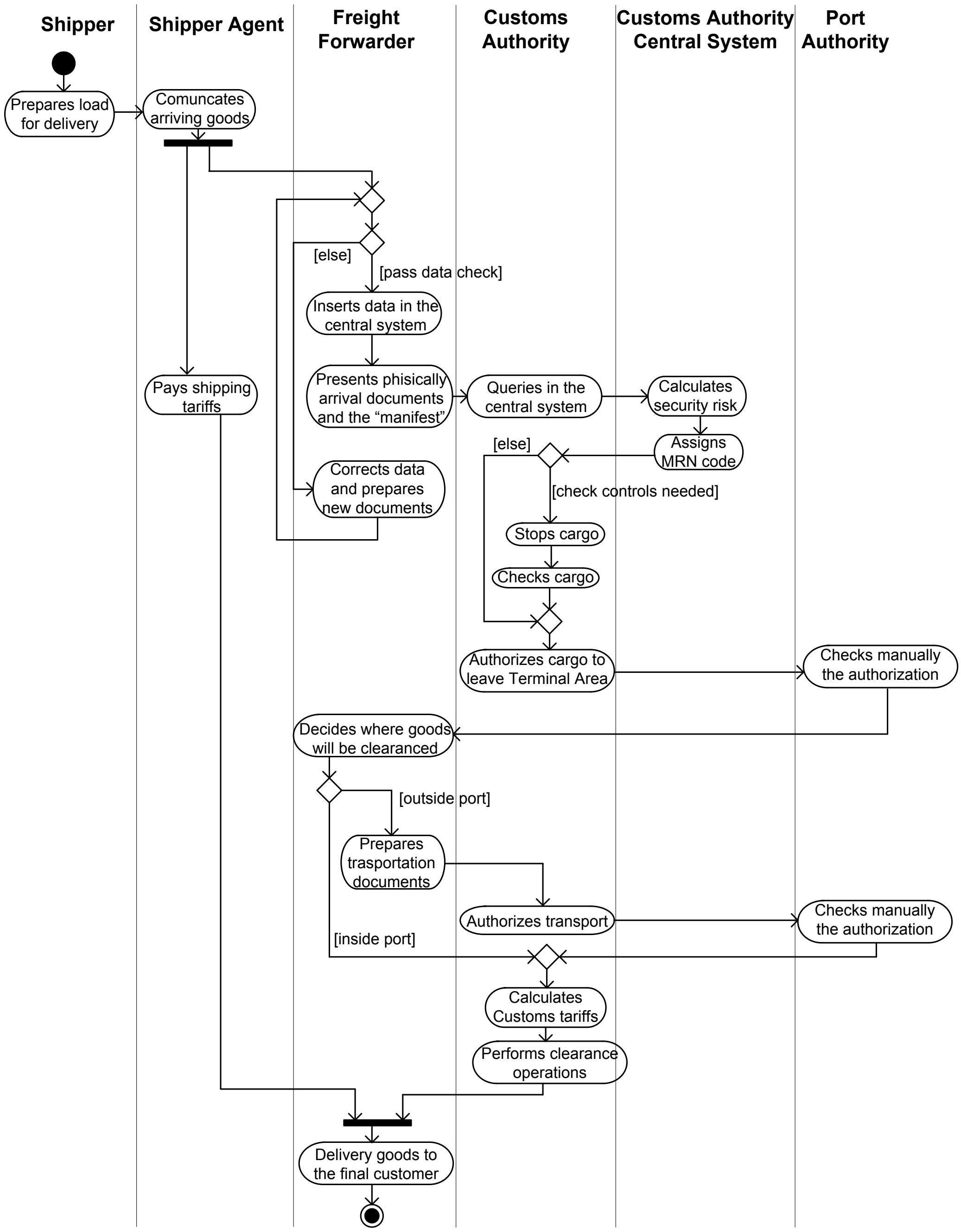

Figure 3.17: The current flow of goods and the CC operations

The sequence of the different phases of the case to be is formally described by the UML activity diagram depicted in Figure 3.18.

