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A holistic approach to hospital material management process reengineering by means of the MRP algorithm

Coodinatore:
Ch.ma Prof. Alessandra Amendola

Candidato:
Ing. Debora Sarno
matr. 8883100014

Tutor:
Ch.mo Prof. Stefano Riemma

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Candidate:
Eng. Debora Sarno
id: 8883100014

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ABSTRACT (ITA.)

Il processo di gestione dei materiali in ambito ospedaliero (*Hospital Materials Management* - HMM) attiene al coordinamento delle attività di ordinazione dei materiali, mantenimento a giacenza, dispensazione e somministrazione ai pazienti. Tale processo è tipicamente gestito mediante tecniche di previsione della domanda (*look-back* o *stock control*), che "spingono" i materiali nelle strutture ospedaliere sulla base dei consumi storici e prediligono elevati livelli di scorta allo scopo di contrastare l'insorgenza di eventuali rotture di stock (processo AS IS).

Questa tesi analizza la possibilità di ridurre i livelli delle giacenze, assicurando al contempo elevati livelli di servizio assistenziale ai pazienti, proponendo un innovativo approccio olistico alla gestione della *supply chain* (*look-ahead* o *flow control*), in cui i dati clinici sono impiegati per definire le quantità degli ordini di materiali, attraverso un flusso informativo "tirato" dal letto del paziente al magazzino di farmacia ospedaliera (processo TO BE).

L'attività di ricerca è stata condotta in due fasi. Nella prima fase si è proceduto alla **modellazione del processo di HMM e alla valutazione della fattibilità tecnica della proposta**. Sulla base dei *requirements* clinici, è stata condotta un'approfondita analisi dei processi ospedalieri ed è stato proposto un nuovo processo – dalle prescrizioni mediche all'emissione degli ordini di farmacia – che consente la tracciabilità dei materiali e la condivisione delle informazioni, semplificando lo svolgimento delle attività da parte degli operatori. Tale processo è stato modellato attraverso la Business Process Model Notation. È stato poi sviluppato il prototipo di un nuovo sistema informativo, le cui usabilità e completezza dal punto di vista clinico sono state verificate attraverso interviste al personale ospedaliero.

La seconda fase della ricerca ha riguardato la **formalizzazione matematica delle politiche di gestione delle scorte dell'HMM e la valutazione della convenienza economica della proposta**. I processi AS IS e TO BE sono stati formalizzati: il primo segue una gestione a periodo di riordino con ripristino della scorta (*par level*), mentre il secondo adotta il metodo Materials Requirements Planning (MRP). Per entrambi i processi è stato sviluppato un modello di simulazione ad eventi discreti attraverso il software Arena Rockwell. È stato definito un indicatore di *performance* dell'HMM che prende in considerazione aspetti tangibili ed intangibili. I dati sulla domanda di farmaci ed i costi dell'HMM sono stati raccolti presso un'azienda ospedaliera universitaria di medie dimensioni. La progettazione degli esperimenti è stata condotta al fine di simulare diversi scenari operativi. All'analisi degli esperimenti è risultato che: i risparmi nell'adottare il modello proposto possono variare dal 2% al 7% del costo complessivo dell'HMM in funzione dello scenario operativo; maggiore è la variabilità della domanda, maggiore è la convenienza derivante dall'impiego del processo TO BE; i risparmi sono poco influenzati da variazioni dei costi di stockout esterni o quelli di emissione di ordini da parte della farmacia. Inoltre, i

risultati mostrano che, nel caso di processo AS IS, i manager potrebbero ottenere risparmi nel bilanciare in maniera oculata i costi di sottostima e sovrastima della domanda di materiali piuttosto che riempire i magazzini ospedalieri.

I risultati di questa tesi sono stati pubblicati in alcuni articoli scientifici (Iannone et al., 2011-2012-2013-2014 and Guida et al, 2012 a-b).

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Intendo esprimere la mia più profonda gratitudine al mio gruppo di ricerca per il continuo supporto e collaborazione, e in maniera speciale al mio tutor, il Prof. Stefano Riemma: la sua curiosità intellettuale, il suo entusiasmo e il pragmatismo che lo contraddistinguono mi hanno guidato nel processo di crescita sia professionale che personale.

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Salerno, 20 Febbraio 2014

ABSTRACT (ENG.)

The Hospital Materials Management (HMM) process deals with the coordination of all activities related to material ordering, holding, and administrating It is usually treated with a look-back approach (called AS IS process), by which materials are pushed into the hospital on the basis of demand forecasts, while high stock levels are distributed throughout the system to prevent stockouts.

In this thesis, the possibility of reducing stocks while assuring a high service level to patients is analysed, proposing a new holistic approach to the supply chain management (called TO BE process). Medical information are used to issue materials orders (look-ahead approach), in a pulled flow of information from bed to hospital pharmacy warehouses.

The research has been carried out in two steps. The first one deals with **the HMM modelling and the technical feasibility evaluation of the proposal**. Taking into account the clinical requirements, a deep analysis of hospital processes has been carried out and a streamlined process - from medical prescription to hospital pharmacy orders - has been proposed, which allows materials traceability and information sharing while simplifying the activities accomplishment by operators. The process has been modelled by using the Business Process Model Notation. A new Information System prototype has been implemented and verified in terms of "clinical" completeness and usability in hospital setting.

The second step copes with **the mathematical formalization of HMM inventory policies and the economic assessment of the proposal**. The AS IS and TO BE processes have been mathematically formalized. In particular, the AS IS process follows the Periodic Review Par Level servicing approach while the TO BE adopts the Materials Requirements Planning (MRP) method. A discrete event simulation model of both processes has been developed in Arena Rockwell software. A cost performance indicator of HMM has been defined taking into account tangible and intangible aspects. Drug demand data and HMM costs have been collected in a medium university hospital. The design of experiment has been developed to simulate different hospital working scenarios. It has been found that: cost savings can range, in dependence on the scenario, from 2% to 7%; the higher is the drug demand variability, the greater is the convenience of the proposal; the savings are slightly influenced by variations in external stockouts and pharmacy ordering costs. Moreover, the results show that, even in the traditional way to manage hospital inventory, managers should try to reach a balance between underage and overage material costs instead of keeping full warehouses.

Results from this thesis have been published in several research papers (Iannone et al., 2011-2012-2013-2014 and Guida et al, 2012 a-b).

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Special thanks are due to my family and friends, for their even increasing encouragements and love.

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CONTENTS

1. HMM IN LITERATURE AND PRACTICE

1.1 INTRODUCTION TO HMM

It is universally recognised that the exponential growth in healthcare expenditure is not only due to the increase in population estimated life and the rise in costs of healthcare services, but also to the considerable amount of wastes in healthcare processes (WHO, 2010), several studies suggesting being up to 30% (Kaplan et al., 2013).

The progressive reduction in public resources – and the subsequent need to restore budgets – makes governments responsible for finding solutions to achieve more operational efficiency. Healthcare facilities, indeed, are complex systems within which many intertwined and sometimes overlapping processes (clinical, logistics, administrative, etc.) contribute to the achievement of the final goal, that is the patient health. Then, hospital leaders have to take a more **holistic approach** to activities management, considering the impact that cost reductions might have on patient outcomes and the quality of care (Association for Healthcare Resource & Materials Management in Stempniak, 2013).

The central role of the **Operations Management** in the healthcare context is therefore emerging. For example, Langabeer (2008) considers healthcare system outcome as a balloon, inflated by operations management and exposed to deflationary pressure from the outside by variety of external factors (lack of information, managed care mechanism, etc.).

Duffy (2009) indicates the average hospital's expenditure on suppliers and on labour to manage supplies is approximately 25% of its total operating budget. Drug expenditure, indeed, is recognised to be a relevant factor in profit and loss account of healthcare systems (Jarrett, 1998), and the **hospital pharmacy management** has to find techniques to reduce materials inventory costs (drugs and medical devices) and maximise the cost-effective use of personnel and resources (Aptel and Pourjalali, 2001; Awaya et al., 2005; Oliveira and Pinto, 2005).

The **Hospital Materials Management (HMM)** process deals with the coordination of all activities related to material ordering, holding, and administrating along the hospital internal supply chain.

Exploring reasons of **inefficiency of the HMM** process, one distinction can be made between logistic and clinical viewpoints.

Awareness regarding the **logistics viewpoint** is getting widespread and many initiatives and studies concerning supply chain integration are undertaken (for example, supply outsourcing strategies (Nicholson et al., 2004; Lapierre and Ruitz, 2007).

The pharmaceutical supply chain, indeed, is relatively complex compared to others, particularly when considering the strict deadlines and sufficiency requirements. Different Information Technologies (ITs), such as product electronic identification by means of barcode or RFID, have been applied to speed the distribution and allow the traceability of the pharmaceuticals, and several studies have been carried out in order to answer to strategic issues, as facility location and vehicle routing problems (Hall, 2006). Anyway, the internal supply chain (vs. external, that is beyond the boundaries of an organization) "remains the sore spot or weak link" (Rivard-Royer et al., 2002) in the process integration and optimization, and this lack of systemic approach reflects on huge costs in materials management and low service quality delivered to patients (Landry and Philippe, 2004).

Regarding to the resource use optimization, the difficulties of transferring directly the manufacturing best practice to the hospital environment are evident (de Vries, 2010) even if several studies and pilot implementations have been carried out (for example in the field of Lean Production, Kim et al. 2006), where the main cause of failure has been addressed to the lack of goal clarity and performance measurement (Langabeer et al., 2009).

Inventory management has been recognised as the first sector of improvement intervention in healthcare (consider, for example, Rivard-Royer et al., 2002 and Little and Coughlan, 2008), and the main problem has been identified in the existence of hidden stocks in order to avoid stock-outs (de Vries, 2010), which seems to be more politically and experience-based driven rather than data-driven (Nicholson et al., 2004).

In the **clinical HMM perspective**, on the other hand, the huge amount of pharmacist's and nurse's consumed time for managerial activities has a negative impact on healthcare service performance **(**order entry, verification, clarification, and follow-up activities (Nold, 2011) for pharmacists, the same applies for nurses with prescription transcriptions, stock level control and administration recording). Moreover, clinical errors in drug prescription or administration are always possible depending on human factor and procedure issues, even if they are controllable adopting risk management policies.

In order to achieve a comprehensive image of HMM process able to lay the foundations of an efficient reengineering of supply chain, reducing healthcare costs without affecting the quality of care (Jarrett, 1998), it is fundamental to consider the previously presented logistical and clinical perspective as both sides of the same coin, in a holistic approach to the system.

In literature, there are many collateral references on how HMM works; in real cases analysed, information systems are usually built for fragmented applications and much information get lost or is not recorded when they flow throughout processes. This implies losses in traceability and increases in clinical risk, while inventory management techniques and logistics are hardly performed, causing high inventory costs.

In literature, there are many collateral references on how HMM works; in real cases analysed, Hospital Information System (HIS) are usually built for fragmented applications and much information gets lost or is not recorded when they flow throughout processes. This implies losses in traceability and increases in clinical risk, while inventory management techniques and logistics are hardly performed, causing high inventory costs.

