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# Evaluating the impact of smart technologies on harbor's logistics via BPMN modeling and simulation

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**Abstract** A smart Information and Communication Technology (ICT) enables a synchronized interplay of different key factors, aligning infrastructures, consumers, and governmental policy-making needs. In the harbor's logistics context, smart ICT has been driving a multi-year wave of growth. Although there is a standalone value in the technological innovation of a task, the impact of a new smart technology is unknown without quantitative analysis methods on the end-to-end process. In this paper, we first present a review of the smart ICT for marine container terminals, and then we propose to evaluate the impact of such smart ICT via Business Process Model and Notation (BPMN) modeling and simulation. The proposed approach is discussed in a real-world modeling and simulation analysis, made on a pilot terminal of the Port of Leghorn (Italy).

**Keywords** Smart harbors · Wireless Sensor Network · RFID · BPMN · Workflow Modeling · Workflow Simulation

## 1 Introduction and motivation

Logistics and freight transport are nowadays key factors of competitive advantage, due to undergoing significant innovation in the smart Information and Communication Technologies (ICT). These developments made possible the emergence of new design paradigms in logistic systems based on the integration of different aspects, such as operation, energy consumption, environmental performance, and so on [3, 60, 30]. An example is given by the European project SuperGreen [51], aimed at supporting the definition and benchmarking of green freight corridors through Europe with respect to environmental, technical, economic, social, and spatial planning aspects. This has been achieved by applying methodologies for the assessment and benchmarking of corridors with smart ICT [28]. With the large-scale integration of smart ICT, new models of organization, planning, and management become possible. In essence, a modern port is characterized by its containers traffic and its incorporation in a logistics network, where land and sea segments are integrated. The efficiency of a port is strongly influenced by its ability to forge links with the hinterland in order to let the goods quickly arrive at destination. Moreover, the European Union encourages with several initiatives the speeding, the safety, and the streamlining of the maritime transport with the other transport modes.

A new phase in ICT integration started in the 2000s, with the emergence of Web Services based on Extensible Markup Language (XML), together with the Service-Oriented Architecture (SOA) paradigm [21]. In parallel, the concept of networked smart devices evolved, due to a convergence of multiple technologies, ranging from wireless communications to the Internet and from embedded systems to sensing systems, yielding the vision of the Internet of Things (IoT) [5].

In the last decade, the integration logic has become an important issue in the development of smart ICT enabled systems, due to the growing complexity of the

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ICT in logistics and the increasing demand for adapting systems to new requirements [22]. To assess the impact of smart ICT in the port logistics, it is necessary to firstly define the specific processes of the considered port and then to discuss how ICT is charging the tasks in the chain. In a traditional design paradigm [26]: (i) each stage of the chain is considered as an independent activity; (ii) economies of scale are key competitive differentiators; (iii) horizontal integration is the main strategic option; (iv) efficiency optimization is fragmented; (v) a considerable amount of uncertainty exists in supply chain performance of other parties; (vi) ICT is mainly used for single task operations. In contrast, a smart ICT-based paradigm is characterized by [43, 12]: (i) business process viewed as an integrated chain of value-adding activities; (ii) reduction in the costs for all parties; (iii) vertical cooperation versus adversarial relationships between parties; (iv) reduction in the uncertainty in supply chain performance; (v) ICT used also at the service level (i..e, integration level) and at the handoff level (i.e., interoperability level).

In essence, the design and implementation of the integration logic can be considered as a high-level organization, where tasks supported by different smart ICT systems represent the building blocks organized by the integration logic itself. Indeed, the goal of a smart ICT is to support the work organization and the collaboration among tasks and resources (humans and machineries) for a number of representative cases. For this purpose, it is not sufficient to equip workers with adequate smart ICT for their individual workplaces, but also to consider the relationships among work activities that are performed by different workers and to provide support for their collaboration, as well as to take into account the responsibility for executing each step in the flow of work. Process models provide the conceptual basis for defining when and under which conditions tasks are actually carried out in the context of an integration scenario [61]. In this context, the Business Process Model and Notation (BPMN) [42] is a standard of the Object Management Group (OMG), with the primary goal of providing a notation that is readily understandable by all business stakeholders. BPMN provides support to represent the most common control flow modeling requirements. Other language proposals in the literature get an abstract representation of business processes [20], but the key aspect is that BPMN is supported by an executable model to enact instances of processes on ICT platforms [44]. Since a BPMN model can automatically be translated into an executable model, it can also be computer-simulated. The main advantage of simulation-based analysis is that it can predict process performance by using a number of qualitative and quantitative measures [22]. As such, it provides a way to evaluate the execution of the business process over a number of cases in order to determine inefficient or inconsistent behavior. Thus, BPMN modeling and simulation can be interchangeably used as a basis for making managerial or technical decisions. From one side, models, when simulated, can even be more realistic than traditional experiments as they allow the efficient observation of a number of cases. From the other side, simulations, when made via BPMN models, allow combining and capturing a number of workflow patterns, thus setting up a coherent environment for integration of complex interaction behavior [25].

In this paper, we present an approach to measure the improvements made possible by smart ICT on maritime container terminals. A literature review of smart ICT for harbors logistics is first provided. Second, the adoption of the BPMN standard to model and simulate a terminal process is discussed. Third, a marine container terminal of the Port of Leghorn (Italy) is modeled and simulated via the BPMN, in order to measure the impact of the application of RFID and WSN in the terminal. Simulation results show that significant saving on both processing time and resources can be achieved. The proposed approach is independent of the terminal and the ICT solutions considered. This study comprises significant outcomes of a Research Project of National Interest (PRIN) founded by the Italian Ministry of Education University and Research (MIUR), in which we carried out a feasibility study.

The paper is structured as follows. Section 2 covers the integration and sensing infrastructures available to the smart harbor's logistics, giving an insight of the state-of-the-art in the application of ICTs to logistics and monitoring of containers. Core concepts of BPMN modeling, together with the pilot case study are presented in Section 3. Section 4 is devoted to fundamentals of BPMN simulation. Experimental studies are described in Section 5. Finally, Section 6 draws some conclusions and future works.

## 2 Integration infrastructures available to smart harbor's logistics: literature review

The application of smart ICT helps to address several issues in the management of maritime and harbor's logistics. The use of vertical solutions, involving the use of sensors and actuators to control part of the port infrastructure, is acknowledged since many years. An example is the Dover's Smart Bridge [58], dated back to the '90, where lift bridges are enhanced with an automatic control system to sense the vessel movements and to adjust the ship-to-shore bridge shape in order to maintain the rail stock transit. The work in [57] shows examples in which port logistics has experienced benefits from investing in smart yard handling technologies, such as: Double Rail Mounted Gantry cranes or DRMG (Hamburger Hafen und Logistik AG), semi-automated DRMG (Ningbo Beilun Container Port), automated crane handling with remote controlling back-office (Shanghai Waigaoqiao Port) and fully automated straddle carrier system (Brisbane). Automated Guided Vehicles (AGVs), as well as Automated Stacking Cranes (ASCs), can be used to increase the container movements' efficiency. AGVs are robotic vehicles that travel along a predefined path defined by electric wires embedded in the ground or a grid of transponders. ASCs move on rails and are controlled by a central operating system. Due to their minimal footprint, they can provide high density container storage. Some terminals of the Rotterdam Port use both AGVs and ASCs technologies [59]. Sensors have also been deployed for increasing the security of critical port areas such as gas and oil terminals or anchored naval vessels [36], both on the surface or underwater. Waterside port security includes a range of activities with preventive purposes, ultimately aiming at controlling who and what enters into the port area from the water side. It includes crews, passengers, and cargo entering on-board of large announced vessels, on-board of small unannounced surface crafts, swimmers, divers or even small submersibles. The most challenging functionality of an autonomous surveillance system resides in the automatic detection of "abnormal" events to call for prompt specific operator attention. This requires features extraction, recognition, and correlation functionalities [27].