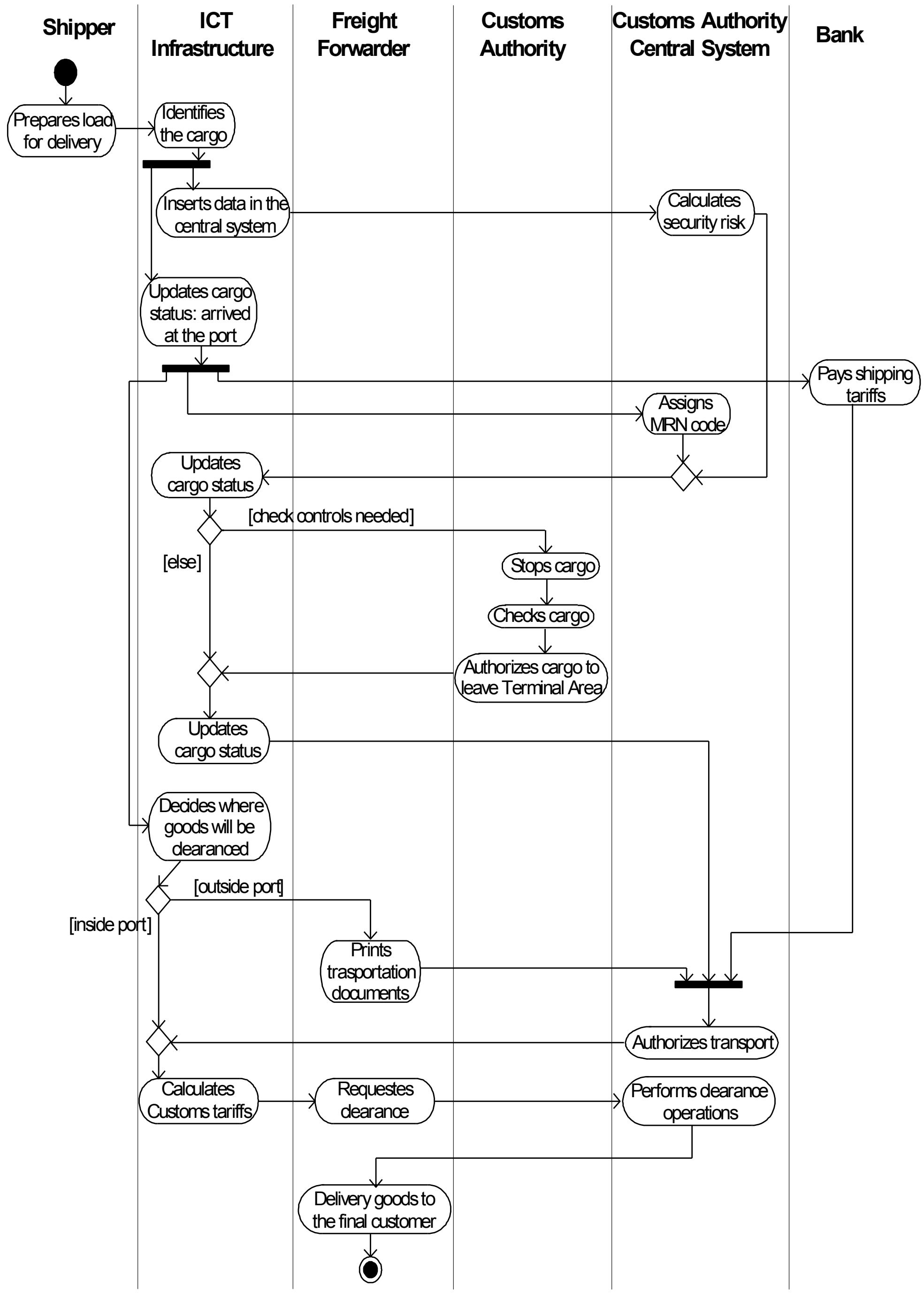

Figure 3.18: The flow of goods and the CC operations under the proposed ICT solution

3.5.3.5 The Simulation Specification and Results

This subsection describes the simulation of the considered intermodal logistic system under the two presented management processes, in order to study and compare the flow of goods and information during the relevant phases of the procedures.

Definition of the Performance Measures

In order to compare the two CC procedures, some performance indicators are defined that are employed to evaluate the current system and to tune the proposed ICT solutions. The task is enhancing the efficiency of the overall logistic system in relation to the security and customs clearance operations. To this aim the basic indicator is considered as the time spent to perform some crucial phases of the customs clearance. More precisely, referring to the list of general performance measures, 3.5.1, this case study takes into account the following:

- **LT1**: it is the average time necessary to unloading goods and to register the arrival of the goods in the Port of Trieste. Such a delay is the time (some hours) requested for the docking and unloading operations of the trucks and for the customs office procedures. It is important to measure this time because in the current scenario it causes a delay in recording the needed data about the goods;
- **LT2**: it is defined as the average time spent for the notification of the security check request. More precisely, it is the time necessary to communicate the security procedures coming from the Central Customs European System;
- **LT**: it is the total time spent during all the phases;
- **LB1**: it is the average time spent by an employee (man-hour) to fulfill the security operations;
- **LB2**: it is the average time spent by an employee (man-hour) to fulfill the CC operations;
- **LB**: it is the total average time spent to fulfill all the phases.

Simulation specification

The simulations start from the unloading of trucks in the terminal area of the port of Trieste and end when goods finish their clearance activity before leaving the port. The discrete event model of the intermodal system is implemented in the Arena environment [67], [102], as in the previous case study.

The simulations compare three different scenarios. The first scenario represents the current system behavior (case *as is*) that is described in Section 3.5.2. Moreover, the second scenario (case *to be1*) simulates the system behavior after the introduction of the ICT infrastructure previously proposed. Finally, the last scenario is the case *to be2* that reproduces the *to be1* scenario with a doubled flow of trucks.

Similarly to the previous case study, Table 3.9 reports the processing times of the phases described for the three scenarios that have triangular distributions: the second column depicts the modal values δ of the processing time distributions of the case *as is*, the third and forth columns show respectively the minimum (dδ) and the maximum (Dδ) values of the range in which the firing delay varies. All times are expressed in minutes.

Moreover, in the cases *as is* and *to be1* the trucks enter the system with an exponentially distributed rate of 10 trucks/day.

All the indices are evaluated by a long simulation run of 12 months with a transient period of 15 days. In particular, since the total average lead time is the most meaningful index of the simulation, the estimates of LT are deduced by 50 independent replications with a 95% confidence interval. Besides, the percentage value of the confidence interval width is evaluated to assess the accuracy of the LT estimation.

<u>Simulation Results</u>

The results of the simulation experiments are summarized in Figures 3.19, 3.20, 3.21 that report the values of the average lead times, the average labor times and the throughputs, respectively. The width of the confidence interval, being less than 0.98% in any simulation, confirms the sufficient accuracy of the total average lead time estimation. In particular, the results show that the management change from the case as is to the case to be1 leads to a noteworthy decrease (about -97%) of LT1 and (about -73%) of LT2. Analogously, the results in Figure 3.20 point out the huge decrease of the labor costs, since LB1 = 0 for the case *to be1*.

Nevertheless, it is interesting to note that the average system throughput for the first two scenarios is almost unchanged: it is about 304 trucks per month in the two cases, see Figure 3.21.

In order to verify the potentialities of the new ICT solution, the case *to be1* is modified in the scenario *to be2* that is characterized by an input rate exponentially distributed with an average of 20 trucks/day. Figure 3.19 shows that the scenario *to be2* exhibits an increment of LT2: it is obvious because the input flow of trucks is greater than in the case *to be1*. On the

Activity	d_δ	δ	D_δ
Communicate	4	5	6
Pay Tariffs	24	30	36
Present manifest	24	30	36
Correct Data	60	720	1080
Insert Data	24	30	36
Calculate Risk	4	5	6
Assign MRN	4	5	6
Check Good	30	60	360
Prepare Transportation Documents	48	60	72
Calculate Customs Duties	4	5	6
Clearance	48	60	72
Terminal Check	4	5	6
Port Check	4	5	6

Table 3.9: Triangular Distribution Specification of Processing Times (minutes)

contrary, the throughput in case *to be2* is much higher than in case *to be1*: this means that the system managed by the ICT solution is able to tolerate a higher workflow by exploiting the same resources.

Indeed, considering the average labor costs shown in Figure 3.20, it is apparent that the amount of hours spent for the customs activities decreases in case *to be1* with respect to the case as is. However, with a rational reorganization of the workflow, in case *to be2* it is possible to increase the service rate of the system. Indeed, it is possible to move the underutilized resources to fulfill the security operations to satisfy the customs clearance operations.