1.2 HMM CONCEPTUAL FRAMEWORK

The proposal of this thesis cannot be introduced without before describing the conceptual framework in which it is grounded. The elements constituting this framework are described in this chapter and deepen in the rest of this thesis. In particular, they are (Figure 1):

- HMM information and physical flows;
- hospital factors;
- performance indicators;
- management parameters.

The *physical and information flow* diagram shows the existing relations among stakeholders and between drug supply and consumption in hospital systems. This system is characterised by variables related to the particular hospital (*hospital factors*) and can be ruled with many different inventory management policies. The adoption of these policies determines different performances (measured by means of *performance indicators*), which can lead to choose the best setting of the *management parameters* that can optimise the system (*optimisation process*).

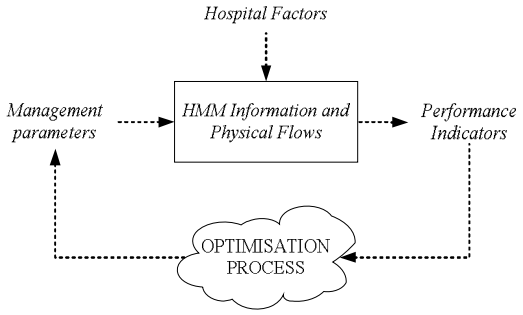

Figure 1 - HMM Conceptual framework scheme

1.2.1 INFORMATION AND PHYSICAL FLOWS AT A GLACE

On the basis of literature review and interviews to stakeholders of different hospitals (for dimension and type), basics about the information and physical flow related to HMM are shown (Figure 2). A detailed analysis is given in chapter 2. This analysis is focused on drugs, even if it is easily extendible to other hospital materials (i.e. medical devices).

The information flow that leads to drug requirements starts with a patient admission. During this phase, the **physician** states a diagnostic hypothesis, attributing (with or without a confirmation) a disease to the patient. Depending on resources availability (beds, laboratories capacity, etc.) and urgency, he also assigns a diagnostic and/or therapeutic pathway to the patient. The hospitalisation in a ward can be immediate or delayed according to a queue list (for Inpatient access, Day Hospital, Day Surgery, etc.); in the case a medical prescription (a part of the Patient Medical Record - PMR) is made, the patient needs for medicines to be administered during the hospitalisation (by nurses) or at home (in this case, depending on drug typology, drugs are dispensed by the hospital – outside dispensing – or taken from a community pharmacy). Each physical flow corresponds to an information flow that allows

medicine traceability (type of drug, expiry date, lot number, etc.), ending with the information storing in PMRs.

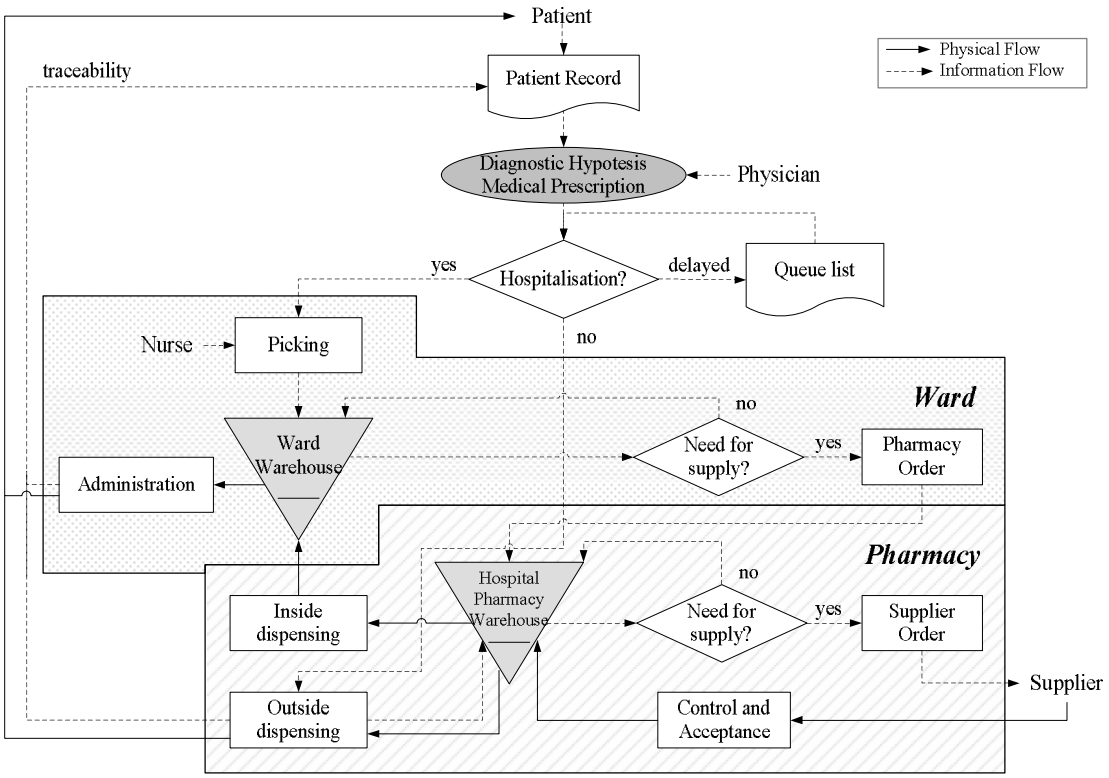

Figure 2 - Main drug information and physical flows in HMM process

At the **medical unit** level, picking and administration of drugs are performed, while orders to pharmacy are issued if needed. In medical units, indeed, there is one of the typical point of distribution of the HMM.

The choice about the *number and location of echelons* is mainly due to clinical and managerial reasons. From a clinical point of view, the usefulness of having centralised patient-oriented pharmacy services to deliver professional services to patients (Carroll and Gagnon, 1984) has been recognised. From a managerial perspective, many authors state the possibility to reduce logistics costs using a satellite pharmacy systems (Poley et al., 2004); numerous studies, finally, suggested the benefits of having central inventory control – rather than allowing each department or region to deal with suppliers individually (O'Hagan, 1995 cited in Jarrett, 2006) – particularly in terms of drug waste reduction (Poley et al., 2004). In addition to a centralised point of distribution, however, it is necessary to have a decentralised drug management system to allow nurses to quickly reach stocks in the proximity of places (beds) where services (administration) are delivered to patients. For these reasons, the inventory system is characterised by centralised and decentralised stores (de Vries, 2010), following a *hub-and-spoke* model), with two points of distribution (warehouses):

- Medical unit warehouse (*spoke*), which delivers materials to the patients of the facility;
- Hospital pharmacy warehouse (*hub*), which is in charge of managing items for inside (to medical unit) and outside dispense (to patients).

At the **hospital pharmacy** level, in particular, orders to be released to suppliers are issued, followed by Control and Acceptance and stocking activities when materials arrive.

1.2.2 HOSPITAL FACTORS

Every healthcare system has its catchment area, dimension, capacity to deliver services, layout, etc., representing boundaries for the optimization problem. The effect of hospital factors on hospital capacity resource decisions has been investigated in Li and Benton (2003). A classification of independent and related dependent variables is proposed in Table 1.

Stochasticity and uncertainty of the in/out patients number and the type of diseases are well known in literature (Iannone et al., 2007). They influence the amount and typology of drugs required together with the drug prescription variability, on equal diseases, due to different clinical condition of patients and professional autonomy of physicians.

Other independent variables are: *space restriction in warehouses* (that influences the maximum quantity of storable items); *drug shelf life* (when short, it needs particular attention in the definition of safety stocks – to minimise deterioration costs – and materials handling – to avoid moving expired medicines) and *lay-out* (it affects, together with the type of internal means of transport, the time needed to reach wards from hospital pharmacy). Layout is considered as an immutable condition because it is generally defined, in the design phase, on the basis of other parameters, such as position of operating rooms, laboratories, etc.

Table 1 - Variables describing hospital environment (hospital factors)

Independent variables	Example of Dependent Variables
Number of patients per disease **Drug prescription variability per disease**	Drug requirements variability (quantity and type)
Warehouses capacity storage	Maximum quantity of drugs stored
Drug Shelf life	Drug wastes
Hospital lay-out	Transportation time

1.2.3 PERFORMANCE INDICATORS

Performance measurement systems have had great success in healthcare sector, for example with the use of the balanced scorecard (Zelman et al., 2003). They are components of the conceptual framework because they permit to evaluate performances of management policies which are implemented for the inventory system optimisation. The indicators of Table 2 may be suitably aggregated (using a hierarchical architecture) and weighted on the basis of the importance attributed by hospital management in order to choose the most performing among different scenarios. Moreover, they

may be used to formulate boundaries or the objective function to the optimisation problem. Many insights about the computation and the usage of the performance measures are given in chapter 4.

With the premise that the presented conceptual framework considers only the supply and distribution (logistical) function aspects but not the clinical pharmacy ones, it is well worth to note that, like every service company, also hospital success is related to the *service level* offered to costumers. Quality of medical services, indeed, is influenced by the availability of medicines for patients therapies (Yurtkuran and Emel, 2008). This availability is a critical aspect of the framework because inventory management optimisation oriented to a cost reduction may lead to an overall decrease in inventory levels. Finding a proper balance between quality metrics and costs is one of the main challenges for logistics (de Vries, 2010). Anyway, a distinction between critical and non-critical (for which little delay can be allowed) items can be a starting point to set desired service levels (Nicholson et al., 2004 suggested considering respectively 99% and 90%). Service level can be viewed as dependent on the efficient management of the two supply phases, i.e. from pharmacy to ward (service level to patient) and from external suppliers to pharmacy (service level to ward). While in the first case understocking can be solved rapidly in the opening hours of pharmacy, in the second case stockout of pharmacy needs a urgent order for suppliers, which implies consuming time and capital.

Another indicator, traditionally used to assess *inventory* management techniques, is inventory turnover. Economically speaking, it can be seen as the measure of efficiency related to the space occupied by an item. Then, there is the combination of inventory levels and incidence of expired quantities. From both cost and quantity points of view, it is the measure of the influence of storage on costs.

Finally, the *logistic cost* related to management policies in terms of personnel and physical resources (inventory costs, transportation resources, etc.) should be considered.

Table 2 - Performance indicators (logistic viewpoint)

Indicator	Method of evaluation
Service level to patient **Service level to ward**	Ratio of request on supply
Inventory turnover **Inventory level** **Percentage of expired drugs**	Costs and quantity
Logistics cost	Total drug management cost

1.2.4 MANAGEMENT PARAMETERS

Summarizing, the conceptual framework describes how physical and information flows of drugs are interrelated and what the characteristics of the environment are. The performance indicators allow to find, in such an environment, the value of the management parameters that are the solution to the drug management optimisation issue. Robustness and reliability of this solution depend on the method used to identify it.

First of all, a distinction has to be made between **push and pull management policies**, often inconsistent among different researchers (Bonney et al., 1999). For example, Material Requirements Planning (MRP) is frequently described as a push system while kanban operated Just In Time (JIT)

system is usually considered as a pull one. The main misunderstanding seems to be related to the type of flow is pulled or pushed:

- speaking about the *physical flow direction*, that is the way the jobs/activities are activated in the production system (Lee et al., 1989) the distinction is between:
  - push systems, when the jobs are queued at the firs required process,
  - pull systems, when the activities are triggered by depleted output kanban stock;
- to the contrary, considering the *information flow direction* or, better, the source of information, Goddard and Brooks (1984) state that:
  - push means to take action in anticipation of a need,
  - pull means to take action on request.