When we focus on smart ICT-based horizontal solutions, involving the use of different technologies in diverse parts of the port environment, we can find works focusing on: optimizing the design and operation of container terminals [57,59,38,53]; enhancing inland and maritime transportation systems [24,18,11]; providing real time locating systems [39,4]. In order to lower the shipment time and to enhance the productivity of container port logistics, also the port management is now advancing to smart ICT-based integration infrastructures focusing, in particular, on cloud-based solutions [32, 31]. This provides critical functionalities by employing ubiquitous computing technologies that allow achieving real-time synchronization of port logistics.

These functionalities can be summarized in two groups: 1) localization, tracking, and identification of objects, and 2) management of cargo freight, such as sea containers transporting goods to be monitored in order to minimize possible economic losses. For this reason, we identified two main areas where smart ICT solutions can boost the performance of harbor's logistics: 1) localization, tracking, and identification, and 2) smart containers.

These two key application scenarios will be investigated in the next subsections in terms of hardware and communication technologies involved.

### 2.1 Localization, tracking, and identification

In the field of outdoor localization, existing solutions based on GPS, sometimes with the support of traditional wireless networks, are de-facto consolidated as standards. Nevertheless, when dealing with harbor's scenarios, several additional issues must be addressed. For example, with GPS-based solutions it is possible to track the position of cranes moving containers by means of centralized geo-databases. This solution is generally effective but there are limits due to the fact that containers are not always moved by means of cranes, but also by trucks and tractors. Furthermore, GPS systems alone are not enough reliable solutions for tracking yard trailers because of a lot of dead zones caused by huge quay cranes and container stacks. An alternative solution to GPS-based systems is the use of Real-Time Locating Systems (RTLSs), which give in real time the exact position of containers when a RTLS tag is attached to them [17]. These systems are characterized by the use of techniques typical for indoor localization scenarios. Usually, the indoor localization process starts from measuring distances between anchors, whose location is predetermined, and mobile nodes. There are attractive solutions for estimating the distance between nodes; among them, the Received Signal Strength Indicator (RSSI) is the predominant approach [49]. It is based on the radio path loss model, in which radio signals exponentially attenuate during transmission. In this field, different technologies can be used, spanning from WiFi [8,41], Bluetooth [45], and wireless sensor networks (WSNs) [33] to ultrasonic sounds [50], Chirp Spread Spectrum (CSS) [54], and Ultra Wide Band (UWB) [19].

A well-established technology for RTLS in the harbor's logistic scenario is the Radio-Frequency IDentification (RFID) [15,17]. RFID systems can provide a less accurate positioning information, usually regarding the relative positioning of objects, but they offer the added possibility to number, identify, catalog, and track objects. These characteristics enable container terminals to be managed in a more efficient way thanks to a quick identification of the containers, but they are less useful to determine their position. Furthermore, RFID systems require a fixed or mobile infrastructure to read the tags, and the process, in many cases, includes human-driven or semi-automated operations. Thus, with current solutions, real-time identification and localization of containers are error-prone activities that still require human intervention to manage anomalous situations (for example, by physically searching the containers that are out of place). In order to overcome these limitations, several works have been proposed to add tracking and tracing capabilities to localization techniques by using wireless sensor networks [14, 35, 62]. WSNs have proven to be useful in different scenarios, from human activity recognition [47, 48] to ambient assisted living [46] as well as for general purpose indoor localization systems [6, 9]. In [2], authors propose an innovative approach where the position of containers can be continuously determined by means of a wireless sensor network. Each container is equipped with a number of nodes that use wireless communication to detect neighbor containers. At the base station, geometrical constraints and proximity data are combined together to determine the relative positions of containers. An interesting hybrid RFID-WSN approach is recently emerging, which puts together the key aspects of both the technologies. In [10], authors propose a new hardware platform that enables an active RFID tag, thought for monitoring temperature in goods, to communicate as a wireless sensor node with single- and multi-hop routing. In [16], authors enhance RFID tags with extended communication capabilities over a ZigBee network. In [63], a way to integrate RFID with WSNs is presented in order to add to the typical identification functionality of RFID the localization possibilities enabled by a WSN.

Following the clear indications provided by the literature review, we choose as booster factors in our simulation model the presence of RFID- and WSN-based RTLSs for localizing, tracking, and identifying smaller objects like containers in the considered scenario.

### 2.2 Smart containers

The progress of machine-to-machine (M2M) communication technologies and wireless sensor networks offers a differentiating factor for logistics companies. As discussed in the previous section, not only it is possible to locate and track a package from origin to destination, but, thanks to WSNs, companies and port authorities can take advantages from monitoring the transportation conditions throughout the container's journey. If there was an excess of moisture in the container, if goods were opened or inspected along the line, if there were temperature fluctuations, it is possible to know when, where, and how these events occurred. This can be made by embedding wireless sensors nodes in the container, providing useful different sensing capabilities. Their wireless communication capacities, autonomous power, and small sizes allow the remote monitoring of goods through the Internet to be maintained with less human effort. Moreover, in cases of container falls, fires, exposure to floods or other risks, sensors (e.g. Waspmotes [1]) can send SMS alerts to the customer, the transportation company, or the law enforcement to call for immediate assistance. This makes a container "smart".

We consider as main goals for a smart container three important features enabled by the presence of a WSN: (i) to detect unexpected container openings, (ii) to monitor transport conditions, and (iii) to identify storage incompatibilities. Sensors (i.e. light, magnetic contacts, temperature) can be placed within a container to determine when it was opened [23]. They can be programmed to acknowledge estimated opening hours and to check if opening times correspond to scheduled inspections, generating alerts by GPRS/3G. In some cases, containers carry humidity and temperature-sensitive items such as food, pharmaceuticals, or artworks. Adding sensors to measure these environmental variables can be essential to ensure that goods are managed and unspoiled during the transportation process [34]. If goods are fragile, registering shock and vibration impacts can assist in identifying responsible authorities in the case of insurance claims. In this case, 3-axis accelerometers can be embedded in sensor nodes to detect such vibrations. Finally, the motes can act as smart tags. Beyond the passive behavior of identifying the content of what is being freighted, sensors can actively exchange information with other pallets or containers stored around by using RFID and Near Field Communication (NFC) technologies. This way, warning messages can be generated if, for example, a pallet of dangerous goods is placed side by side with flammable materials [52].

## 3 BPMN modeling: core concepts and pilot case study

The BPMN language has been developed with a solid mathematical foundation provided by the process calculus theory, which is an essential requirement to automate execution and to easily provide proofs of general consistency properties. To describe a workflow, BPMN offers the business process diagram, with a rich set of elements and attributes. For the sake of significance, in

[1] http://www.libelium.com/products/waspmote

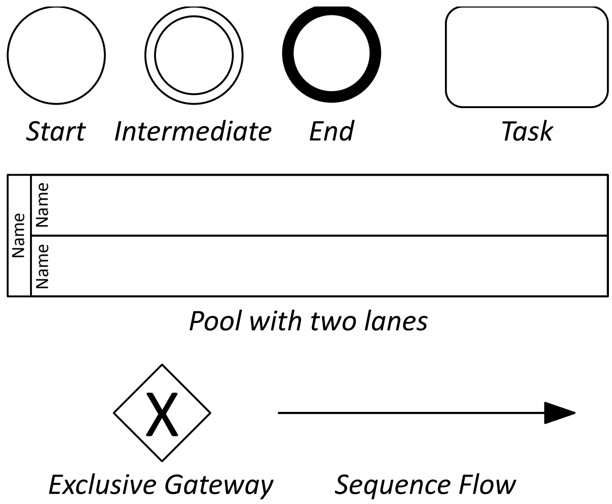



Fig. 1: BPMN basic elements

this paper we report on the basic elements shown in Figure 1.