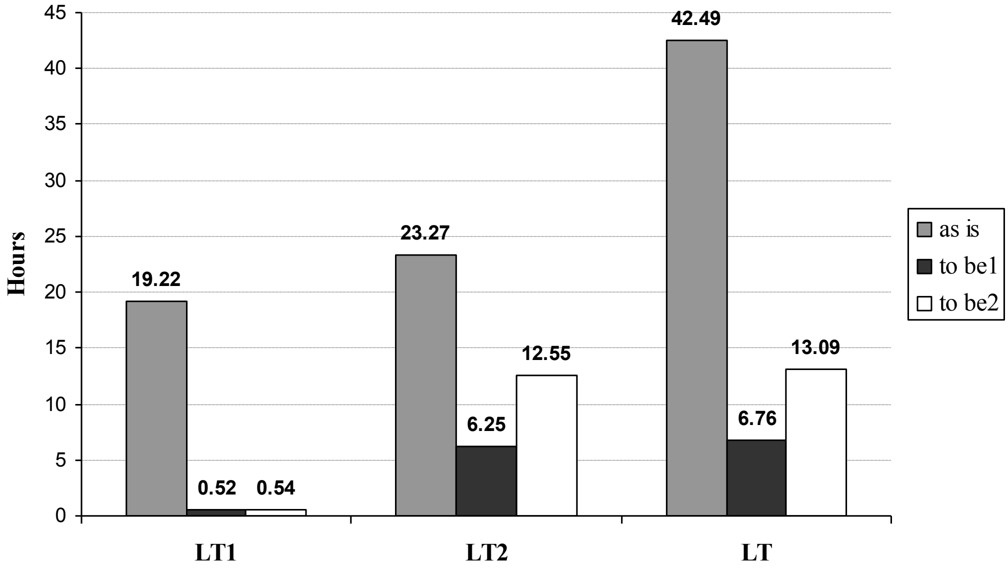

Figure 3.19: The average lead times

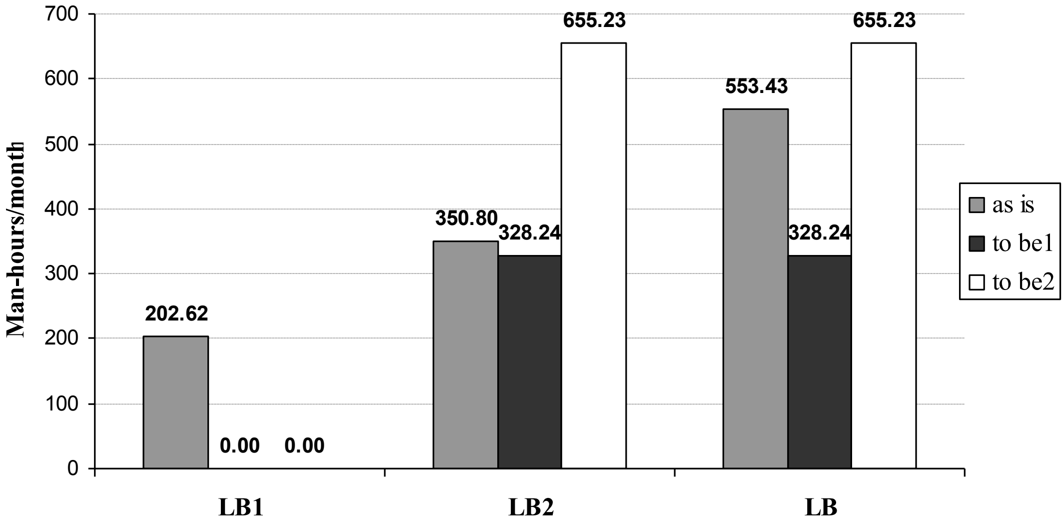

Figure 3.20: The average labour costs

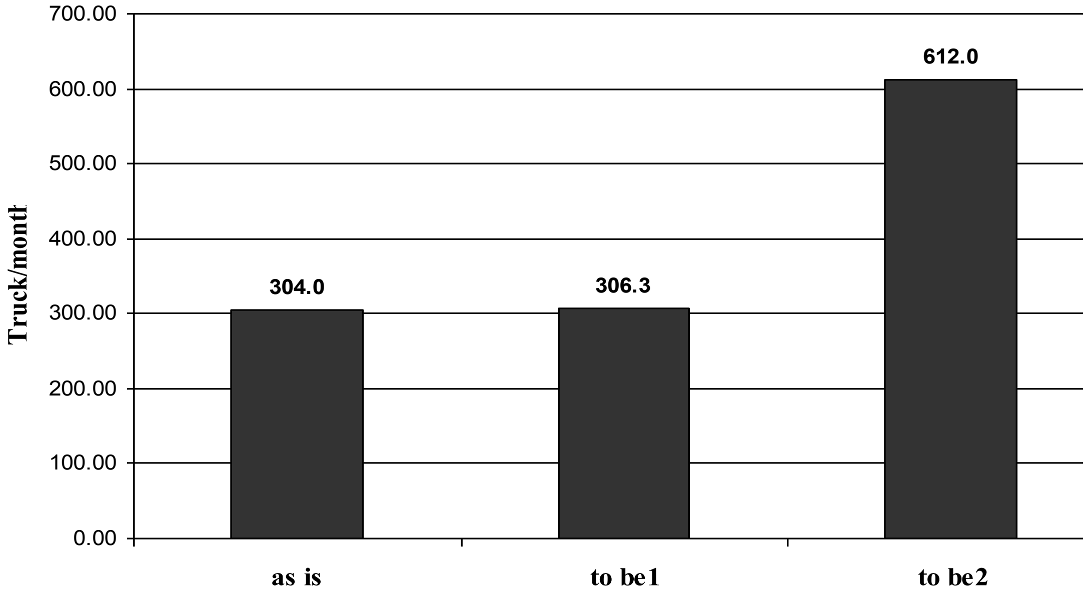

Figure 3.21: The average throughput

Chapter 4

MAS protocols for Distributed Networks of Agents

4.1 Introduction

This chapter is focused on a topic that is widely discussed in the scientific literature related to the study of the **multi-agent collective behaviors in a distributed network**. The interaction protocols that allow the agents to reach the convergence to a common value is called ***consensus* or agreement problem**.

This research problem is particularly studied in the context of cooperative control of MASs because the agents are autonomous, independent and have to interact in a distributed network. From this perspective, a *consensus* algorithm is the interaction rule that specifies the information exchange between an agent and all of its neighbors on the network [86].

Initially the chapter gives an overview of the *consensus* problem taken from the related literature and the description and the formalization of the problem.

Then, the chapter presents some research results concerning the **investigation of new and fast alignment protocol**s that can be applied to the discrete time model of *consensus* multi-agent networks. To this aim, starting from the considerations that the standard iteration protocols exhibit low speed of reaching a consensus for particular topologies of the digraph, an approach, based on the **triangular splitting of the standard iteration matrix**, is presented and discussed.

The results explained in this chapter are based on the following author's publications: [16] and [17].

4.2 A review of the scientific literature on the *consensus* problem

The research related to the topic of networked systems has widely increased during the last years attracting the attention of researchers from different fields such as mathematicians, computer scientists and engineers, [50], [51], [82], [87], [93]. This is due to the recent technological advances in communication and computation following the miniaturization of electronic components which have allowed the realization of large groups of embedded systems, such as sensors and robotic networks.