Taking into account the information aspect, De Toni et al. (1988) consider the following equivalence, coming from Da Villa (1985):

- push = look-back;
- pull = look-ahead.

Moreover, De Toni et al. (1988) identify, in the inventory management systems, that:

- push means to take action in anticipation of a need, launching an order based on previous consumption (for example, the re-order point);
- pull means to take action on request, launching an order on the basis on requirements (for instance, the MRP).

The two fields of intervention of the management parameters in the HMM, which need to be globally optimised, are medical unit supplies and pharmacy supplies. Here look-back, look-ahead or mixed (for example, Consignment Stock (CS)) approaches can be used. All these approaches can be implemented inside the same healthcare system depending on the item typology (ordering cost, inventory cost, shelf life, demand mean and deviation, etc.). Cluster analysis has to be performed in order to group items that can be similarly managed. For example, galenics may have little or no stock, their components may be managed differently (bill of materials can simplify evaluations).

A first attempt to manage materials on the basis of available patient information (*look-ahead approach*) was made by O'Neill et al. (2001), describing a MRP inventory system to convert data about surgical schedules and bills of materials into actions for surgical linen management in a hospital. In this study, the absence of an automated tracking system did not allow the stock availability to be considered when running of the MRP algorithm. Another application was on chemotherapy drugs (Masselink et al., 2012), with the objective of reducing the patient waiting time slightly increasing the pharmacy costs.

This approach enhances the role of the Patient-Centred Management (PCM), which emphasizes "the selection and coordination of services from the patient's perspective and considers all of the patient's circumstances" (Sweeney et al., 2007). In the field of service, the concept has been translated into case management, "which includes the identification and coordination of plan benefits and ancillary services" (Sweeney et al., 2007).

On the other hand, many studies have been carried out (see, for example, Nicholson et al., 2004) on hospital inventory management policies based on past consumption data *(look-back approach*), without taking into account the HIS data.

In particular, the medical unit replenishment system implies a large number of items managed in a small quantity. Mainly because of the widespread absence of keeping a perpetual inventory control, medical units tend to reorder the required materials at fixed **Reorder** (or review) **Periods** (*RP*) (Little and Coughlan, 2008; Kelle et al., 2012; Yurtkuran and Emel, 2008; Nicholson et al., 2004) (another replenishment method is described by Augusto and Xie (2009), whereby pharmacy technicians are in charge of replenishing the medical unit warehouse by refilling closets, thus freeing the medical unit nurses from inventory management). Evidently, the *RP* has to be set on the basis of the demand variability and the cost of ordering, keeping, and delivering materials. One way to define it is as the **Period-Order Quantity** (POQ) (Arnold, 1998).

Three main policies characterised by *RP*, well known look-back approaches of inventory management literature, are adopted in *medical units*:

– the **Reorder Cycle**, whereby orders are placed only if stocks are below a predetermined quantity (called re-order point);

– the **Periodic Review Par Level** (or order up to level), whereby orders are placed each *RP* as the difference between a predetermined maximum quantity to keep in stock (par level, *S*) and the available inventory on hand (*AV*) (Nicholson et al., 2004);

– the **Min-Max Par Level**, a mixture of the first two, in which maximum (Max-level) and minimum (Min-level) quantities to keep are fixed in advance, orders are placed only if the Min-level is reached, while the quantity ordered is the difference between the Max-level and the inventory on hand (an example is given by Kelle et al. (2012); Dellaert and van de Poel (1996) proposed an extension introducing a "can reorder level").

As explained by Toomey (2000), factors determining these fixed quantities are demand forecasts, internal replenishment lead time (*TT*), review period (*RP*), and safety stock (*SS*), which takes into account the uncertainty of drug demand (Kelle et al., 2012). The choice among these policies depends on the values of the parameters, set according to the value of the inventory costs involved.

At the *hospital pharmacy* (the other point of distribution) a continuous control of the inventory level is easy to perform through HIS features, widespread for accountability and administration reasons. In this case, while many authors and practitioners usually adopt the Reorder Period policy, the **Reorder Level** policy can also be implemented (it means to release orders when the inventory on hand reaches a minimum value).

In Table 3 management parameters for both the distribution points are listed. Along with supplying techniques, a topic of discussion can be the effect on global performances of safety stocks centralisation, substituting them in wards with an efficient mechanism of "real-time" replenishment from the pharmacy. Theoretically, this can allow a balance among consumption forecast errors of wards – in similar demand conditions for each ward, the centralized stock is calculated using Maister's "Square Root Law" (1976). In this way, wards can obtain advantages in terms of releasing spaces occupied by stock and reducing management difficulties related to the control of a high number of items. The concept can be extended from one hospital to others belonging to the same region, shaping a constellation of hospital systems, with a central warehouse and a number of decentralized virtual warehouses (hospital pharmacy) able to be, depending on the real consumption, also mutual safety buffers.

Safety stocks (defined for drug clusters) and *logistics resources* (in terms of personnel and physical resources) location and sizing depend, inter alia, on frequency and quantity of transports from pharmacy to wards, quantity to handle in the central warehouse due to arrivals, characteristics of material handling equipment. All these decisions impact on the resource costs.

The last parameters are *shifts scheduling and opening hours of pharmacy*, which can influence internal transport frequency. For example, Yurtkuran and Emel (2008) describe a pharmacy unit that operates on a daily basis; during the night shift, pharmacy staff begins to prepare the medication packages.

Table 3 - Management Parameters

Optimisation fields	Management Parameters
Medical unit policies	Look-back / look-ahead policies Safety stock level
Pharmacy management policies	Look-back / look-ahead policies Safety stock level Number and type of logistics resources Pharmacy shifts and opening hours

1.3 HMM SUPPLY CHAIN INTEGRATION

The **integration of supply chain** (already mentioned at the end of paragraph 1.1) has been topic of discussion of many researchers. According to the definition of Kaufman (1997), it is the way to remove communication barriers and eliminate redundancies through coordinating, monitoring and controlling processes.

The main elements of such an integration are the management of (Handfield and Nichols, 1999):

- Information and financial flows;
- Product and material flows;
- Relationship between supply chain actors.

It is clear that, whether the process for integration is, the requirement for it is inherently strategic and represents a potential source of competitive advantage for all actors involved, then a holistic and systemic approach is needed (Power, 2005).

Reliable production and delivery orders (based on requirements), simplified core processes, streamlined physical and information flows, and, overall, limitations to the bullwhip effect information distortion have been recognised as some of the obtainable benefits (Lee et al., 1997).

In the field of **HMM**, a way to integrate the clinical and logistic perspectives has been recognised, during the past decades, in the information-sharing among supply chain actors, which has shown significant economic advantages in the reduction of the total systems costs (Liao and Chang, 2011). An example of HIS oriented to pharmaceutical supply chain integration has been presented by Kim (2005), in which is stated a decrease in total inventory of about 30%.

Data sharing demands integrated information systems (Kaplan et al., 2013), together with ad hoc algorithms able to handle plain data to obtain synthetic, ready-to-use information in order to make decisions at each ring of the supply chain.

Under the objective of hospital supply chain integration, some studies have concentrated on quantifying the **advantages of an electronic medication ordering, dispensing, and administrating process** compared with a manual one.

For example, Wong et al. (2003), in considering the adoption of Computer Physician Order Entry (CPOE) system in a hospital, built a simulation model to evaluate the potential reduction in turnaround time and pharmacokinetic failures of drug administration due to late deliveries. The results demonstrate drastic improvements to the manual management of medical prescriptions in terms of the service level to patients—but no evaluation was conducted on the optimisation of the inventory management process.

Another example of the benefits of HIS in materials management is from Yurtkuran and Emel (2008), who studied by means of discrete event simulation the same objective to minimise patient drug delivery turnaround time using the available resources.

1.4 PROPOSAL OF THIS STUDY

This thesis aims at demonstrating the convenience of adopting a holistic approach to HMM by using medical information to issue orders (look-ahead approach, Bonney et al., 1999), enhancing the role of the patient-centred service management (Sweeney et al., 2007). In particular, an innovative materials management technique for the healthcare sector is proposed, able to combines the advantages of CPOEs with those of an agile inventory control HIS. By means of the MRP method, the idea is to exploit the data in the medical prescription not only for clinical purposes, but also to pull medical units replenishments and then pharmacy orders with suppliers, in order to reduce and centralise stocks, while assuring a high service level to patients.

As already mentioned, the attention is focused on drugs, even if the method is extendible, with a few variations, to all hospital materials.

In order to demonstrate the proposal suitability, two different processes are compared:

- the first one (**"AS IS" process, look-back**) deals with the "traditional way to manage hospital materials", that is, a usually long reorder period with a quantity forecasted on the basis of past consumption (Periodic Review Par Level), while keeping distributed safety stocks (among ward warehouses) to prevent stockout problems;
- the second (**"TO BE" process, look-ahead**) involves a more frequent delivery schedule based on patient needs as derived from medical prescriptions, exploiting the advantages of the stock centralization.

The technical feasibility and completeness from the clinical and logistical point on view of the TO BE process is the objective of the first part of this thesis, while the two processes are illustrated, represented, simulated, and measured in terms of performances by means of an inventory cost function, which takes into account the overall cost sustained for the HMM by a hospital in the second part of it.

The structure of this thesis is represented in the IDEF-0 diagram of **Figure 4** (whose syntax is reported in Figure 3).

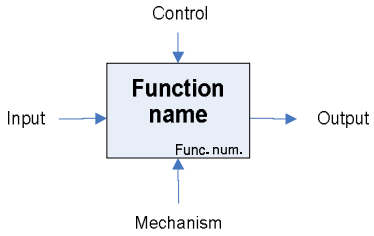

Figure 3 - IDEF-0 syntax. The meaning of the input parameters is different in dependence with the collocation of the arrows on the box.

On the basis of literature review and the interviews to the stakeholders of the HMM process, paragraph 2.2 deals with the description of all the activities of the HMM (deepening the information and material flow description given in paragraph 1.1.1). By means of a holistic approach to the HMM - then taking into account also the clinical requirements, mainly the need for traceability and clinical risk

reduction in administrations - a streamlined business process model of the HMM is proposed, which allows to adopt the AS IS and TO BE processes while simplifying the activities accomplishment by operators (paragraph 2.3). The process, represented using the BPMN and executed with Bizagi Suite, is tested and verified in terms of "clinical" completeness and usability in hospital setting.

Chapter 3 copes with the mathematical formalization of the AS IS and TO BE processes for HMM, defining the related inventory control algorithms that embody the management parameters chosen for this comparative study.

In chapter 4, a HMM process cost function is defined, based on tangible and intangible costs to be sustained by a hospital in adopting a certain inventory policy for a period of time. The cost comparison between the two processes (percentage of cost savings) is the performance indicator of this thesis.

Chapter 5 is about the design of the simulation models that reproduce the behaviour of the AS IS and TO BE processes over the time.

The demand data (drug consumption over the time), the value of the cost parameters and other HMM attributes and variables are collected from a hospital database, and elaborated in order to be generalised in the chapter 6.