The interested reader may refer to [42] for a detailed study of the language. More precisely, *events* (represented as circles) model something that can happen during the process. A workflow is activated by a *start event* (a circle with a single thin border) and terminated by an *end event* (a circle with a single thick border), while *intermediate events* (circles with double border) can occur anywhere within the flow. *Tasks* (rounded-corner rectangles) are atomic activities of the workflow, whereas *gateways* (diamonds) are decision points to control the flow of work. The exclusive gateway routes the incoming flow to one of the mutually exclusive outcoming flows, on the basis of a logic condition. The *sequence flow* is represented by a solid arrow, and it models the order of execution of activities in the workflow. Finally, *pools* and *lanes* are represented by rectangles and they model different responsible subjects/areas.

Given the above elements, an essential BPMN model of a marine container terminal system is presented in the following subsection. The model is related to a terminal located in the Port of Leghorn (Italy) and it takes into account some scenarios.

### 3.1 Workflow modeling of the pilot marine container terminal

In this section, the emphasis is put on internal logistics, since the aim of the study is to assess the extent to which smart ICT solutions can improve the overall efficiency of the process [55,57]. A marine container terminal is the place where containers arriving by sea vessels are transferred to inland carriers, such as trucks, trains, and *vice versa*. Each marine container terminal performs four basic functions: receiving, storage, staging, and loading for both import and export. Receiving involves container arrival at the terminal, either as an import or export, recording its arrival, retrieving relevant logistics data and adding it to the current inventory. Storage is the function of placing the container in a known and recorded location in order to retrieve it when needed. Staging is the function of preparing a container to leave the terminal. The containers that are to be exported are identified and organized so as to optimize the loading process. Import containers follow similar processes, although staging is not always performed. An exception is a group of containers leaving the terminal via rail. Finally, the loading function involves placing the correct container on the ship, truck or other mode of transportation.

Figure 2 represents the layout and the resources of a container terminal system. More precisely, the berth (a space for a vessel to anchor) is equipped with quay cranes to unload containers. Unloaded containers are first transported to yard positions (the storage area), usually structured into stacks and differentiated into sub-areas for export, import, special, and empty containers. The transport between quay and yard can be performed either by trucks with trailers, straddle carriers (SC), and automatic guided vehicles (AGV). The formers can also serve the landside operation, where containers departing or arriving by road or railway are handled within the truck-and-train areas.

Figure 3 shows a BPMN model of the container terminal system. The model is based on 8 main lanes, 24 tasks, 7 gateways and 6 types of resources (different types of machinery). After the arrival at the *roadstead*, vessels are berthed according to a priority assigned via commercial, security, and traffic management policies. Non-priority vessels enter the roadstead and lie at anchor there, whereas priority vessels directly enter into the harbor. The vessel is then assigned to a berth, moved via berthing tugs and finally moored. Unloaded containers are transported to the *quay*. Here, a container can be placed on the top of a stack (accessible location) or under other containers of the stack (inaccessible location). The former is usually performed for short storage, whereas the latter for medium-long storage. Since there is no sufficient information to exactly establish the storage duration, sometimes a number of movements are required for a container before picking-up it. Each movement may place the container to a next location (accessible or inaccessible). Once picked-up, the container is moved, if needed, to a *de-consolidation area* (where multiple shipments from various suppliers are unpacked for delivery) via a trailer, where it is *con-*

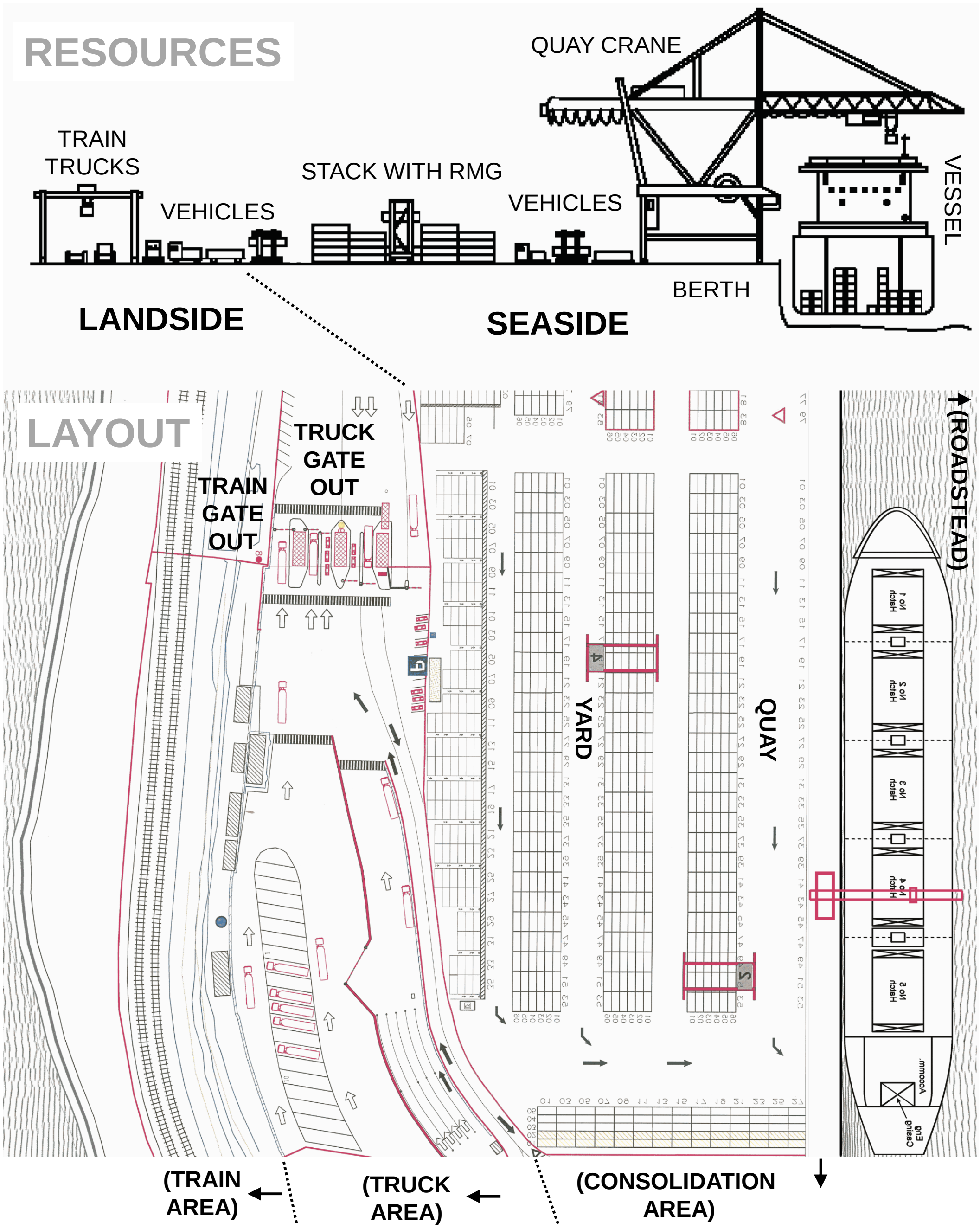



Fig. 2: Resources and layout of the pilot container terminal system

*solidated*. If consolidation is not needed, the container is directly moved to the train or truck area, where it is loaded and checked out in the train or truck gate out, respectively.