In fact, many different problems that involve interconnection of dynamic systems in various areas of science and engineering are closely related to the so called consensus problems for multi-agent systems [82], [85], [93]. As a consequence of this growing interest, the applications of the consensus protocols increased in the last few years and involved fields such as the problem of synchronization of coupled oscillators, flocking theory, networked control systems, deployment and task allocation, rendezvous, vehicle routing [82], [85], [78].

More in detail, the cooperative control for multi-agent systems can be categorized as either formation control problems with applications to mobile robots, unmanned air vehicles, autonomous underwater vehicles, satellites, aircraft, spacecraft, and automated highway systems, or non formation cooperative control problems such as task assignment, payload transport, role assignment, air traffic control, timing, and search [93].

In networks of agents, *consensus* means to reach an agreement regarding a certain quantity of interest that depends on the state of all the agents. A *consensus* algorithm (or protocol) is an interaction rule that specifies the information exchange between an agent and all of its neighbors on the network [64].

From this definition, cooperation can be informally interpreted as "giving consent to provide one's state and following a common protocol that serves the group objective" [85].

Moreover, such networks are intended to be large-scale, i.e., the number of connected devices can be large to be able to cover large surface areas. Hence, such networks need scalable algorithms, i.e., algorithms whose computational complexity grows moderately with respect to the number of network nodes, and decentralized algorithms able to solve problems addressing the topological communication network constraints. Some examples of the consensus algorithms are shown and discussed in [85]. The theoretical framework for posing and solving consensus problems for networked dynamic systems are introduced by Olfati-Saber and Murray [86] and Fax and Murray [43]. Moreover, Jadbabaie et al. in [64] study the alignment problem involving reaching an agreement and provide convergence results. Recently, the problem of achieving faster consensus algorithms has attracted considerable attention from many researchers [85]. In [118] the choice of the weights of a network is considered and solved using semi-definite convex programming. This leads to a slight increase in the so called algebraic connectivity of a network that represents the measure of the speed of convergence of the consensus algorithm. Many research works address the study of the consensus protocols with fixed and switching topologies by using concepts and tools taken from algebraic graph theory. In particular, the network of agents is described by a directed or undirected graph and the associated graph Laplacian matrix L plays an important role in the convergence and alignment analysis [46], [80].

In particular, the discrete time model of the consensus network is described by a directed or undirected graph and the associated graph Laplacian matrix L plays an important role in the convergence and alignment analysis [43], [61]. Indeed, the nominal state evolution of the agents is governed by a discrete time consensus equation defined by $x(k+1) = (I - \varepsilon L)x(k)$, where I is the identity matrix and $\varepsilon > 0$ is step-size parameter. However, such standard protocols exhibit low speed of reaching a consensus for particular topologies of the digraph.

4.3 Definition and Notation of the *consensus* problem

The following consideration are taken from the scientific literature to describe the formalization of the *consensus* problem, [86], [85]. Consider a network of n autonomous agents labeled by an index $i \in V$ with $V = 1, 2, .., n$. Let $x_i \in \Re$ denote the value of the agent i that can represent a physical quantity, such as, for instance, altitude, position, temperature, voltage, and so on. The interaction topology of a network of agents is represented using a directed graph $G = (V, E)$ where $V = 1, 2, .., n$ is the set of nodes and $E \subseteq V \times V$ is the set of edges. Moreover, matrix $A = [a_{ij}]$ denotes the adjacency matrix and $N_i = \{j \in V : a_{ij} \neq 0\}$ the set of neighbors of agent i.

More precisely, agent i communicates with agent j if j is a neighbor of i (hence $a_{ij} \neq 0$). The nodes of a network have reached a *consensus* if and only if (iff) $x_i = x_j$ for all $i, j \in V$. Whenever the agents of a network are all in agreement, the common value of all nodes is called the agreement state and can be expressed as $x^* = \alpha\mathbf{1}$, where $\mathbf{1} = [1, 1, ..., 1]^T$ and α is a collective decision of the group of the agents.

A well-known consensus algorithm that solves the agreement problem in a network of agents with discrete time model is the following [85]:

$$x_i(k+1) = x_i(k) + u_i(k) \tag{4.1}$$

$$u_i(k) = \varepsilon \sum_{j \in N_i} a_{ij}(x_j(k) - x_i(k)) \tag{4.2}$$

$$x_i(k+1) = x_i(k) + \varepsilon \sum_{j \in N_i} a_{ij}(x_j(k) - x_i(k)) \tag{4.3}$$

and the algorithm can be written as:

$$x(k+1) = P_\varepsilon x(k) \tag{4.4}$$

where matrix $P_\varepsilon = (I - \varepsilon L) = [p_{\varepsilon ij}]$ is the iteration matrix, ε is the step-size parameter, I is the identity matrix and $L = [l_{ij}]$ is the graph Laplacian induced by the graph G, and defined as:

$$l_{ij} = \begin{cases} \sum_{k=1, k \neq j} a_{ij} & \text{if } j = i \\ -a_{ij} & \text{if } j \neq i. \end{cases} \tag{4.5}$$

Denoting by $\Delta = max_i l_{ii}$ the maximum node out-degree of graph G, P_ε is a nonnegative and stochastic matrix for all $\varepsilon \in (0, \frac{1}{\Delta})$. According to the definition of graph Laplacian in 4.5, all row-sums of L are zero because $\sum_{j=1}^{n} l_{ij} = 0$ for $i = 1, ..., n$.

Now, in order to study the convergence of algorithm 4.4, the following properties about non-negative matrices are recalled.

Definition 4.1 *, [99]*

An $n \times n$ non-negative matrix $B = [b_{ij}]$ is irreducible if for every pair i, j of its index set, there exists a positive integer m such that $b_{ij}^m > 0$. An irreducible matrix is said to be cyclic (or periodic) with period d, if the period of any one of its indices satisfies $d > 1$, and is said to be acyclic (or aperiodic) if $d = 1$.

Note that the graph associated with an irreducible non negative matrix B is a strongly connected graph. Moreover, the graph associated with a cyclic matrix with period d is said d-periodic [18] and has the property that the set of all cycle lengths has a common divisor $d > 1$.

The following Theorem 4.3.1 gives a necessary and sufficient condition to have a non negative inverse of a matrix $A \in \Re^{n \times n}$.

Theorem 4.3.1 *, [61]*

Let $A \in \Re^{n \times n}$, the following conditions are equivalent:

1. *A^{-1} exists and $A^{-1} \geq 0$,*
2. *$\forall b \geqslant 0 \; \exists \; x \geqslant 0$ such that $Ax = b$.*

The convergence analysis of the discrete-time consensus algorithm relies on the following well-known Lemma in matrix theory (Perron-Frobenius [99]):

Lemma 1 *Let B be a primitive (an irreducible stochastic acyclic matrix with only one eingenvalue $\lambda = 1$) with left and right eigenvectors w and v, respectively, satisfying $Bv = v$, $w^T B = w^T$, and $v^T w = 1$.*

Then $lim_{k \to \infty} B^k = vw^T$.