Finally, chapter 7 shows the design of experiments and makes the comparisons among different HMM working scenarios by means of the simulations, drawing the demonstration of the thesis.

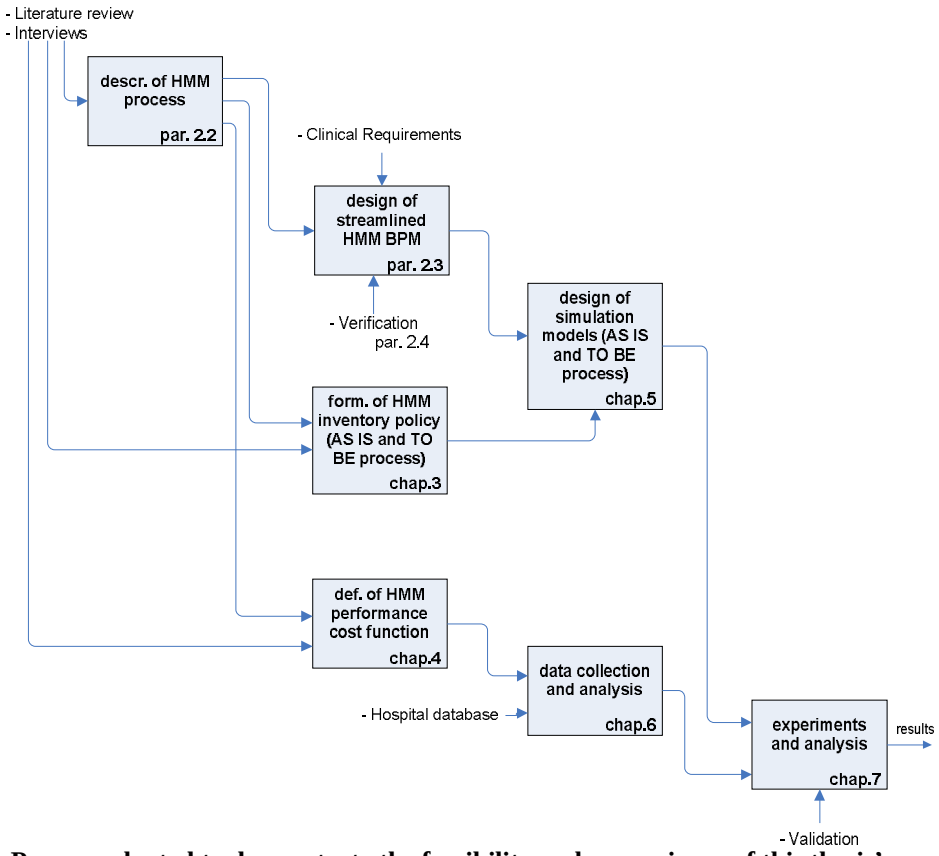

Figure 4 - Process adopted to demonstrate the feasibility and convenience of this thesis' proposal.

2. MODELING THE HMM PROCESS

The first step to conduct the hospital pharmacy "micro-world" reengineering process towards optimization is to identify the behaviour of this system, such as what to manage in terms of materials, actors and processes, taking into account information and legal constraints. In the remainder of this chapter, a detailed description of actors, materials and processes is carried out, followed by a thorough explanation of all activities involved in the HMM. Moreover, a process representation is given, in order to present the dependencies among activities, trace the detailed information and physical flows and, finally, evaluate the feasibility of a prototype of HIS able to operate with different inventory policy while assuring clinical risk reduction.

2.1 PROCESS ELEMENTS

Actors

First of all, it is fundamental to profile all the actors that take part to materials management processes, distinguishing by the level at which they participate to them, that is:

- Medical Unit actors: together with patient needing for care, physician (who delivers the care), nurse (who dispenses the care) and nurse manger (who supervisions the dispense of care) are basically the other actors involved at the medical unit materials management stage;
- Pharmacy Unit actors: international health care standards require a central pharmacy unit in hospitals that maintains and provides the inpatient pharmacy needs (Joint Commission International, 2011). The pharmacy unit is usually composed by hospital pharmacists, storekeepers and transporters;
- Other organizational functions: the Medical Director, the Superintendence and Treasure's Office, the Accounting Office take part to the process.

Materials

Management of materials in healthcare involves two kinds of items' clusters, that is drugs (or medicines) and medical devices, subjected to different regulations harmonized by countries according to international guidelines.

The properties of medicines in a HIS may be mandatory or optional depending on the contextual workflow (IHE, 2010). A fundamental "identifier" is the ATC, Anatomic – Therapeutic – Chemical classification, internationally accepted and maintained by the World Health Organization. In addition to commercial drugs, drug administrations can also refer to galenics, such as personalized medicines prepared as a "mixture" of commercialized products at the bedside, in hospital pharmacy or in another defined medical unit. In parallel, medical devices can be required as surgical kit and apparatus compounded by many of them, that can be managed as single items by pharmacists or directly supplied as a pack.

The item list (in other words, the set of medicines or medical devices that can be administered/dispensed or implanted to patient in a healthcare system) changes from hospital to hospital, depending not only on healthcare services managed, but also on physician's expertise and preferences, and following pharmaco-economics principles.

Processes

Irani et al. (2002) sustain that businesses should not be analysed in terms of the functions in which they can be decomposed to or in terms of the output they produce, but taking into account the key processes they perform.

The hospital medication workflow is triggered by patient needing drugs and medical devices. In this perspective the Technical Framework, developed for the pharmacy domain by the initiative Integrating the Healthcare Enterprise (IHE), was born to stimulate the integration of healthcare information systems operating with different standards (such as DICOM, HL7, etc.).

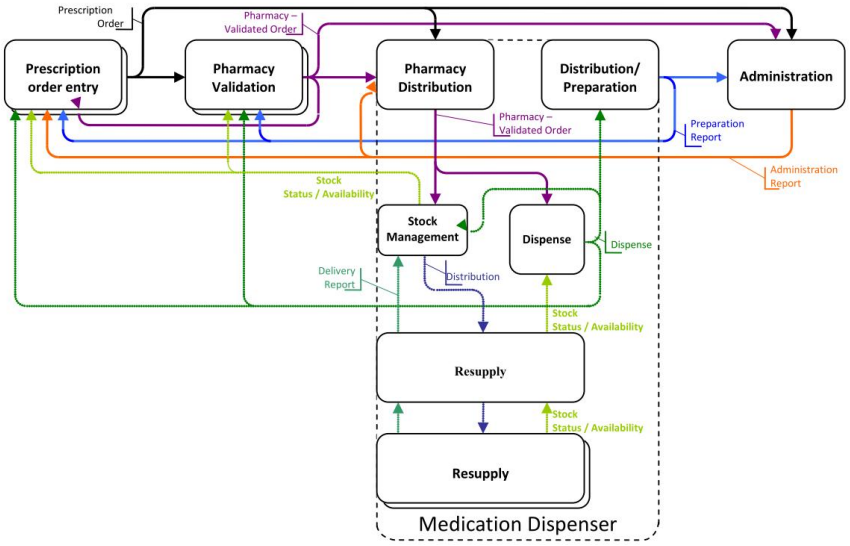

Figure 5 - Pharmacy Interoperability Model. IHE Pharmacy Technical Framework Supplement – Hospital Medication Workflow (HMW), 2012.

In the proposed pharmacy interoperability model (IHE, 2012, see Figure 5), the care path (clinical perspective) is orthogonally combined with the supply path (logistical perspective) in the phase of

distribution but - as explicitly stated - supply chain of ordering/delivering medication and stock management are out of IHE scope.

According to the Irani et al. (2002) opinion, in this thesis it is adopted and refined the IHE pharmacy interoperability model as an "information track" to classify and describe all the elements depending on logistics decisions in the hospital medication workflow. The model is, then, readapted to define in more detail different care paths, distinguishing among the type of medicine or medical device employed; moreover, the management area is explored, depicting all the processes involved.

Analysing some hospital cases, literature review and international guidelines and considering the clinical/logistical perspective, the HMM is defined as to be composed by the main following sub-processes, respectively Patient Management Process (a), Medical Unit Inventory Management (b) and Hospital Pharmacy Inventory Management (c). The first one deals with the phases of medical prescription (with the relative pharmacist advice) and administration; the second is about the materials management at the medical unit level, that is handling, stock level check and re-ordination; the third deals with the Hospital Pharmacy inventory management, that is the owner of the internal delivery supply chain. The processes are fully described, together with their activities and connections (reported in Figure 6) in the next sections:

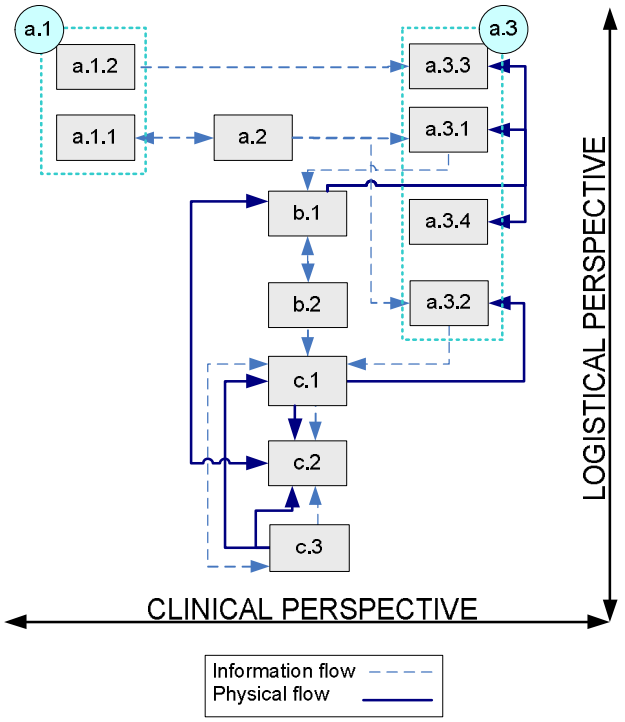

Figure 6 - Process Framework of Materials Management in a Hospital

a) Patient management
    a.1) Prescription
        a.1.1) Drug Prescription or surgical intervention plan
        a.1.2) Exam prescription
    a.2) Pharmacy prescription validation
    a.3) Materials delivery to patient
        a.3.1) Preparation, administration or implant (inside dispense)
        a.3.2) Dispense to patient (outside dispense)
        a.3.3) Exam accomplishment
        a.3.4) Low cost and generic goods usage

b) Medical unit inventory management
    b.1) Medical unit stock management and re-ordination
    b.2) Pharmacy order assessment

c) Centralized inventory management
    c.1) Pharmacy stock management, order disposition and supplying activities
    c.2) Internal distribution
    c.3) Materials Admission and Quality control and Payment

2.2 PROCESSES DESCRIPTION

a) Patient management process

The first process is the patient management, since the need for care (and then the hospital medication workflow) triggers materials requirements.

When a patient admission occurs (in emergency or outpatient department), a physician states a diagnostic hypothesis, attributing (with or without a confirmation) one or more diseases to the patient.

Depending on resources availability (beds, laboratories capacity, etc.) and urgency, (s)he also assigns a diagnostic and/or therapeutic pathway to be followed in the hospital or at home.