The handling machinery employed by the terminal systems are: (i) *Portainer* (PT), a large dockside gantry crane for loading and unloading containers from ships; (ii) *Rubber Tyred Gantry* (RTG), a mobile gantry crane running on rubber tires to ground or stack containers; (iii) *Rail Mounted Grantry* (RMG), a mobile gantry crane running on rails; (iv) *Reach Stacker* (RS), to pile the containers; (v) *Trailer* (TR), to move containers from a place to another one; (vi) *Berthing Tugs* (BT), to move the vessel into the harbor.

For each activity, Table 1 shows the area, the needed resources, the duration interval, and the estimated duration, derived by a number of interviews and measurements. In this paper, the focus is on the activities that can be improved by using smart ICT.

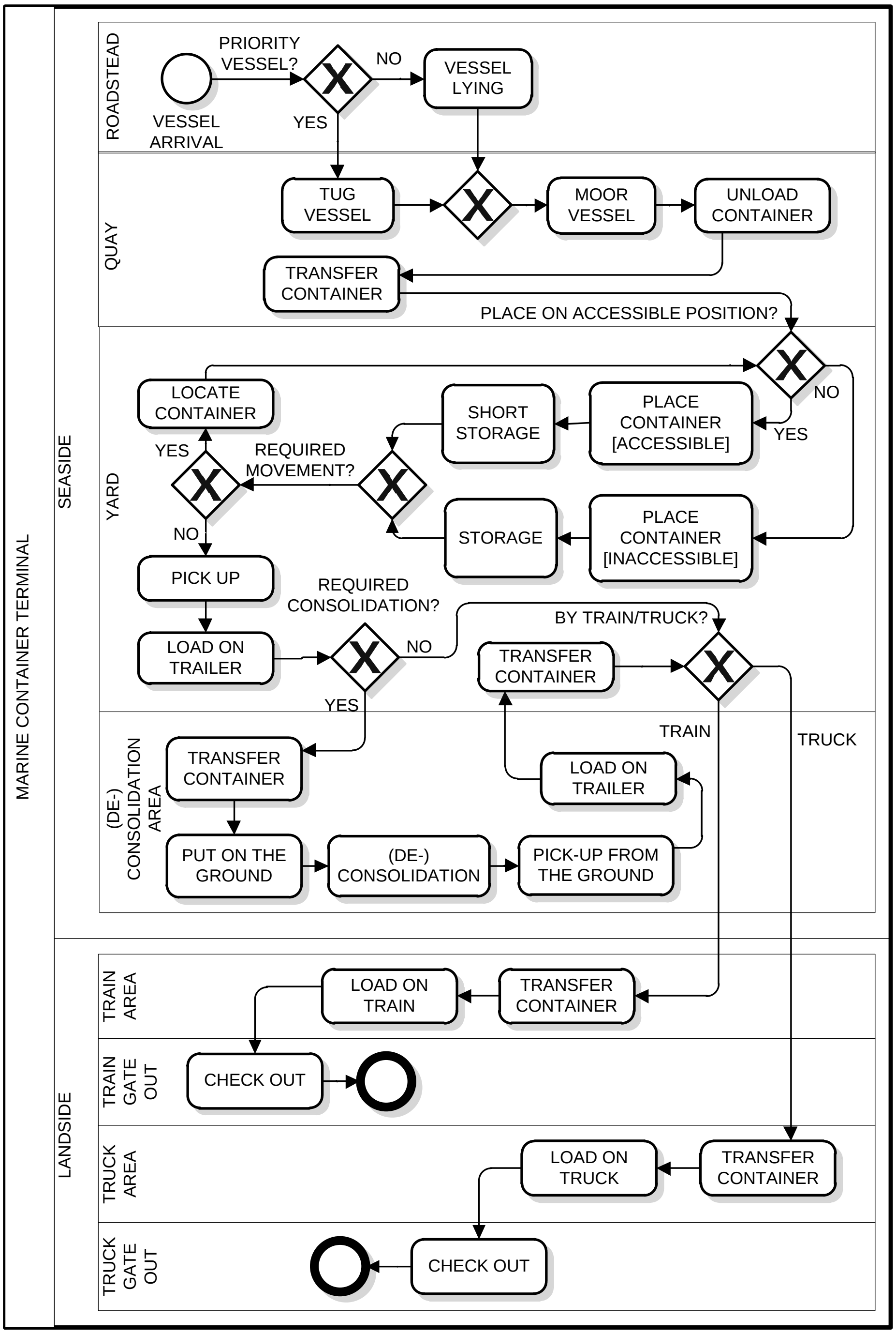



Fig. 3: BPMN model of a container terminal system.

## 4 BPMN simulation

In this Section, simulation functionality is first defined and illustrated on a basic BPMN model. Then, simulation is used to evaluate the impact of selected smart ICT on the BPMN model of Figure 3. Simulations have been carried out using a specific simulation tool, namely *Visual Paradigm Logizian*[2]. However, it is worth noting that the presented approach is independent of the BPMN simulation tool. The next subsection is devoted to the analysis of the BPMN simulation tools. The interested reader may refer to [22] for a comprehensive study on BPMN simulators.

[2] www.visual-paradigm.com/features/process-simulation/

Table 1: Resources employed and duration of each activity in the pilot scenario

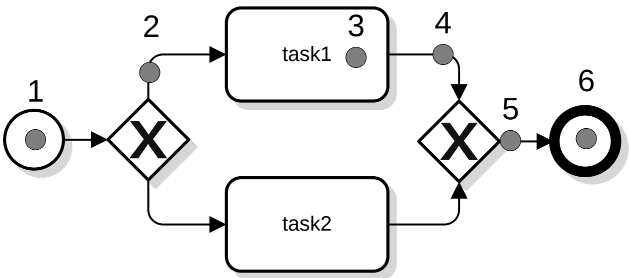
| **Activity** | **Area** | **Needed Resources** | **Duration Interval** | **Estimated Duration** |
|---|---|---|---|---|
| Tug vessel | Quay | Berthing Tugs | [20 m, 40 m] | 30 m |
| Moor vessel | Quay | Berthing Tugs | 10 m | 10 m |
| Unload container | Quay | Portrainer | [3 m, 5 m] | 4 m |
| Transfer container | Quay | Trailer | [5 m, 8 m] | 6.5 m |
| Place container (accessible) | Yard | Rubber Tyred Gantry | 2 m | 2 m |
| Place container (inaccessible) | Yard | Rubber Tyred Gantry | [4 m, 14 m] | 9 m |
| Short storage | Yard | - | 1 d | 12 h |
| Storage | Yard | - | [2 d, 3 d] | 2.5 d |
| Locate container | Yard | Yard staff | [10 m, 20 m] | 15 m |
| Pick up | Yard | Rubber Tyred Gantry | 2 m | 2 m |
| Load on trailer | Yard | Rubber Tyred Gantry | 2 m | 2 m |
| Transfer container | (De-)consolidation | Trailer (de-)consolidation | [5 m, 8 m] | 6.5 m |
| Put on the ground | (De-)consolidation | Reach Stacker Trailer (de-)consolidation | 2 m | 2 m |
| (De-)consolidation | (De-)consolidation | Consolidation staff | 20 m | 20 m |
| Pick-up from the ground | (De-)consolidation | RTG on consolidation | 2 m | 2 m |
| Load on trailer | (De-)consolidation | RTG on consolidation | 2 m | 2 m |
| Transfer container | Yard | RTG on consolidation | [5 m, 8 m] | 6.5 m |
| Transfer container from Yard to train/truck area | Train/Truck area | Trailer | 8 m | 8 m |
| Load on train/truck | Train/Truck area | Reach Stacker (truck) Rail Mounted Grantry (train) | 4 m | 4 m |
| Check out | Train/Truck gate out | Gate out staff | 15 m | 15 m |