The convergence and group decision properties of iterative consensus algorithms with row stochastic matrices is stated in the following result proved in [85].

Theorem 4.3.2 *Consider a network of agents $x_i(k+1) = x_i(k) + u_i(k)$ with topology G applying the distributed consensus algorithm 4.4 with $0 < \varepsilon < \frac{1}{\Delta}$. Let G be a strongly connected graph. Then:*

1. *a consensus is asymptotically reached for all the initial states;*

2. *the group decision value is $x^* = \sum_i w_i x_i(0)$ with $\sum_i w_i = 0$;*

3. *if the graph is balanced (undirected), an average-consensus is asymptotically reached and $x^* = \sum_i \frac{x_i(0)}{n}$.*

Moreover, in [82] it is shown that the decision value is

$$lim_{k \to \infty} x(k) = v(w^T x(0))$$

where $v = \mathbf{1}$ is the right eigenvector of P_ε and w is the left eigenvector of P_ε associated with the eigenvalue $\lambda = 1$.

4.3.1 Some comments on the convergence of the *consensus* problem

Following the considerations made in Section 4.3 and before addressing the specific *consensus* problems addressed in this dissertation, the author analyzes the convergence properties of the standard convergence algorithm 4.5 in relation with the choice of coefficient ε and the network topology.

Proposition 4.3.3 *Let G be a strongly connected graph. Setting $\varepsilon = \frac{1}{\Delta}$, matrix $P_\varepsilon = (I - \varepsilon L)$ is cyclic iff G is a periodic graph and each node of G has the same out-degree.*

Proof. (**if part**): Let assume that G is a d-periodic graph and each node of G has the same out-degree. Hence, the adjacency matrix A is cyclic and matrix L has equal diagonal entries l_{ij}. If the following is chosen $\varepsilon = \frac{1}{\Delta} = \frac{1}{l_{ij}}$ then it is obtained that $p_{\varepsilon ij} = 0$ for $i = 1, ..., n$ and $P_\varepsilon = \varepsilon A$. Since A is cyclic, then P_ε is cyclic too.

(**Only if part**): Let assume that matrix P_ε is cyclic. Consequently, it holds $p_{\varepsilon ij} = 0$ for $i = 1, ..., n$ and the diagonal entries of matrix L are

$l_{ii} = \frac{1}{\varepsilon} = \Delta$ for $i = 1, ..., n$. Since $l_{ii} = \sum_{k=1,k\neq j}^{n} a_{ij}$, each node of G has the same outdegree. Moreover, by 4.5 it holds $P_\varepsilon = \varepsilon A$. Hence, if P_ε is cyclic, then the adjacency matrix A is cyclic too and G is a periodic graph. ■

By Lemma 1, if matrix P_ε is cyclic, then the convergence of the iterative scheme 4.4 is not guaranteed. Hence, Proposition 4.3.3 justifies the well-known choice of $\varepsilon \in (0, \frac{1}{\Delta})$: the convergence of 4.4 is assured using $\varepsilon = \frac{1}{\Delta}$ provided that the graph G is not periodic and each node of G has the same outdegree. Moreover, it is shown that in the cases in which the convergence is guaranteed, the maximum value $\varepsilon = \frac{1}{\Delta}$ provides the maximum convergence speed of the iteration scheme 4.4, [118].

4.4 New *consensus* protocols for networks with discrete time dynamics

This section introduces a new class of consensus protocols to reach the agreement in networks of agents with a discrete time dynamics in the framework of the non-negative matrix theory. On the basis of the considerations made in Section 4.3, a methodology that based on the triangular splitting of the standard iteration matrix is proposed. This approach is faster than the standard consensus protocols, guarantees good performances in reaching the right group consensus decision and the independence of the iterative matrix from the step-size parameter.

Starting from the consensus algorithm 4.4 and the following splitting of matrix P_ε is defined.

Definition 4.2 *Triangular splitting of matrix P_ε is denoted by the couple of matrices belonging to the following set:*

$Q(\varepsilon) = \{R \in \Re^{n\times n}, S \in \Re^{n\times n} | R \neq 0$ with $r_{ii} \neq 1$ and $r_{ii} \neq 0$ for $i = 1, ..., n$ is a lower triangular matrix, $S \neq 0$ is an upper non negative triangular matrix and $R + S = P_\varepsilon\}$.

Each splitting $R, S \in Q(\varepsilon)$ induces the following iterative scheme [104]:

$$x(k+1) = Rx(k+1) + Sx(k), \qquad k \geq 0 \tag{4.6}$$

It is important to remark that R is a triangular matrix and by the assumption $r_{ii} \neq 1$ for $i = 1, ..., n$, the matrix $(I - R)$ is non singular and the iterative scheme 4.6 can be written as follows:

$$x(k+1) = (I-R)^{-1}Sx(k), \qquad k \geq 0 \tag{4.7}$$

Matrix $\Gamma = (I - R)^{-1}S$ denotes the iteration matrix associated with the triangular splitting $R, S \in Q(\varepsilon)$.

4.4.1 Convergence properties of the iterative schemes

The following results characterize the convergence properties of the obtained iteration schemes. In particular, under some conditions on the triangular splitting, the presented results show that the iterative algorithm 4.8 converges to the same group decision value $x^* = \sum_i w_i x_i(0)$ of Theorem 4.3.1.

To this aim, the conditions to obtain a primitive iterative matrix Γ are proved, so that the convergence of the consensus algorithm is assured.

The proofs show the following properties of matrix Γ:

1. Γ is a stochastic matrix;
2. $\lambda = 1$ is a simple eigenvalue of Γ;
3. there exists a triangular splitting $R, S \in Q(\varepsilon)$, such that Γ is irreducible and acyclic.

The following two Lemmas 4.4.1 and 4.4.2 prove property 1).

Lemma 4.4.1 *Let consider $R, S \in Q(\varepsilon)$, then matrix $(I - R)^{-1}$ exists and is non-negative.*

Proof. By definition it holds $r_{ii} \neq 1$ and $r_{ii} \neq 0$ for $i = 1, ..., n$. Moreover, since $0 \leq s_{ii} + r_{ii} \leq 1$ and $s_{ii} > 0$, then $r_{ii} \leq 1$ and $(I - R)$ is non singular.

Now, by Theorem 4.3.1 if $\forall b \geq 0 \; \exists \; x \geq 0$ such that $(I - R)x = b$ then $(I - R)^{-1}$ is non-negative.

Let consider a vector $b \geq 0$ and write $b = \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix} = b_1 e_1 + ... + b_n e_n$, where e_i for $i = 1, ..., n$ are the canonical basis of R^n.