The hospitalisation in a medical unit can be immediate or delayed according to a queue list (for Inpatient access, Day Hospital, Day Surgery, etc.); hospitalisation or not, a patient anamnesis and a previous and current therapies recording are always required to know if they are compatibles with the pathway to perform.

The patient management sub-process is composed by 3 activities:

a.1) Prescription

a.2) Pharmacy prescription validation

a.3) Materials delivery to patient

a.1) Prescription

A prescription is the outcome of a clinical decision, is issued by a physician for one patient and may be the input of pharmaceutical validation and dispense. Sometimes, there can be a medication dispensed or administered outside the context of a prescription (for example, in case of urgency in the Emergency Department). They are considered as attached to an order session, which can be associated with a prescription.

Two kinds of prescriptions are related to materials consumption:

a.1.1) Drug Prescription or surgical intervention plan

a.1.2) Exam prescription

a.1.1) Drug Prescription or surgical intervention plan

In addition to pharmaceutical validation, a drug prescription is also the input of nurses' instructions to administer the drug for hospitalized patients or, in case of outside dispense, for patient home care. Variations in the content of prescriptions can occur, being dependent on country regulation, responsibilities and standard developed but the medical prescription data set is mainly compounded, among others, by:

- date,
- actors Id (Patient and Physician),
- reason for prescribing,
- number of refills (for dispense),
- active substance,
- brand,
- dosage,
- frequency of intake/administration time(s),
- quantity.

Alerts about prescribing restrictions and potential Intolerance, Contra-indication and Allergies (ICA) should be easily consulted.

The active substance(s), as stated before, is usually a key element because it permit evaluations about pharmaco-economics and availability (for example, to distribute the cheapest brand name stored in satellite or central pharmacy or to prescribe what is stored in the local warehouse), but clinical considerations can imply a more rigid selection. The active substance(s), together with the pharmaceutical form, may allow to entry the medicine database and look for the most frequent disease for which it is adopted, ICA, maximum dosage per administration, frequency and times of standard intake depending on patient age, gender or weight. Physicians and pharmacists have to take into account all these data and combine them with patient characteristics to assure the best choice and to prevent mistakes.

In case of surgical intervention, some materials have to be explicitly prescribed (for example, an orthopaedic prosthesis and its size or surgical kit).

a.1.2) Exam prescription

The physician can prescribes some diagnostic examinations to patients, such as laboratory exams (e.g. blood, RX) or other activities that require materials.

a.2) Pharmacy Prescription Validation

After a prescription act, prescription information may be made available to pharmacists as a pharmacy validation can be delivered. It can be advisable but not mandatory, so that many organizations tend to jump this step. This implies no double reviews and, hence, no possibility of medical error reduction (IHE, 2012).

A detected problem can be a supply issue (suspended medication, out-of-stock., etc.), a legal issue (medication recalled or not allowed under certain conditions), or a medical issue (redundancy, interaction, contra-indication, etc. as an ICA).

a.3) Materials delivery to patient

The diagnostic or therapeutic pathway involve materials requirements that can be indirectly related to patient because it is not convenient to address their usage to a specified activity performed (“Low cost and generic goods usage”) or directly related to it, as the case of “drug prescription or surgical intervention plan”. Exam prescription triggering materials usage can fall in both of these classes. In more detail, four events can imply materials delivery to patient which are described in the following paragraphs.

a.3.1) Preparation, administration or implant

When it’s time to administer a medication (depending on the prescription), a message is sent to the nurse in charge and a preparation may take place. However, many hospitals do not have such an information tool or do not have an information system at all, so nurses are in charge of transcribing prescriptions on provided diaries, checking them to know when to administer. This implies risk of errors in transcription and administration execution (right time, person, etc.).

Preparation is the phase in which nurses take drugs from the stock and prepare them to be administered. Some hospitals manage patient unit doses packed by robots or nurses at hospital pharmacy

or medical unit warehouse, while others manage the most part of materials in the original package up to the patient bed.

Galenics (that are, as said before, extemporaneous composition of commercial drugs), are a special case because the preparation, depending on type and organization, may involve pharmacists and requires an appropriate recording of all actions and items used (information about drug id, lot number, quantity used, etc.) for traceability reasons. While an intravenous injection of cortisone diluted in 0.9% sodium chloride solution can be prepared at patient bed, oncological galenics are usually made in a dedicated medical unit and later transported. Labelling with patient and galenic Id is the right way to reduce clinical risk while assuring traceability.

According to IHE suggestions, the assignment of a medication unit to a specific patient means a "dispense"; a galenics dispense can be considered as the instant in which labelling occurs.

All the medication are usually collected in a trolley or an already filled trolley is used, with a number of drawers containing the most frequently used drugs and other drawers destined to specific patients' needs (this is the case described in Augusto and Xie, 2009). Moreover, some medical devices such as syringes, glovers, roller bandages etc. have to be added to the trolley.

Updated inventory information is crucial, because previous checks should be done in order to assure that each patient has his own medication available at the administration time. Together with quantity availability at the due date, expiration date control has to be made and the package with the closest expiration date should be used.

Administration follows. Nurse goes to patient bed and does the 7 "rights" checks (right patient, right drug, right dose, right route, right time, with the right information and documentation), administers the medication and records all the connected information, according to traceability and medical risk reduction objectives. Dispense (if done) or administration coincide with the recording of the consumption of medicine used from medical unit virtual stock, so that warehouse management system is always up to date.

In case of surgical intervention, medical devices, kits or apparatus have to be used. After it, information about these materials has to be recorded as indicated before for drug administered, in order to satisfy clinical, traceability and inventory management requirements.

a.3.2) Dispense to patient

In some healthcare organizations, hospital pharmacy can be charged also of materials dispensing for home care (from outpatient departments or for discharged patient). These materials are almost overlapping to that used by inpatients but, instead of the administration time, a dispensing period is fixed by the physician.

The outside dispense can be liken to medical unit dispense, because prescription is checked, material is taken from warehouse, recorded and given to the patient.

a.3.3) Exam accomplishment

Differently from "low cost and generic goods usage" explained later, the consumption of some medical devices can be directly attributable to one patient (a bill of materials may exist). Inventory levels are usually updated when examination is performed (back-flushing method).

a.3.4) Low cost and generic goods usage

This activity regards with medical devices utilisation not planned nor directly attributable to one patient care. This distinction is trivial because it is always possible to record each activity performed for one patient and its requirements in terms of materials, but most of the accountability/information systems does not elaborate on this function. For this reason, medical devices belonging to this process

are considered “low cost and generic goods” for hospitals (examples are glovers to handle test-tube or elastic bandages).

Considerations about “Materials delivery to patient (a.3)”

Materials traceability, from their admission to hospital till their consumption by a patient, is extremely important for clinical reasons (all information about medical processes should be recorded and available for checks), accountability reasons (to monitor expenditure and its attributions) but also for managerial motivations. A prescription, i.e., the step before materials delivery to the patient in the most part of cases, can be used in scheduling replenishments or orders on the basis of patient needs. Materials requirements programmability can have an enormous impact on inventory management techniques, but it has not been developed because of the lack of managerial culture in the healthcare environment, together with the difficulties in implementing accurate and usable HIS.

Materials requirements programmability as a function of materials consumption traceability is illustrated in Figure 7.

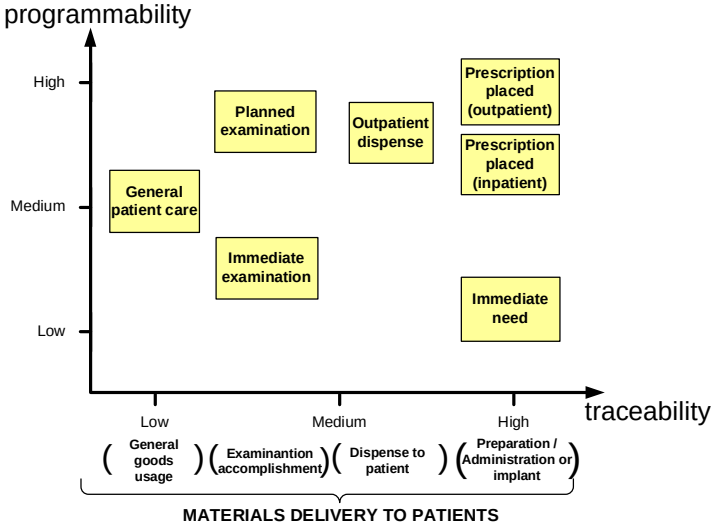

Figure 7 - Programmability of hospital materials requirements as a function of traceability of consumption

In particular, events involving materials consumption are ranked from the least traceable to the most (the independent variable) as follows: low cost and generic goods usage (by definition untraceable), materials employed for examinations (traceable if the information system provides this feature), materials dispense (not traceable in terms of administration because it is performed at the patient’s home) and materials administration/implant (traceable until the end of the process, because the usage of an identified material, with its characteristics, expiration date, batch number, etc., can be fully recorded). The other axis shows the materials requirements programmability, which goes from the possibility only to forecast the consumption of some materials in a period of time, to the highest probability that a

particular consumption is going to take place in a specific moment. The diagram presents the activities concerning patient care.

Given that "a plan must cover a period at least equal to the time required to accomplish it" (Fogarty et al., 1991), the "can-program interval" (the time between prescription and administration/usage) is a fundamental data related to prescriptions because it is the maximum time available for medical unit replenishments or supply activities.

On the other hand, generic goods usage is predictable with low uncertainty, since, due to the big volumes, it is easily forecasted by time series techniques. Almost the same applies for examinations demand. Outpatient dispense is in the middle of this plane because it concerns a prescription kept by the pharmacy for a given period while the consignment (or administration) time is not known.

b) Medical unit inventory management process

In what follows, the description of the two activities constituting the Medical Unit Inventory management process is reported.

b.1) Medical unit stock management and re-ordination

Medical and surgical supplies close to the point of delivery (i.e. wards, operating rooms or laboratories) are usually managed by medical units, who are in charge of:

- handling incoming materials and materials to dispose;
- keeping warehouse management system up-to-date;
- dispensing and recording the dispense of materials triggered by a validated prescription (for preparation and administration or implant), materials for exam accomplishment, low cost and generic goods;
- controlling stock levels and determining that a warehouse replenishment is needed.

A medical unit order (that is a replenishment request to hospital pharmacy) can be delivered for different motivations, depending on materials typology:

- there is a warehouse but a stock is not provided for this material, rarely prescribed;
- it is an out-of-stock item (also the safety stock has been consumed);
- the no-stock policy is adopted, as happens in Wong et al. (2003), where a medication ordering-dispensing and administration process triggered by patient needs is evaluated.

The order can be transmitted in form of a list to be sent to the hospital pharmacy, as a kanban (in case of JIT method), as a requirement for each patient or, as happened in Augusto and Xie (2009), in the form of a mobile medicine closet to be partially refilled.