## 4.1 State of the art of BPMN simulation tools

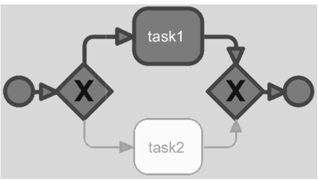
Since to conduct simulative experiments is an interactive activity, an important choice of our approach is the simulation tool. Today, most Business Process Management (BPM) systems provide simulation facilities. A modern simulation tool should provide building blocks for a certain application area, to support the composition of a simulation model via a visual notation, as well as a scripting language to model complex behavior. However, scripting languages force to chart the situation in terms of a programming language, make modeling time-consuming and the simulation program itself provides no insights. The best tool combines a visual design environment and a scripting language, to offer graphical analysis capabilities and animation. The interested reader is referred to [22] for a summary of the available business process simulation tools. A negative feature of a simulation tool is the use of proprietary building blocks, which makes it hard to interchange simulation models between packages. Simulation tools based on more widely used languages, such Petri Nets or BPMN, are more open and can exchange process models with different analysis tools [1]. BPMN, EPC (Event-driven Process Chain), UML AD (UML Activity Diagrams), and other business process modeling notations have in common that they all use token-based semantics. Therefore, there are many techniques and tools to convert Petri Nets to such languages, and vice versa. As a result, the core concepts of Petri nets are often used indirectly, to enable analysis, to enact models, and to clarify semantics. However, Petri Nets imply a severe representational bias, which is relevant for the understandability of the results and vital to guide process modeling and simulation via the majority of the involved actors. In contrast, BPMN 2.0 is the de facto standard notation for modeling business processes understandable by a wide audience of people. An absolute majority of freeware and commercial BPM tools and Business Suites, like Oracle BPM Suite, IBM Business Process Manager, jBPM, Activiti, Appian BPM Suite, Bizagi BPM Suite, MagicDraw Enterprise Architect (Sparx), Mega Process (MEGA), Signavio Process Editor and others, either natively support BPMN or provide conversion in order to stay compatible and up to date. In the literature, the modern simulation studies in the context of port logistics are based on BPMN [13, 40, 37, 56, 7].

## 4.2 Fundamentals of BPMN simulation

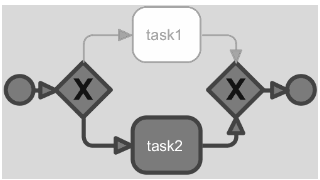
In order to define the BPMN simulation, we introduce the concept of *token* traversing the sequence flow and passing through the elements in the process [22]. Fig-




(a) Routing of a token in a basic BPMN model




(b) Scenario 1




(c) Scenario 2

Fig. 4: Simple simulation scenarios of a basic BPMN model

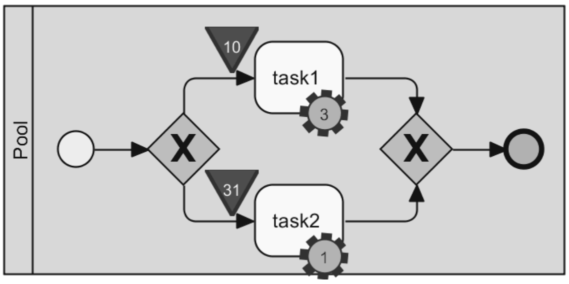
ure 4a shows a token as a gray circle, in a basic BPMN model. Every time a new process occurs, the *start* event creates a token (1). The exclusive gateway takes the incoming token and, according to a given condition, decides to which sequence flow it would be routed (2). An activity receives a token and forwards it after completion (3). The join exclusive gateway just takes an incoming token (4) and moves it to the outgoing sequence flow (5). Finally, the end event removes the token (6). It should be noted that the token does not carry any information, other than a unique identifier of the process occurrence. Figure 4b and 4c show the two scenarios of the BPMN model, respectively.

Since many process instances may be generated, many tokens can be created during time. When the needed resources are assigned to a *task*, the task is said to be *started*. If the task gets completed without interruptions, the task is said to be *completed*. Tokens can also be processed in parallel by different tasks when sufficient resources are available. Otherwise, tokens will be processed in series and queued at the input of tasks. The workflow status is determined by the position of all available tokens.

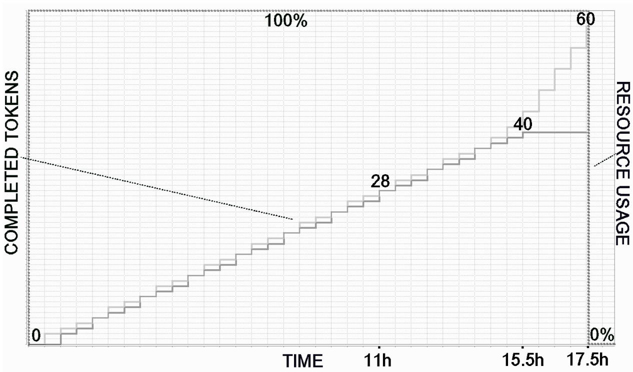
A *simulation* is generally made of a number of combined scenarios, whose tokens are competing for resources. Each scenario is characterized by a well-defined *path* (from a start event to an end event), a *number of process occurrences* (tokens) and their *arrival rate*. An example of typical simulation question is "How long will it take to process?". To answer this question, several variables need to be declared: the duration of each task, the branching proportion of each outgoing flow of each gateway, the resources needed by each task, and the available resources. Cost and other quality parameters can be also defined. Cost can include the variable cost related to the duration (e.g. hourly wages of the involved human resources) as well as a fixed additional cost (e.g. shipping cost). During simulation, the simulator keeps track of the time each process instance spends in an activity and the time each resource assigns to that activity. Hence, it provides a realistic way for measuring and analyzing the actual costs of the activities.

Basically, a workflow simulator takes the workflow model and the above mentioned additional information as an input, and provides the Key Performance Indicators (KPIs) as an output. The simulation also provides animation, showing the tokens' position, the task status, and the queues' size, when simulation takes place, to help understanding relevant phenomena in an interactive manner. As an example, Figure 5 shows some qualitative and quantitative results of a simulation of the basic BPMN model of Figure 4, with the following additional simulation information: task1 duration: 60 min.; task2 duration: 30 min.; pool available instances: 4; number of arriving tokens: 100; inter-arrival time: 0 min; branching proportions: 40% (scenario 1), 60% (scenario 2). More precisely, Figure 5a shows the status of the workflow after 11 h of simulated time. Here, the number and the position of tokens waiting at the input of tasks are represented by an overturned triangle: 10 and 31 waiting tokens for task1 and task2, respectively. The number of processing tokens for each task is represented by a gear: 3 and 1 for task1 and task2, respectively. Indeed, since the overall number of available instances of the pool is 4, the workflow can only process 4 tokens in parallel. The other 41 tokens are then queued. In this basic model, the pool is the unique resource type. In general, other resource types can be defined and associated to a pool, with a quantity for each type. In this way, each task can be associated to a needed quantity of the available resource types. In Figure 5a, the workflow is overall handling 13 + 32 tokens, belonging to scenario 1 + scenario 2, respectively. Since scenario 1 and scenario 2 are supplied with 40 and 60 total tokens (due to the branching proportion), 27 and 28 tokens were already handled by the respective scenarios.