Hence the equation $(I - R)x = b$ can be written as:

$$(1 - r_{ii})x_i = b_i \qquad \text{for i=1,...,n} \tag{4.8}$$

Since by Definition 4.2 $r_{ii} < 1$ for $i = 1, ..., n$, the solution of 4.8 is:

$$x_i = (1 - r_{ii})^{-1} b_i \geq 0 \qquad \text{for i=1,...,n} \tag{4.9}$$

Hence $x = x_1 e_1 + ... + x_n e_n \geq 0$.

By Theorem 4.3.1 the Lemma 4.4.1 is proved. ■

Lemma 4.4.2 *Let consider $R, S \in Q(\varepsilon)$, if P_ε is stochastic, then matrix $\Gamma = (I - R)^{-1} S$ is stochastic too.*

Proof. By Lemma 4.4.1 it holds $(I - R)^{-1} \geq 0$. Observing that S is a non-negative matrix, it immediately follows that Γ is non-negative too.

Since $P_\varepsilon \mathbf{1} = (R+S)\mathbf{1} = \mathbf{1}$, it holds $(I-R)\mathbf{1} = S\mathbf{1}$ and $(I-R)^{-1}S\mathbf{1} = \mathbf{1}$. Then $\nu = \mathbf{1}$ is the right eigenvector associated with the eigenvalue $\lambda = 1$ and Γ is a stochastic matrix. ■

Now the following Theorem 4.4.3 proves 2).

Theorem 4.4.3 *Let P_ε be a stochastic irreducible matrix and w be the left eigenvector of P_ε associated with the eigenvalue $\lambda = 1$. Let consider $R, S \in Q(\varepsilon)$, then for matrix $\Gamma = (I - R)^{-1}S$ the following statements hold true:*

i $\rho(\Gamma) = 1$*;*

ii $\lambda = 1$ *is a simple eigenvalue of* Γ*;*

iii *the left eigenvector of matrix $\Gamma = (I - R)^{-1}S$ associated with the eigenvalue $\lambda = 1$ is $w'^T = w^T S$*

Proof.
Statement i) is a direct consequence of Lemma 4.4.1.

Statement ii) follows from the fact that there is a unique right eigenvector $\nu = \mathbf{1}$ corresponding to the dominant eigenvalue $\lambda = 1$ of the irreducible matrix P_ε. On the other hand, $P_\varepsilon \nu = \nu$ implies and is implied by $(I - R)^{-1}S\nu = \nu$. Hence matrices P_ε and $(I - R)^{-1}S$ have the same number of independent right eigenvectors associated with the eigenvalue $\lambda = 1$. Therefore the geometric multiplicity of $\lambda = 1$ is the same for both matrices and it equals one. Now, by Lemma 1 the algebraic multiplicity of $\lambda = 1$, as eigenvalue of Γ, equals its geometric multiplicity. Therefore, statement ii) is proved.

To prove iii) vector w is assumed to be the left eigenvector of P_ε associated with the eigenvalue $\lambda = 1$, i.e.: $w^T(R + S) = w^T$. Then:

$$w^T S = w^T (I - R) \tag{4.10}$$

and

$$w^T (I - R)(I - R)^{-1} S = w^T (I - R) \tag{4.11}$$

and by substituting 4.10 in 4.11 it is possible to infer

$$w^T S(I - R)^{-1} S = w^T S \tag{4.12}$$

Hence $w^T S$ is the left eigenvector of $(I - R)^{-1}S$ associated with the eigenvalue $\lambda = 1$. ■

As it is shown in [63], given a state set and a stochastic matrix there exists a Markov Chain associated with them. Hence, let MC be the Markov Chain associated with the stochastic matrix $(I - R)^{-1}S$. By Theorem 4.3.2, Γ has only one eigenvalue equal to 1, consequently MC has only one recurrent class. The following proposition 4.4.4 proves a sufficient condition assuring Γ irreducible with $|\lambda| < 1$ for each eigenvalue $|\lambda| \neq 1$ of Γ, i.e., Γ is primitive.

Proposition 4.4.4 *Let P_ε be a stochastic irreducible matrix and $R, S \in Q(\varepsilon)$. If S has no zero columns, then $\Gamma = (I - R)^{-1}S$ is irreducible and acyclic.*

Proof. Let consider the vector $w'^T = w^T S$ and let MC be the Markov Chain associated with Γ. Since w'^T is the left eigenvector of matrix $\Gamma = (I - R)^{-1}S$ associated with the eigenvalue $\lambda = 1$, w' is proportional to the steady state vector of MC. Now let observe that $w > 0$ is the steady-state probability vector of the recurrent states of the Markov Chain associated with P_ε . Now let observe that the *i-th* entry of w' is zero iff the *i-th* column of S has all zero entries. Remarking that only states in recurrent classes can occur with positive steady state probability, since S has no zero columns, Γ is irreducible.

It is proved by contradiction that Γ is acyclic. Let suppose that matrix Γ is cyclic, and therefore it has all zero entries along the main diagonal. By Lemma 4.4.1, $\Gamma = (I - R)^{-1}S$ is a non negative upper triangular matrix, hence all the entries along the main diagonal of $(I - R)^{-1}$ are positive. Consequently, the first element of matrix Γ is zero iff the first column of S (that is upper triangular) is zero: this contradicts the assumption and the proposition is proved. ■

The following theorem guarantees the convergence of algorithm 4.8 that is induced by a triangular splitting.

Theorem 4.4.5 *Let P_ε be a stochastic irreducible matrix and w the left eigenvector of P_ε associated with the eigenvalue $\lambda = 1$. Let consider $R, S \in Q(\varepsilon)$ and S has no zero columns. If there exists $\mu > 0$ such that $w^T S = \mu w^T$,* *i.e.,* w^T *is the left eigenvector of S for an eigenvalue* $\mu > 0$*, then algorithm 4.8 converges for all the initial states and the group decision value is* $x^* = \nu w^T x(0)$*.*

Proof. If $R + S = P_\varepsilon$ is a triangular splitting of P_ε and S has no zero columns, then by Proposition 4.4.4, $\Gamma = (I - R)^{-1}S$ is primitive with right and left eigenvectors $\nu' = \mathbf{1}$ and $w'^T = w^T S$ respectively, associated with the eigenvalue $\lambda = 1$. Consequently, the iterative algorithm 4.8 converges and gives the decision value $lim_{k\to\infty} x(k) = \nu(w^T S x(0))$.