The typical materials' list, headed with list Id, date and requesting medical unit, contains items Id and quantity for each one, being comprehensive of raw materials belonging to galenics' bill of materials. According to the policy applied, in case of drugs, the item Id can refer to the brand name or the general name.

b.2) Pharmacy order assessment

If medical units are in charge of inventory management, pharmacists usually have to control re-orders' adequacy in terms of frequency and quantity for each material, real requirements and stock

availability. Here, clarifications and changes can be made. The process ends with the validation of the orders.

c) Centralized inventory management process

The final process links the internal requirements to the external supply chain.

c.1) Pharmacy stock management, order dispositions and supplying activities

After pharmacist order assessment, the stock management and supplying activities take place. Operationally speaking, the tasks to carry out are:

- handling of incoming order and expiration materials;
- keeping warehouse management system up-to-date;
- budget reconciliation assessment. Each cost centre/medical unit typically has its own budget to manage for each expenditure class, and the same for materials belonging to bids, that have their specific budget. Materials have to be transferred according to budgets, otherwise a budget integration has to be requested - to Superintendence and Treasurer office - reporting quantities and extra-fund amount needed;
- stock levels control and authorization to dispense;
- supplying activity.

An exception case is the out-of-stock of life-saving drugs or medical devices. Provided that hospital pharmacy has its own fund, a supplier different form the bid winner or more expensive than usual ones can be contacted if provisioning lead time are supposed to be shorter.

c.2) Internal distribution

This activity is carried out starting from pharmacists authorization triggered by medical unit replenishments, eventually fulfilled by supply order (also transient materials).

Inside hospital pharmacy delivery systems have a key role in hospital's service quality (Yurtkuran and Emel, 2008). The diffusion of multi-echelon inventory problem opposed to scheduling oriented ones (Lapierre and Ruiz, 2007) has often coped with in literature, and different transportation solutions or search for optimized routing problems (for example, see Augusto and Xie, 2009) are presented, in which transportation costs and resources (both personnel and physical resources, as means of transports etc.) are some of the main variables taken into account. The reason is the pervasiveness of satellite pharmacies and hub and spoke models in which geographical distances among medical units to be served can be great. Another issue is resource sizing that depends, inter alia, on frequency and quantity of transport from pharmacy to medical units, quantity to handle due to arrivals, characteristics of material handling equipment.

The order preparation, performed by storekeepers, consists in printing (also virtually) the materials list released by pharmacists for a medical unit (if the list exists and no refilling method is applied), labelling and filling a bag/receptacle with all materials listed. First In – First Out (FIFO) logic should be adopted, considering materials expiration date.

The second task, that is the delivery to medical unit, can be carried out immediately or according to a schedule by transporters (that can belong to pharmacy personnel or medical units' nurses staff).

Materials are considered as booked for medical unit till the drawing occurs, when it is subtracted from pharmacy inventory records and registered as "incoming" in medical unit warehouse system. In the end, it is virtually added to medical unit warehouse stock. This operation can be immediate or delayed

depending on the information system, the traceability features involved and the other tools available for technicians.

c.3) Materials Admission and Quality control and Payment

When the order is dispatched and the incoming materials are delivered, pharmacy personnel has to:

- Check the correspondence in type and quantity between ordered and delivered goods;
- Accept with reserve the goods;
- Verify label conformity, item code, quantity, batch number, physical integrity;
- Transmit the definitive acceptance to the Accounting Office to perform the payment.

If the item arrived is managed by pharmacy, products are handled and stored in the dedicated warehouses (chilled or not), otherwise (in case of "transient" material or belonging to a urgent order), it has to be transported (internal distribution is activated). Quantity and Lot Number are registered where materials are firstly handled.

For transient materials kept in CS, the consumption corresponds to an invoice and a replenishment order release.

2.3 PROCESSES REPRESENTATION IN BPMN

The Business Process Management (BPM) analysis is worldwide accepted to play "a major role in the perception and understanding of business processes" (Vergidis et al., 2008), which spans from organizational, managerial issues to information systems and even social problems (Trkman, 2010). Davenport and Stoddard (1994) state that understanding and analysing a business process "helps to recognize the sources of problems and ensure that they are not repeated in the new process", thus providing a measure of value for the proposed changes.

Process models are a way to communicate and share among actors how a process take place. Many authors have provided frameworks for presenting and classifying different business process modeling techniques. For example, Vergidis et al. (2008) propose the classification among Diagrammatic, Formal/Mathematical and Business Process Language (BPL) models (Figure 8).

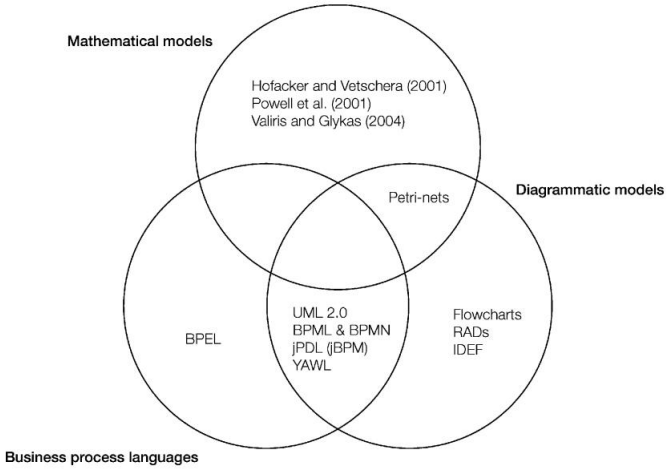

Figure 8 - Classification of business process modeling techniques (Vergidis et al., 2008)

Some BPM model are provided also of BPM suites or workflow engines, which enable process designer to define, for example, methods to carry out activities, activities ownership and responsibility, exception management.

Such kind of process-driven software results to be very flexible if a process re-engineering has to be made, helping organizations to answer to continuous improvements and changes.

One technique from the BPL models area, in particular, allows for "tackling the complexity of the formal models but retaining their consistency and potential for further analysis" (Vergidis et al., 2008). Business Process Modeling Language (BPML), being the most distinctive in this area, has been defined by the Business Process Modeling Initiative (www.bpmi.org). It is also an XML-based language that encodes the flow of a business process in an executable form. BPML is accompanied by Business Process Modeling Notation (BPMN), a graphical flowchart language that is able to represent a business process in an intuitive visual form (Figure 9). Each BPML process has a name, a set of activities, a handler and also supports sub-processes.

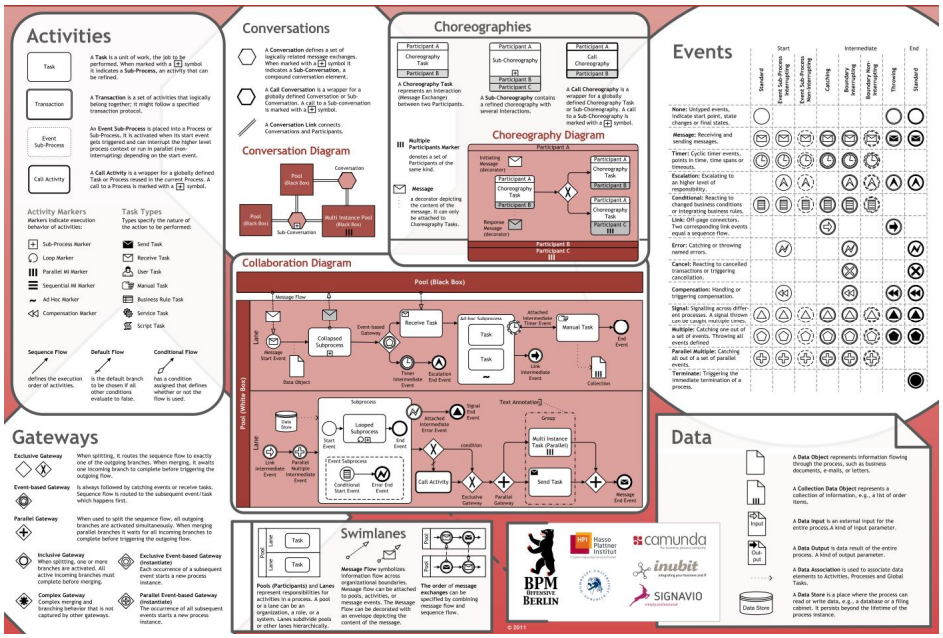

Figure 9 - BPMN 2.0 – Business Process Model and Notation Poster (BPMI)

In what follows, the detailed BPM model of the HMM process, as described in the paragraph 2.2, is shown by using BPMN. It has the objective to consolidate the achieved knowledge about the HMM process in a synthetic framework, in order to hypothesize an aware new thesis on its functioning.

On the basis of the literature review and interviews, a new HIS model is presented, able to tackle all the information from patient requirements to usage, from replenishment requests to supplying and handling activities. It has been conceived in order to support different inventory policies, according to streamlined process perspective, information and materials traceability and clinical risk reduction. Thanks to BPML executability, it has been validated in usability and completeness of information against users interaction.

For clarity and easiness understanding, the representation of the HMM has been confined within the limits of drugs to be administered, excluding the other reasons of consumption.

The modelling has been developed by using Bizagi software.

a) Patient management process

Three actors take part to the process, in different moments: physician, nurse and pharmacist. Two are the milestones: prescription placement (which involves physician prescription and pharmacists validation) and administration to patient (in which the preparation and administration of the drug is provided, with the possibility of late administrations if physician gives a positive feasibility judgment). The representation is given in Figure 10.

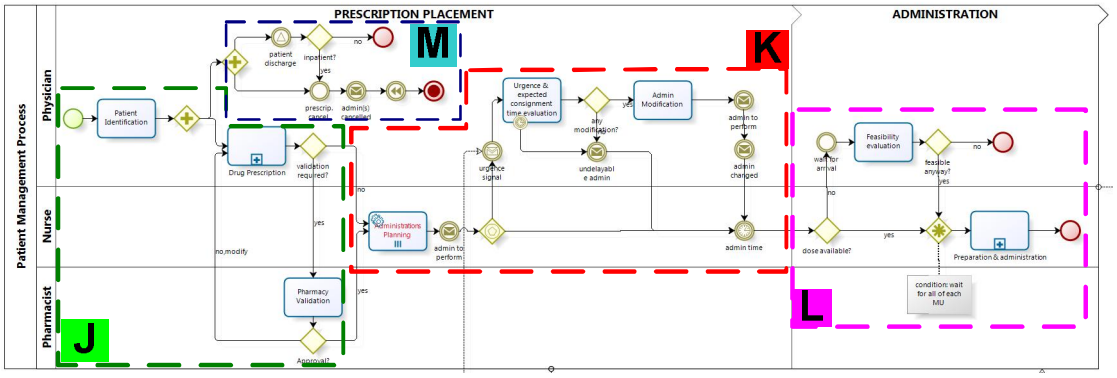

Figure 10 - Patient Management Process frames (J, K, M and L)

a.1.1) Drug Prescription or surgical intervention plan

In the BPM, the process entity that flows throughout the system, that starts and can interrupt the process (if a cancellation occurs), is the drug prescription. According to clinical risk reduction, in the J frame of Figure 10, the patient identification is performed before the prescription, that is provided also of diagnosis, anamnesis and double reconciliation (the details about the drug prescription sub-process are shown in Figure 11). In the M frame of Figure 10, moreover, the cancellation of a prescription or the discharge of an inpatient are transmitted to process b).