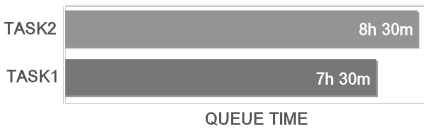
All the tokens were processed in 17 days and 30 hours of simulated time. Figure 5b shows the number of tokens completed in time, for each scenario. Here, the dark and light gray curves are related to the scenario 1 and 2, respectively. Both scenarios are characterized by the same linear trend, which means that the number of completed tokens per time unit is the same. For this purpose, scenario 1 used, on average, more resources




(a) Ongoing simulation




(b) Completed tokens and resource usage against time




(c) Queue time

Fig. 5: Qualitative and quantitative result of a simulation run

than scenario 2, since task 1 duration is higher than task 2 duration. More precisely, after 11 h and 15.5h each scenario completed about 28 and 40 tokens, respectively. The former instant of time corresponds to the status illustrated in Figure 5a, whereas the second instant of time corresponds to the end of the scenario 1. At the end of scenario 1, all resources were available to scenario 2, and then its linear trend suddenly increased, thus handling 20 tokens in about two hours. Figure 5b also shows the resource usage against time. It can be observed that the four available pools are fully used all the time (100%), because it is a general-purpose resource. In other circumstances, different types of resources are constrained to a subset of tasks; then, their use is determined by the availability of tokens at the entry of such tasks. Finally, Figure 5c shows the queue time at each task, which is important to determine the internal efficiency of the workflow. The queuing on task 2 is higher because, as discussed above, scenario 2 had fewer resources than scenario 1, although task 1 duration is twice as long as task 2 duration.

The discussed example is representative of the features of BPMN simulation function, although it is numerically simple and then non-representative of its complexity. In general, the behavior of BPMN models is highly non-linear, due to their structural complexity. Although the BPMN has been founded on a mathematical model, analytic solutions of a workflow are often impossible, too complicated, and extremely expensive to validate. Moreover, it is often impossible or extremely expensive to observe the occurrence of different scenarios in the real world. For these reasons, BPMN modeling and simulation are a valid and fundamental approach to study the operation of a workflow and to infer properties concerning the behavior of an actual system.

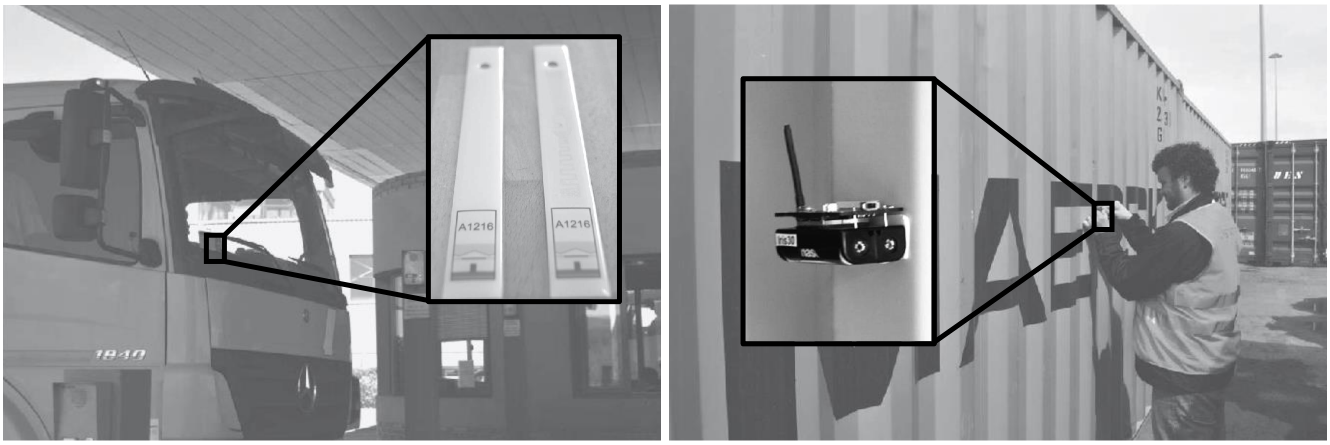
With regard to the illustrated BPMN model of a container terminal system, some additional simulation information has been already presented in Table 1. In the following subsection, other useful information for the simulation is derived.

### 4.3 Considered scenarios and smart ICTs used

Our analysis is focused on the assessment of an important KPI of a port's performance from the point of view of the exporter/importer: the dwell time of cargo in port, measured in terms of the number of days that a given amount of cargo remains in port after a peak in demand. Considering the pilot container terminal with its available resources, in order to determine a typical peak situation we exploited the data log available in the Tuscan Port Community System [3](tpcs.tpcs.eu). More precisely, the peak scenario consists in the arrival of 5 vessels of 750 containers, almost at the same time. It is considered a critical situation because the terminals layout does not allow the processing of 5 vessels at the same time.

Figure 6 shows the smart ICT technologies experimented, together with the application context. More precisely, the purpose of the simulation is to evaluate the impact of RFID and WSN technologies on the overall flow of work, when used for speeding the truck *check-out* and the *locate container* tasks. The optimized version of a business process (called *to-be* process) is carried out starting from the current version (called *as-is*

[3] The Tuscan Port Community System is a web-services based information hub for the procedures of import and export of goods. It enables the efficient exchange of relevant logistics information and ensures the smooth flow of shipments from cargo origin to destination




(a) RFID installed on the truck at the gate-out

(b) WSN installation on the container

Fig. 6: The smart ICTs used during the experimentation[4]. Photography supplied courtesy of Leghorn Port Authority and Paolo Barsocchi.

Table 2: Duration of the considered activities when using smart ICTs

| **Activity** | **Duration (*as-is*)** | **Duration after using smart ICT (*to-be*)** | **smart ICT used** |
|---|---|---|---|
| Truck check-out | 15 min | 0.5 min | RFID |
| Locate container | 15 min | 1 min | WSN |

process). Table 2 shows the duration of the two considered activities, considering an *as-is* view (as in Table 1) and the *to-be* version of the processes. Such data have been derived from the data log of the information systems available at the Truck Gate Out and at the Yard. More precisely, it can be observed that the use of RFID sensibly speeds up the check-out operations at the Truck gate-out area. Indeed, the *as-is* version implies a number of manuals steps, such as stopping the truck, delivering the hard copy of documents to the gate officer, and waiting for the pass before restarting the truck. In contrast, by using RFID technology the activities are almost totally automated, since, when the truck approaches the access gate, the RFID allows registering and controlling the container, thus allowing opening the gate. Sometimes additional documents are needed, and for this reason the average time spent is about 30 seconds. Currently, this method is successfully working at different gates of the Port of Leghorn. The use of the WSN technology for container localization has been previously proposed by [2]. In essence, each container is equipped with a number of nodes that use a WSN to detect neighbor containers. At the base station, geometrical constraints and proximity data are combined together to determine the relative positions of containers, thus speeding up their localization. It can be observed that the adoption of WSNs reduces the duration of the activity from 15 to about 1 minute. Indeed, the existing solution for localization and identification is based on GPS and RFID technologies. GPS enables the tracking of the position of the crane moving the container. This solution is generally effective, but there are also some limits, mainly due to the fact that containers are not always moved by means of cranes, but also by trucks and trailers. RFID solutions enable a quick identification of containers, but they are less useful to determine their position. Moreover, RFID systems require a fixed or mobile infrastructure to read the tags, but the process is usually human-driven. Thus, with current solutions, real-time identification and localization of containers are error-prone activities, requiring human intervention.

Table 3 shows the five considered simulation scenarios. They basically differ in the number of movements needed before going to the truck area.

[4] The devices shown in figure are IRIS Motes. They are 2.4 GHz Mote modules used for enabling low-power, wireless sensor networks. The technology underlying the sensor network works on IEEE 802.15.4 compliant RF transceivers using 2.4 to 2.48 GHz band, a globally compatible Industrial, Scientific, and Medical (ISM) band. It involves the use of direct sequence spread spectrum radio which is resistant to RF interference and provides inherent data security at a 250 Kbps data rate.