Moreover, if there exists $\mu > 0$ such that $w^T S = \mu w^T$, then it holds $lim_{k\to\infty} x(k) = \mu\nu w^T x(0)$ and by the normalizing condition it holds

$$lim_{k\to\infty} x(k) = \nu w^T x(0)$$

This proves the theorem. ■

4.4.2 The proposed consensus algorithms

This subsection considers the consensus algorithms based on the iterative schemes 4.8 that can be described by as follows:

$$(1 - r_{ii})x_i(k+1) = \sum_{j=1}^{i-1} p_{\varepsilon ij} x_j(k+1) + s_{ii} x_i(k) + \sum_{j=i+1}^{n} p_{\varepsilon ij} x_j(k) \qquad (4.13)$$

for $i = 1, ..., n$.

In other words, the iterative algorithm 4.13 establishes an order to update the values of each agent state. More precisely, to update the state at the time $k+1$, agent *i-th* uses the already determined values of the states $x_j(k+1)$ for $j = 1, ..., i-1$. Hence, the iterative scheme 4.13 leads to the set of triangular splitting of matrix P_ε, with $R, S \in Q(\varepsilon)$.

In order to obtain an upper triangular matrix S that satisfies the conditions of Theorem 4.4.5, the following problem is defined:

$$min \quad \mu$$

$$
\text{s.t. } \varphi(P_\varepsilon, w) = \begin{cases} \mu > 0 & \\ \sum_{j=1}^{i} w_j s_{ji} - w_i \mu = 0 & \text{for } i = 1, ..., n \\ s_{ii} \geq 0 & \text{for } i = 1, ..., n \\ \mathbf{1}^T S > 0 & \\ s_{ij} = 0 & \text{for } i > j, i, j = 1, ..., n \\ s_{ij} = p_{\varepsilon ij} & \text{for } i < j, i, j = 1, ..., n \end{cases} \tag{4.14}
$$

It is important to remark that 4.13 with any solution of 4.14 gives a consensus algorithm associated with graph G describing the interaction topology of a network of agents. Moreover, if G changes, then the consensus can be reached by updating in the iterative scheme 4.13 the values of s_{ii} and r_{ii} by solving 4.14. The following proposition proves that problem 4.14 admits a solution for each P_ε.

Proposition 4.4.6 *Let P_ε be a stochastic irreducible matrix and w the left eigenvector of P_ε associated with the eigenvalue $\lambda = 1$. Then there exists a triangular splitting $R, S \in Q(\varepsilon)$ such that S satisfies the constraints $\varphi(P_\varepsilon, w)$.*

Proof. Let consider the constraints

$$
\sum_{j=1}^{i} w_j s_{ji} - w_i \mu = 0 \tag{4.15}
$$

for $i = 1, ..., n$.

Assuming

$s_{ij} = 0$ for $i > j$, $s_{ij} = p_{\varepsilon ij}$ for $i < j$, with $i, j = 1, ..., n$

the following considerations are obtained:

$$
s_{11} = \mu
$$

and

$$
s_{ii} = \mu - \sum_{j=1}^{i-1} \frac{w_j}{w_i} s_{ji} \qquad \text{for } i = 2, ..., n. \tag{4.16}
$$

Since $s_{ii} \geq 0$, it follows:

$$min \quad \mu = max_i \quad \sum_{j=1}^{i-1} \frac{w_j}{w_i} s_{ji} = \sum_{j=1}^{i^*-1} \frac{w_j}{w_{i^*}} s_{ji^*} \tag{4.17}$$

where i^* denotes the i^*-*th* column corresponding to the maximum value of 4.17.

Hence, a solution of is the following matrix S^*:

$$s_{ij} = 0 \quad \text{for } i > j, s_{ij} = p_{\varepsilon ij} \quad \text{for } i < j, \text{ for } i, j = 1, ..., n \tag{4.18}$$

$$s_{11} = \mu = \sum_{j=1}^{i^*-1} \frac{w_j}{w_{i^*}} s_{ji^*} \tag{4.19}$$

$$s_{ii} = \sum_{j=1}^{i^*-1} \frac{w_j}{w_{i^*}} s_{ji^*} - \sum_{j=1}^{i-1} \frac{w_j}{w_i} s_{ji}, \qquad \text{for } i = 2, ..., n. \tag{4.20}$$

Since $s_{ii} > 0$ for $i = 1, ...n$ and $i \neq i^*$, the *i-th* columns with $i \neq i^*$ are no equal to zero.

Moreover, for $i = i^*$ it holds $s_{i^*i^*} = 0$. Assume by contradiction that the i^*-*th* column of S^* is equal to zero. This implies that $\sum_{j=1}^{i^*-1} \frac{w_j}{w_{i^*}} s_{ji^*} = 0$ and, by 4.17, $\sum_{j=1}^{i-1} \frac{w_j}{w_i} s_{ji} = 0$ for $i = 1, ..., n$. Now, since S is a lower triangular matrix with $s_{ij} = p_{\varepsilon ij}$ for $i < j$ with $i, j = 1, ..., n$, if $s_{ij} = 0$ for $i < j$ with $i, j = 1, ..., n$, then P_ε is upper triangular: this contradicts the assumption that P_ε is irreducible and the proposition is proved. ■

Now, $R^*, S^* \in Q(\varepsilon)$ are denotes as the matrices satisfying 4.14 and obtained by 4.18 - 4.20. The following result proves that the corresponding iteration matrix $\Gamma^* = (I - R^*)^{-1} S^*$ is independent from ε.

Proposition 4.4.7 *Let P_ε be a stochastic irreducible matrix and w the left eigenvector of P_ε associated with the eigenvalue $\lambda = 1$. Let $R^*, S^* \in Q(\varepsilon)$ be the matrices obtained by 4.18 - 4.20. The iteration matrix $\Gamma^* = (I - R^*)^{-1} S^*$ is independent from ε.*

Proof. Since $s_{ij} = p_{\varepsilon ij} = -\varepsilon l_{ij}$ for $i < j$ with $i, j = 1, ..., n$. Now let

$$\sum_{j=1}^{i-1} \frac{w_j}{w_i} l_{ji} = L_i, \qquad \text{for } i = 2, ..., n. \tag{4.21}$$

and

$$max_i \sum_{j=1}^{i-1} \frac{w_j}{w_i} s_{ji} = -\varepsilon \sum_{j=1}^{i^*-1} \frac{w_j}{w_{i^*}} I_{ji^*} = -\varepsilon L_{i^*} \tag{4.22}$$

The matrices S^* and $(I - R^*)$ can be written in the form:

$$S^* = \varepsilon \begin{bmatrix} -L_{i^*} & -l_{12} & \cdots & -l_{1n} \\ 0 & -(L_{i^*} - L_2) & \cdots & -l_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & \cdots & -(L_{i^*} - L_n) \end{bmatrix}$$

$$(I - R^*) = \varepsilon \begin{bmatrix} l_{11} - L_{i^*} & 0 & \cdots & 0 \\ l_{21} & l_{22} - (L_{i^*} - L_2) & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ l_{n1} & \cdots & \cdots & l_{nn} - (L_{i^*} - L_n) \end{bmatrix}$$