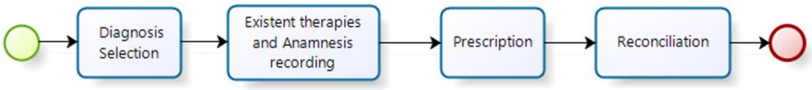

Figure 11 - Drug prescription subprocess

a.2) Pharmacy Prescription Validation

See J frame of Figure 10.

a.3.1) Preparation, administration or implant

In the K frame of Figure 10, the administrations dependent on the prescriptions placed are evaluated in terms of dose availability at the administration time (the "Administration Planning" is a multiple instance Service Task with a parallel none condition flow) and possibly activate the Medical Unit Inventory Management process b), by means of a throw message caught in Figure 14.

The possibility of managing urgent deliveries caused by unavailability of administration materials is also presented in the K and L frame of Figure 10. Delivery urgency means lead time compression and, consequently, higher delivery costs, not excluding being behind schedule. However, deliveries may be easily evaluated by the physician before being activated. Indeed, a time can be given to the physician to confirm the feasibility of the administration behind the schedule on the basis of the delivery scheduled time.

All the feasible administrations for the same time are batched (complex gateway as an element of convergence). Finally (Figure 12), picking and preparation activities take place (user or service task depending on logistics choices) and are performed for each patient dose. A picking list is proposed to the nurse. After transportation and patient identification, the prescription check is performed, administration is done and recorded.

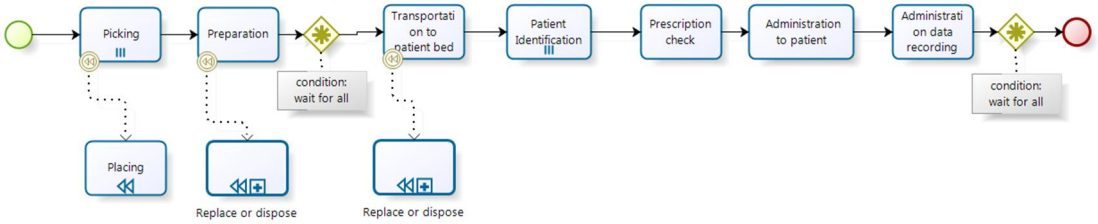

Figure 12 – Preparation & administration sub-process

The compensation event deriving from cancelling a prescription can have an impact in this phase, if the nurse already has drawn the drug. The further re-usable sub-process (in BPMN slang) is reported in Figure 13, which contemplates the possibility to replace or dispose the drug in dependence with the type.

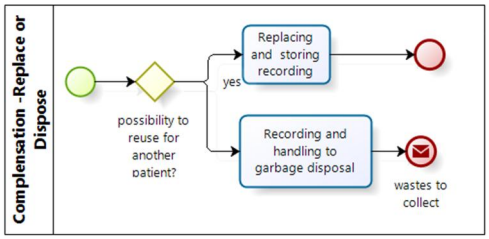

Figure 13 - Replace or dispose sub-process.

b) Medical unit inventory management process

The feature added in this representation is what later in the thesis is called TO BE process. The process (Figure 14) starts when an administration is planned. In this way the process, without defining a provisioning policy, is able to introduce the real requirements data in the definition of an order, allowing medical unit (and hospital pharmacy, as a consequence) to manage its stocks facing patient requirements when they emerge.

The actors involved in this process are the nurse manager and the pharmacist, the entity that flows throughout the system is the requirement for an administration. After the stock level check and the preparation to disposal of expired drugs (with the relative signal to be caught by transporters in process c)), there is the availability check of the quantity of the drug at the administration time. When the drug is not available in the real/virtual stock or stock level is too low (all the inventory policy can be adopted), an order has to be released.

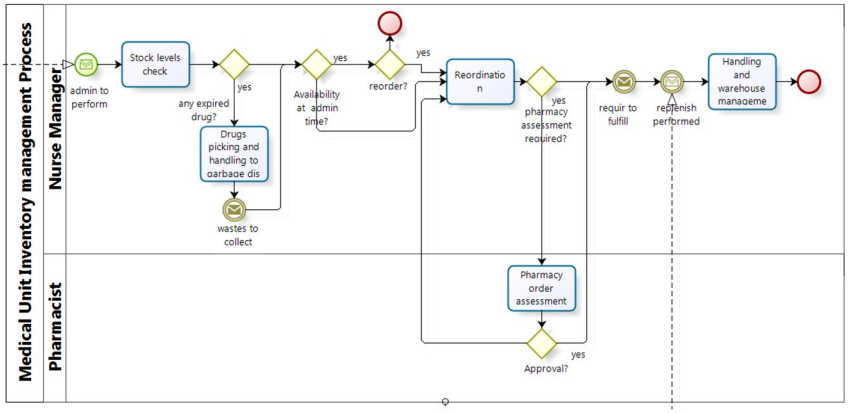

Figure 14 - Medical Unit Inventory Management Process

Possibly after a pharmacy order assessment, the requirement is finally placed and sent to hospital pharmacy (process c)). When materials arrive at the medical unit warehouse, the nurse manager updates warehouse management system and stocks the goods.

c) Centralized inventory management process

This process (Figure 15) is triggered by a medical unit requirement, that is a drug in a quantity defined by a single administration or a replenishment order defined by the nurse manager.

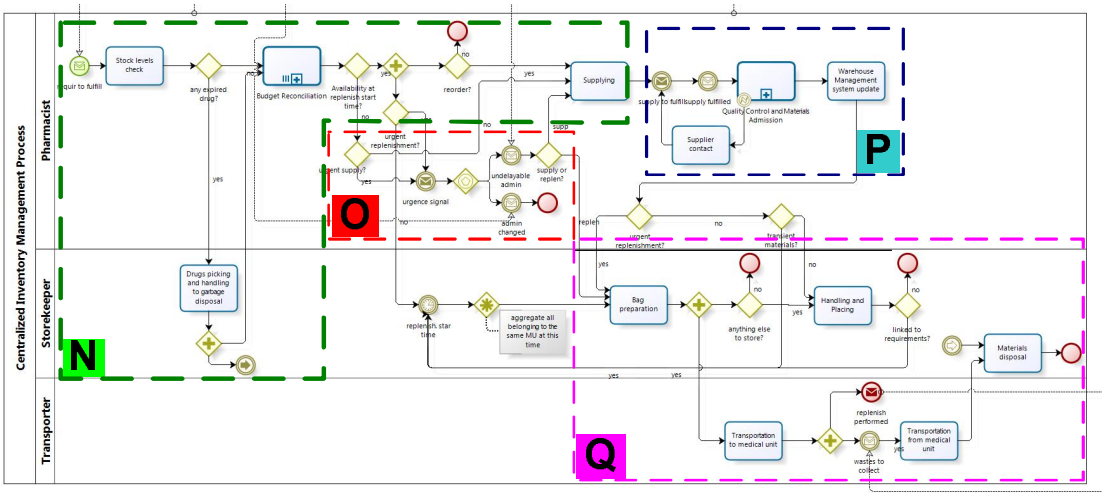

Figure 15 - Centralized Inventory Management Process frames (N, O, P and Q)

c.1) Pharmacy stock management, order dispositions and supplying activities

As happened to medical unit inventory management (b) process), in frame N (Figure 15) a stock levels check is carried out and expired drugs are taken to be disposed. The budget reconciliation (availability for each medical unit expenditure class) is performed (Figure 16) before replenishment or supplying activities. Stock availability for medical unit requirements are carried out, and orders to suppliers can be released, even if the requirement is fulfilled, in order to restore a certain stock level.

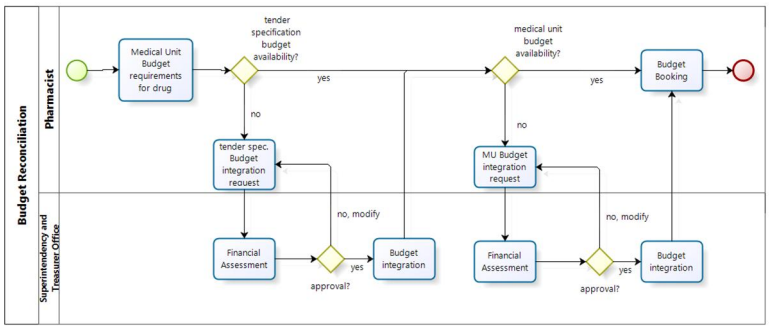

Figure 16 - Budget reconciliation sub-process

In the frame O of Figure 15 it is reported the design of the urgent deliveries management process, that is subsequently transmitted to the physician as described in process a). If the replenishment request coming from the medical unit is linked to an administration, indeed, an option is given to the pharmacist that can ask the physician who prescribed it to evaluate the real urgency of the requirements and, eventually, avoid useless urgent procedures.

c.2) Internal distribution

In the Q frame of Figure 15, if the process is “on time” or materials are not linked to a medical unit immediate requirements, the storekeeper handles and places them in the warehouse. The system collects all the items to be transported to the same medical unit each time period to generate a list of withdrawals for the storekeeper.

A urgent transportation (caused by a urgent medical unit requirement or a late supply delivery time with respect to the one expected/stated) is managed by its own going directly to the bag preparation task. After it, the storekeeper completes the placing of incoming materials (of packages broken to prepare an eventual urgent dispatch) and, in parallel, the bag is given to the transporters to be consigned.

When transportation is completed, the process can end (sending an end event message to the needing medical unit) or can continue in case of wastes to collect (an intermediate event message is caught), if the medical unit has something to dispose. The transporter is then in charge of taking the materials and carrying them to the hospital warehouse, where the storekeeper disposes them.

c.3) Materials Admission and Quality control and Payment

When materials arrive at the pharmacy (frame P of Figure 15), the “Quality control and Material Admission” sub-process is performed (Figure 17) and, in case of problems, a supplier contact is needed. Finally, the Warehouse Management System is updated.

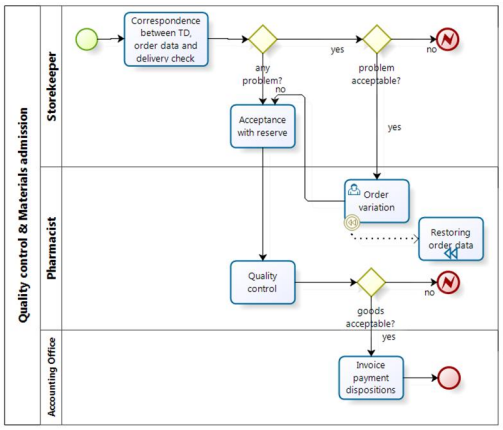

Figure 17 - Quality control and Materials Admission sub-process.

2.4 PROCESS EXECUTION AND VERIFICATION

New technologies, such as CPOEs, introduce great potential for better managing healthcare complexity. The expected gains in quality, safety or cost, anyway, require thoughtful execution, implementation, and coordination (Kaplan et al., 2013). A new technology, indeed, could add unnecessary steps to clinical workflows, thereby lowering efficiency, or be poorly designed, thus becoming a source of errors and potential safety challenges.

Some studies about the impact of the increased investment in health IT in recent years has show that gains in productivity and patient outcomes have not been seen (Kellermann and Jones, 2013), the main reasons being the lack of interoperability and the redesign oriented to take advantage of the efficiencies offered by health IT (Kaplan et al., 2013).

A usability and "clinical" completeness test of the designed model was carried out making an executable version. In particular, following the Bizagi Wizard (Figure 18), after the process modelling step, the data modelling has to be designed.