Table 3: Considered simulation scenarios

| **Scenario** | **Sequence of Gateway Conditions** | **Sequence of Choices** |
|---|---|---|
| Zero movement | 1) Priority vessel? | Yes |
| | 2) Place on accessible position? | No |
| | 3) Required movement? | No |
| | 4) Required consolidation? | No |
| | 5) By Train/Truck? | Truck |
| One movement | 1) Priority vessel? | Yes |
| | 2) Place on accessible position? | Yes |
| | 3) Required movement? | Yes |
| | 4) Place on accessible position? | Yes |
| | 5) Required movement? | No |
| | 6) Required consolidation? | No |
| | 7) By Train/Truck? | Truck |
| Two movements | 1) Priority vessel? | Yes |
| | 2) Place on accessible position? | Yes |
| | 3) Required movement? | Yes |
| | 4) Place on accessible position? | Yes |
| | 5) Required movement? | Yes |
| | 6) Place on accessible position? | Yes |
| | 7) Required movement? | No |
| | 8) Required consolidation? | No |
| | 9) By Train/Truck? | Truck |
| Three movements | 1) Priority vessel? | Yes |
| | 2) Place on accessible position? | Yes |
| | 3) Required movement? | Yes |
| | 4) Place on accessible position? | Yes |
| | 5) Required movement? | Yes |
| | 6) Place on accessible position? | Yes |
| | 7) Required movement? | Yes |
| | 8) Place on accessible position? | Yes |
| | 9) Required movement? | No |
| | 10) Required consolidation? | No |
| | 11) By Train/Truck? | Truck |

## 5 Experimental studies

Simulation is handled over specific scenarios and by incrementally changing the model parameters. More specifically, the methodology is called *what-if* analysis, and it consists in a data-intensive simulation activity whose goal is to inspect the behavior of a part of the enterprise business model under some given hypotheses called scenarios. In practice, the what-if analysis measures how changes in a set of parameters impact on the process performance with reference to the simulation model offering an abstract representation of the significant features of the business, and tuned according to the historical enterprise data [29].

This Section is devoted to the simulations of the *as-is* and *to-be* systems. Two types of business process improvements have been carried out: (a) *to reduce the number of resources, keeping the process duration constant*, in order to establish whether or not some machines can be removed, thus reducing the cost and the environmental impact of the process; (b) *to reduce the duration of the process by adopting new smart ICT*, for a better efficiency of the process. In the following, the simulation details and the obtained results for the two types of improvements are described.

### 5.1 Simulation of the *as-is* model with full resources

Table 4 shows the quantity available of each resource in the pilot container terminal. The first simulation is made by using all the available resources. As a result, the total duration for processing the 5 vessels of 750 containers is 7 days, 15 hours and 53 minutes. Since this temporal duration is calculated without any improvement initiative, it will be used as a baseline for measuring progresses. Moreover, the resource usage against time has revealed that the resources PT, TR, and RTG are fully used in some intervals of the simulation. Thus, reducing them implies an increase of the total simulation duration. In contrast, the RS resource has a maximum usage of 1 unit, which means that it is possible to

Table 4: Resources and quantity available for the pilot scenario

| **Resource** | **Quantity** |
|---|---|
| Portrainer (PT) | 10 |
| Rubber Tyred Gantry (RTG) on Yard | 10 |
| RTG on consolidation area | 5 |
| Reach Stacker (RS) | 14 |
| Trailer (TR) waterside, train/truck areas | 30 |
| Trailer (TR) (de-)consolidation area | 6 |
| Rail Mounted Grantry (RMG) | 3 |
| Berthing Tugs (BT) | 12 |
| (De-)Consolidation staff | 10 |
| Train Gate out staff | 5 |
| Truck Gate out staff | 6 |
| Yard Staff | 15 |
| Train gate out | 3 |
| Truck gate out | 3 |

load truck one-by-one, since the flow of tokens is sufficiently sparse at the end of the workflow. Thus, the next improvement will be based on reducing underexploited resources of the *as-is* process.

### 5.2 Simulation of the *as-is* model with reduced resources

Table 5 summarizes the simulation results of the *as-is* model with reduced resources. In particular, simulation *S01* shows the starting point with no resource reduction at all, calculated in the previous section. Starting from simulation *S01* with the maximum of RS availability, i.e. 14, the total duration is not affected by the progressive reduction in the RS units up to 1, as shown by simulation *S02*. Here, the down-arrow at the right of *RS* means that the type of resource has been reduced with respect to the previous simulation, whereas the left-right-arrow in the *Variation* column means that no variation occurred in the total duration. From the queue time generated by simulation *S2* it is possible to discover that (i) the *locate container* and (ii) the truck *check out* activities are bottlenecks. Indeed, (i) all yard staff is involved for a relevant amount of the total duration; (ii) all check-out staff and the gate-out areas are busy for a lot of time. By reducing the number of trailers, as shown by simulations *S03-S07*, it can be observed that the minimum number of needed trailers is 13. Indeed, in simulations *S05-S07* in the face of a reduction of *TR*, there is a positive variation in the total duration. Moreover, by reducing the number of RTG, it can also be observed by simulations *S08-S11* that the best RTG number is 3. Finally, by reducing the PT resource in *S12-S14*, it results that the best number is 6. Indeed, from animation it can be observed that in the first phase the bottleneck is at the *locate container* task, and then varying RTG does not produce any significant variation. It is worth noting that to reduce the other machinery or the staff is not useful, since they are already fully used. As a result, Table 6 summarizes the resources and correspondent saved quantities in the simulated scenarios with the *as-is* model with reduced resources.

### 5.3 Simulations of the *to-be* model with full resources

The first simulation is made by using the resources in Table 4, and removing the gate out staff of the Truck area caused by the use of RFID. It can be observed by simulation *S15* in Table 7 that the total time duration is 7 days, 6 hours, and 50 minutes, which is lower than in the cases of the *as-is* model (7 days 15 hours and 53 minutes). This temporal duration will be used as a baseline for measuring progresses. Similarly to the approach adopted in the *as-is* model, the resource usage against time allows to choose the next resource to reduce, thus providing a *to-be* model with reduced resources.

### 5.4 Simulations of the *to-be* model with reduced resources

The first step is to reduce the RS resource usage to 1 unit (simulation *S16* in Table 7). Subsequently, the resource usage against time has shown that the number of TR can also be reduced to 13 units (simulation *S17*). Surprisingly, with respect to the *as-is* model, the number of RTG can be further reduced to 2 units (simulations *S18-S20*). The reason is that the *locate container* activity is sensibly faster, and then there is a larger queue on the *place container (accessible)* activity, which acts as a more powerful buffer. Furthermore, by reducing the number of PT, the resulting optimal value is 2 (simulations *S21-S23*), i.e., lower than in the *as-is* model. We can also sensibly reduce the Yard staff from 15 to 1 (simulations *S24,S25*) thanks to the faster *locate container* activity made by means of WSNs. Finally, since the truck gate out is very fast with RFID, we can reduce the number of gate out from 2 to 1. This also reduces the implementation costs, because only 1 RFID reader is needed, in place of 3.