Thus, it is possible to deduce immediately that $\Gamma^* = (I - R^*)^{-1} S^*$ is independent from ε. ■

4.4.3 Algorithm convergence properties

In order to evaluate the convergence properties of the proposed algorithms, a network of 20 agents with different topologies is considered. More precisely, the adjacency matrices of the strongly connected aperiodic graphs describing the network topology are randomly generated and each associated consensus problem is solved by considering four different consensus algorithms. The average convergence properties and convergence times are evaluated on 1000 randomly generated adjacency matrices. For each system, the convergence time k^* is considered to be the number of broadcasts such that the following condition is satisfied:

$$k^* : \frac{||x(k^*) - \overline{x}^*||_2}{||x(0) - \overline{x}^*||_2} < 0.01 \tag{4.23}$$

The results of the convergence study are reported in Table 4.1 and 4.2 where the first column shows the iterative matrices of consensus algorithms that are applied to undirected and directed graphs, respectively. More precisely, the first and second iterative matrices are associated to the iterative algorithm 4.6 with $\varepsilon = \frac{0.8}{\Delta}$ and $\varepsilon = \frac{0.5}{\Delta}$, respectively. The iterative scheme $\Gamma_1 = (1-\varepsilon)I + \varepsilon D^{-1}A$ is proposed in [64], where A is the adjacency matrix of graph G and D is the diagonal matrix whose *i-th* diagonal element is the valence of vertex i within the graph.

The previous iterative schemes are compared with two algorithms based on the positive splitting of matrix P_ε:

$\Gamma^* = (I - R^*)^{-1} S^*$ where $R^*, S^* \in Q(\varepsilon)$ are obtained by 4.18 - 4.20.

Consensus algorithm	$\overline{k}^*$	σ^2	$\overline{\lambda}_2$
P_ε $\varepsilon = \frac{0.8}{\Delta}$	12.93	6.04	0.73
P_ε $\varepsilon = \frac{0.5}{\Delta}$	18.97	10.60	0.83
Γ_1	6.83	0.54	0.44
Γ^*	11.26	3.54	0.67

Table 4.1: Convergence properties of the *consensus* algorithms for undirected graphs

Consensus algorithm	$\overline{k}^*$	σ^2	$\overline{\lambda}_2$
P_ε $\varepsilon = \frac{0.8}{\Delta}$	11.77	4.77	0.66
P_ε $\varepsilon = \frac{0.5}{\Delta}$	17.58	8.82	0.79
Γ_1	10.59	2.60	0.61
Γ^*	5.77	0.22	0.26

Table 4.2: Convergence properties of the *consensus* algorithms for directed graphs

The second and third columns of Table 4.1 and 4.1 show respectively the average value $\overline{k}^*$ and the variance σ^2 of the convergence time, calculated on the 1000 randomly generated undirected and directed graphs, respectively. In addition, the last columns show the average value $\overline{\lambda_2}$ of the second eigenvalue of the corresponding iterative matrix. Indeed, the average time depends on the largest eigenvalue of the stochastic matrix characterizing the consensus algorithm: the smaller the eigenvalue λ_2 is, the faster the algorithm is [17].

The results in Table 4.1 and 4.1 illustrate that the proposed algorithms exhibit good performances. In particular, Table 4.1 shows that the iterative scheme Γ^* improves the convergence obtained by the matrices P_ε with $\varepsilon = \frac{0.8}{\Delta}$ and $\varepsilon = \frac{0.5}{\Delta}$, since the average number of iterations decreases from $\overline{k^*} = 12,93$ and $\overline{k^*} = 18,97$ respectively, to $\overline{k^*} = 11.26$.

Moreover, an efficient numerical behavior of the iteration process is given Γ_1, but it converges to a different group decision value (there is an average error of -0.52%).

In addition, a set of cases is analyzed where the network topologies are described by periodic graphs of 12 nodes. More precisely, five cases of periodic graphs with $d = 2, 3, 4, 6$ and 12 are considered. Table 4.3 reports the convergence time and properties: for each value of d the value of k^* decreases using the new algorithm scheme Γ^*. Hence, the performed tests show that the proposed consensus algorithm works very well in all cases, including the cases in which the standard algorithms exhibit low performances.

Consensus algorithm			$d = 2$	$d = 3$	$d = 4$	$d = 6$	$d = 12$
P_ε	$\varepsilon = \frac{0.2}{\Delta}$	k^*	48.1	42.2	29.7	38.8	144.5
		λ_2	0.97	0.94	0.89	0.91	0.98
P_ε	$\varepsilon = \frac{0.8}{\Delta}$	k^*	23.1	19.5	29.8	40.7	207.7
		λ_2	0.90	0.76	0.82	0.89	0.98
Γ_1		k^*	25.8	18.2	19.6	35.4	118.4
		λ_2	0.91	0.80	0.75	0.87	0.97
Γ^*		k^*	21.2	13.8	10.5	10.3	103.4
		λ_2	0.87	0.72	0.57	0.57	0.96

Table 4.3: Convergence properties of the *consensus* algorithms applied to periodic digraphs

Chapter 5

Conclusions

In this dissertation, the study of the models and methods to apply to Multi-Actor Systems, MASs, is discussed in relation of two different examples of MASs in two very diverse perspectives.

The analyzed multi-agent systems are taken into account purely to their distinctive features of complexity and, especially, because the decision making mechanism in MASs is a very complex process, due to the dynamical and large scale nature of the networks, the hierarchical structure of decisions, and the randomness of various inputs and operations. The multi-agent systems studied in this thesis are focused on actors that can be considered agents only in relation to their autonomous, distributed and interaction capabilities.

In particular, this dissertation is focused on two main different topics that are analyzed from two different perspectives; nevertheless the examined issues have significant commonalities, because the studied problems are both characterized by a high level of complexity.

The approach and the methodology, that are proposed to study the intermodal logistic systems and, in particular, to specify of the Integrated System to manage the intermodal transportation networks at the operational and tactical levels, present noteworthy and innovative features.

First of all, the proposed metamodeling approach is able to describe with high level of detail such complex systems, in a modular and structured approach. Then, the decision support strategies can be easily applied, updated and changed by exploiting the modular configuration of the model.

Concerning the study of the *consensus* problem in distributed networks of agents, the new alignment protocols presented in this thesis guarantee two basic properties: on one side, the right group decision is asymptotically reached, and, on the other side, the iterative matrix does not depend from the step-size parameter. Hence, the algorithms exhibit good performances even in the cases in which the standard consensus protocols converge slowly.

The examined examples, the models and the methodologies applied to analyze them, are very different in the two cases and this testifies the large extent of research problems related to the MASs.

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