### 5.5 Simulations of the *to-be* model with reduced time

In order to further reduce the total time duration, let us consider the highest bottleneck, where some resources

Table 5: Total durations of the *as-is* model with reduced resources (↓ reduction, ↑ increase, ↔ constant)

| Simulation | Type of resource | Availability | Total duration (*as-is*) | Variation |
|---|---|---|---|---|
| S01 | **RS** | **14** | **7D 15h 53m** | |
| S02 | RS ↓ | 1 | 7D 15h 53m | ↔ |
| S03 | TR ↓ | 27 | 7D 15h 53m | ↔ |
| S04 | **TR ↓** | **13** | **7D 15h 53m** | ↔ |
| S05 | TR ↓ | 12 | 7D 16h 07m | ↑ |
| S06 | TR ↓ | 11 | 7D 18h 06m | ↑ |
| S07 | TR ↓ | 10 | 7D 19h 35m | ↑ |
| S08 | RTG ↓ | 5 | 7D 15h 53m | ↔ |
| S09 | **RTG ↓** | **3** | **7D 15h 53m** | ↔ |
| S10 | RTG ↓ | 2 | 7D 15h 55m | ↑ |
| S11 | RTG ↓ | 1 | 7D 16h 10m | ↑ |
| S12 | PT ↓ | 9 | 7D 15h 53m | ↔ |
| S13 | **PT ↓** | **6** | **7D 15h 53m** | ↔ |
| S14 | PT ↓ | 5 | 7D 16h 14m | ↑ |

Table 6: Resources and quantity saved in the simulated scenarios

| Resource | Quantity |
|---|---|
| Portrainer (PT) | 10 → 6 |
| Rubber Tyred Gantry (RTG) on Yard | 10 → 3 |
| Reach Stacker (RS) | 14 → 1 |
| Trailer (TR) waterside, train/truck areas | 30 → 13 |

can be added. The queue time reveals that the bottleneck on the *truck area* is the most relevant. Here, we can increase up to 4 (simulations *S28-S34* in Table 8) the number of truck areas and RS available. This way, there is a significant reduction in the total time duration. A further study of the queue time reveals that the major queues are still located at the truck area. However, there is no significant improvement by increasing the size and the resources of the area (simulation *S35*).

As summarized in Table 9, relevant economies result by adopting RFIDs and WSNs. More specifically, considering Table 7: (i) the truck gate-out staff can be removed, due to results of Simulation *S15*; (ii) the number of RTG and PT can be reduced from the initial 10 (Table 4 ) to 5 and 2, respectively (Table 7, Simulation *S18* and *S22*) ; (iii) the number of RS and TR can be diminished from 14 to 4 and from 30 to 13, respectively (Table 7 Simulations *S34* and *S17*). The number of Yard staff can be reduced from 15 to 1, due to Simulations *S24* and *S25* of Table 7. Finally, the number of Truck gate out and Truck are modified from 3 to 1 and from 1 to 4, due to Simulations *S27* and *S30-S34*.

## 6 Conclusions and future work

In this paper, an approach for evaluating the impact of smart ICT technologies in the logistics has been discussed. The approach is based on workflow modeling and simulation. The main motivation comes from the intrinsic nature of smart ICT as enabler of synchronized interplay of different key factors operating at workflow level, whose integration logic is often impossible to be tackled and validated with analytic solutions. The effectiveness of the approach is founded on the BPMN language, which offers a comprehensive technology for modeling patterns, as well as standardized simulation engines. The executable character of BPMN also represents a bridge between the workflow design/simulation and its implementation on a service-oriented environment. The approach has been discussed and applied to a real-world analysis on a marine container terminal of the Port of Leghorn. For this purpose, a BPMN model of the terminal system has been provided, together with a comprehensive survey of smart ICT for harbor's logistics. Finally, the impact of the application of RFID and WSN has been measured by simulating the operation of the modeled workflow, revealing significant properties on the behavior of the actual system. This study has been carried out in the framework of a national research project founded by the Italian Ministry of the Universities and the Research (MIUR), and has been currently focused on the hardware ICT technologies for harbor's logistics. The adoption of the approach to software ICT in the same application context is considered a key investigation activity for future work.

Simulation results show that the adoption of the considered smart ICT allows achieving relevant potential savings: (i) 53.2 % of saving on processing time; (ii) 67.7 % of saving on machinery (PT, RG, RS); (iii)

Table 7: Total duration with the *to-be* model with resources reduction (↓ reduction, ↑ increase, ↔ constant)

| Simulation | Type of resource | Availability | Total duration | Variation |
|---|---|---|---|---|
| S15 | Truck gate out staff ↓ | 0 | 7D 06h 50m | ↓ |
| S16 | **RS ↓** | **1** | **7D 06h 50m** | ↔ |
| S17 | **TR ↓** | **13** | **7D 06h 50m** | ↔ |
| S18 | **RTG ↓** | **5** | **7D 06h 50m** | ↔ |
| S19 | RTG ↓ | 3 | 7D 06h 50m | ↑ |
| S20 | RTG ↓ | 2 | 7D 09h 13m | ↑ |
| S21 | PT ↓ | 6 | 7D 06h 50m | ↔ |
| S22 | **PT ↓** | **2** | **7D 06h 50m** | ↔ |
| S23 | PT ↓ | 1 | 7D 12h 55m | ↑ |
| S24 | Yard staff ↓ | 15 | 7D 06h 50m | ↔ |
| S25 | **Yard staff ↓** | **1** | **7D 06h 50m** | ↔ |
| S26 | Truck gate out ↓ | 2 | 7D 06h 50m | ↔ |
| S27 | **Truck gate out ↓** | **1** | **7D 06h 50m** | ↔ |

Table 8: Total duration with the *to-be* model with time reduction (↓ reduction, ↑ increase, ↔ constant)

| Simulation | Type of resource | Availability | Total duration | Variation |
|---|---|---|---|---|
| S28 | Truck area ↑, RS ↑ | 2, 1 | 4D 22h 31m | ↓ |
| S29 | **Truck area ↑, RS ↑** | **2, 2** | **4D 15h 12m** | ↓ |
| S30 | Truck area ↑, RS ↑ | 3, 2 | 3D 23h 38m | ↓ |
| S31 | Truck area ↑, RS ↑ | 3, 3 | 3D 22h 28m | ↓ |
| S32 | Truck area ↑, RS ↑ | 4, 2 | 3D 14h 35m | ↓ |
| S33 | Truck area ↑, RS ↑ | 4, 3 | 3D 14h 16m | ↓ |
| S34 | **Truck area ↑, RS ↑** | **4, 4** | **3D 14h 08m** | ↓ |
| S35 | Truck area ↑, RS ↑, Gate out ↑ | 4, 5, 2 | 3D 14h 07m | ↓ |

Table 9: Resources and quantity saved in the simulated scenarios

| Resource | Quantity |
|---|---|
| Truck gate out staff | 6 → 0 |
| Portrainer (PT) | 10 → 2 |
| Rubber Tyred Gantry (RTG) on Yard | 10 → 5 |
| Reach Stacker (RS) | 14 → 4 |
| Trailer (TR) waterside, train/truck areas | 30 → 13 |
| Yard Staff | 15 → 1 |
| Truck gate out | 3 → 1 |
| Truck area | 1 → 4 |

95.24 % of saving on staff involved at the Truck Gate Out and Yard. In terms of potential implementation hurdles: (i) the adoption of RFID at the Truck Gates achieved a patent license owned by a company participating to the project (www.itpass.eu), which started to effectively implement a number of installations on various gateways; (ii) the adoption of WSN is currently handled within the overall standardization of the Smart Container technology. Indeed, since maritime containers move around the world on different ports, it is more convenient to include other sensors in order to increase scalability, robustness, and interoperability.

In our analysis, we do not measure the performance variability because it is not significant with respect to the average in a peak scenario. In other scenarios, an indication of both the average and variability of the performance of the process might be provided. Hence, task execution times and process arrival rates can be defined by an average value plus some distribution information. BPMN simulators can incorporate statistical distributions to model non-deterministic decision flows. However, the use of broad spectrum statistical simulation introduces relevant complexity, increasing the chance of meaningless results for the business analyst [21]. An interesting approach is to adopt the interval-valued simulation in place of statistical-based simulation: it allows an easier understanding of the process by means of multi-valued representations [21]. For this purpose, future work will investigate the use of interval-valued simulation in the same context.

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