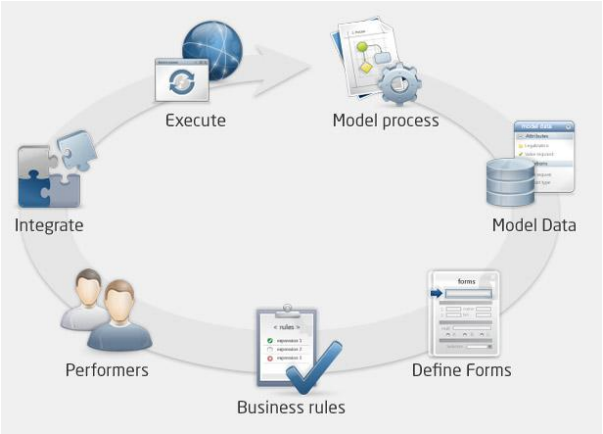

Figure 18 - Bizagi Wizard

An example of the database related to the process a) of Figure 10 – excluding the urgency management of frame K – is reported in Figure 19.

Then, the activity-related user forms were designed (Figure 20). Finally, elementary business rules were implemented.

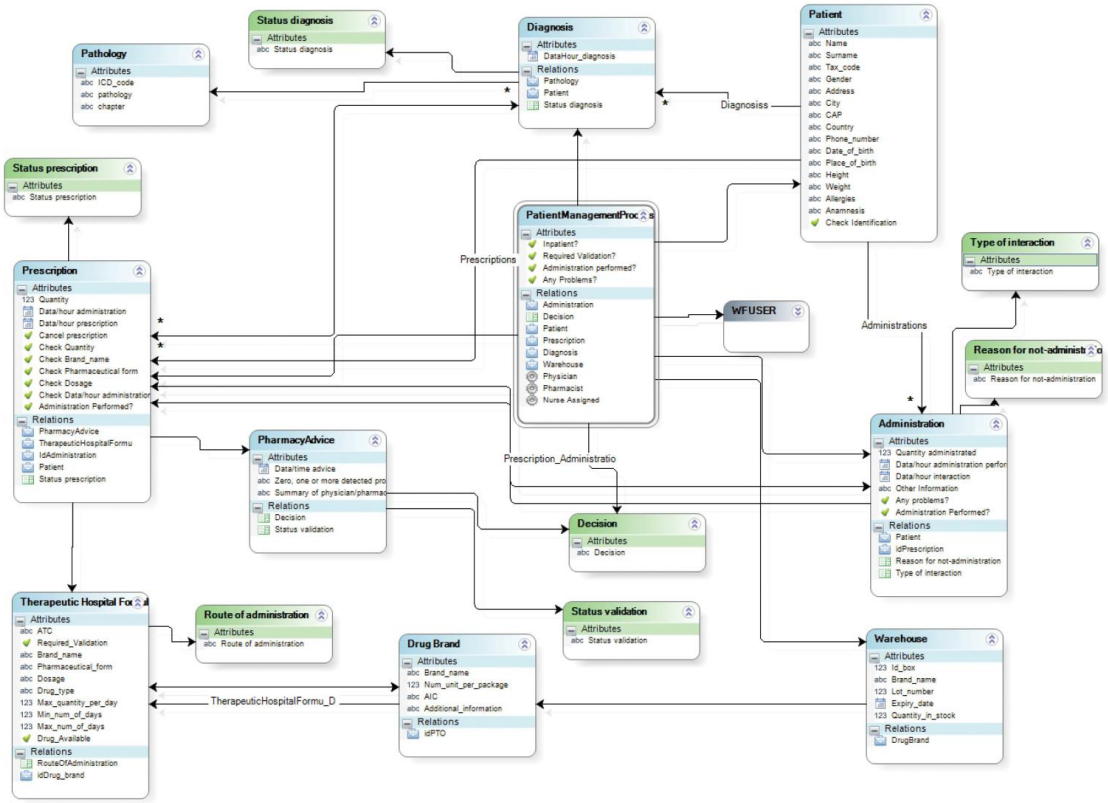

Figure 19 - Process a) database implemented with Bizagi Suite

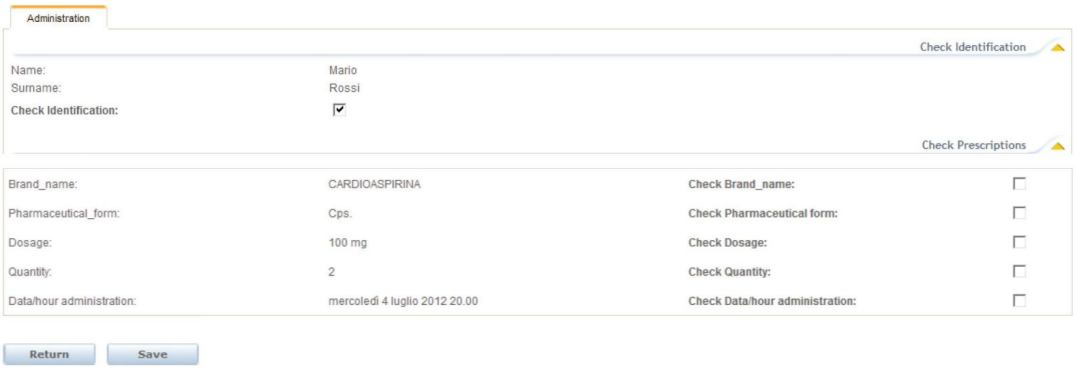

Figure 20 - User form of a drug administration check

One medical unit and the pharmacy personnel of an Italian acute care hospital with 200 beds and 16 specialist medical areas were subjected to this prototype.

Specifically, the following have been involved:

- Medical unit (cardiology) personnel:
  - 2 physicians,
  - 1 nurse manager,
  - 1 nurse;
- Hospital pharmacy personnel:
  - hospital pharmacy director,
  - 2 pharmacists,
  - 1 storekeeper.

The users feed-backed improvements to the modelling, helped better characterize user requirements and realize customizations (to be adapted to physical resources and the type of available job positions).

Overall, great satisfaction was recorder in the adoption of the model, as shown in Table 4, which compares the score obtained by users during the first (after the first implementation) and the last prototype experimentation (at the end of the study, when the prototype included all the suggested improvements).

Table 4 – User performance assessment of the HMM IS prototype at the first and the last usage

USER EVALUATIONS (Score from 0 to 10, 8 users)	First usage		Last usage	
	Mean	St. dev.	Mean	St. dev.
Usability (intuitive, easy, quick)	6.2	1.1	7.2	1.4
Completeness (able to provide all the information needed, totally substituting papers in the process)	8.3	0.8	9.1	0.5
Absence of redundancy (lacking of redundant information)	6.1	2.1	9.2	0.4

3. MATHEMATICAL FORMALIZATION OF HMM INVENTORY POLICIES

This chapter is aimed at defining the mathematical modelling underlying the TO BE process, that is proposal of this thesis. Summarizing chapter 2, the HMM process can be described by means of three sub-processes:

a) Patient management. The drug logistics in a hospital is triggered by patient therapy prescriptions. A process starts when a physician does a medical unit round according to a defined schedule. For each round, the physician can add, change, or cancel the prescriptions attributed to each patient (the period of time between two rounds is the period of invariance of prescriptions, except in cases of adverse reactions or other patient problems). Such a decision is recorded through the CPOE, with details about the drug (mainly active principle, dosage, and pharmaceutical form), quantity, and date–time of administration being recorded on the administration schedule, defining a plan of administrations. At the administration time, the nurse gives the drugs to the patients and registers the delivery in the CPOE, thus updating the virtual stock of the HIS.

b) Ward warehouse management. The drugs to be administered are stored in a medical unit warehouse, replenished at each *RP* in variable quantities. The medical unit nurse manager in charge of ordering the drugs transmits the request to the pharmacy.

c) Hospital pharmacy management. In the hospital pharmacy, in addition to the appropriateness evaluations carried out by pharmacists for some drugs, the suitability of the quantity requested by medical units is verified and the delivery is authorized. The quantities are prepared and consigned in packages within the replenishment lead time. Moreover, orders to suppliers are issued at each *RP* and, after the supplier lead time, incoming materials are controlled and stored.

3.1 INVENTORY MANAGEMENT NOTATION

The time base unit is known as the *time bucket* (t_j) (according to the MRP slang - Chase et al., 1998), with $T = \{t_1, \dots, t_j, \dots, t_J\}$ being a given observation time.

The following notation is defined:

Drug attributes

- *f:* drug code, with $f \in F$ being the list of drugs used in a hospital, with the following attributes:
  - N_f*:* number of units of drug contained in a package of *f*.
  - LT_f*:* supplier lead time (*LT*) of a certain drug f.

Medical Unit attributes

- *m:* medical unit, with $m \in M = \{1,2 \dots, m, \dots, h\}$ being the list of medical units belonging to a hospital (*h* is the index for the hospital pharmacy warehouse) and the attributes being as follows:
  - PT_m: time between two physician rounds in the medical unit *m*, with $PT_h = 0$.
  - TT_m*:* internal replenishment lead time (*TT*) that passes from the medical unit m order delivery to the hospital pharmacy till the consignment of drugs, with $TT_h = 0$.

Prescription attributes

- p*:* medical prescription for a patient, with $p \in P$ being the list of prescriptions made by physicians, with the following attributes (beyond the time–date at which the physician states the prescription):
  - Q_{p,m,f,t_j}: administration quantity of drug f, attributed to a prescription p for a patient hospitalised in medical unit m, to be administered at the end of t_j.

Inventory decision variables

- $LS_{m,f}$: level of service (*LS*). It is the percentage of total demand of the drug *f*, within a reference period, which the medical unit *m* is able to administer without delay or urgent procedure activation.
- $S_{m,f}$: par level. As explained in section 1.1.4, it is a fixed maximum quantity to keep in stock according to the *Periodic Review Par Level* policy).
- $RP_{m,f}$: review period (*RP*). As explained in section 1.1.4, it is the fixed period between to consecutive orders in some inventory policies.
- $SS_{m,f}$: safety stock (*SS*). Quantity of *f*, proportional to $LS_{m,f}$, which *m* keeps in stock to manage variability if demand during a blind period of time.

Inventory dynamic data

The quantities that change over the time as related to *m,f* and observed at the beginning of the time bucket t_j, are the following:

- AV_{m,f,t_j}: availability (*AV*), quantity available for administrations.
- GR_{m,f,t_j}: gross requirement, the total quantity required by medical prescriptions (to be consumed at the end of the time bucket).
- NR_{m,f,t_j}: net requirement, actual quantity required but not available for administrations. In case *m=h*, it is the quantity required by medical units and not available for consignments.
- POH_{m,f,t_j}: quantity projected on hand, which takes into account availability, gross requirement and scheduled receipts.
- POL_{m,f,t_j}: planned order releases, the quantity planned to be released to the medical unit *m* by the hospital pharmacy to cover the medical unit requirement of $RP_{m,f}$. In case *m=h*, it is the quantity that the suppliers should release in case of hospital pharmacy order to cover the hospital pharmacy requirement.

- POR_{m,f,t_j}: planned order receipts, the quantity planned to be received (but not already delivered) from the hospital pharmacy. In case *m=h*, it is the quantity that the pharmacy plans to receive from suppliers.
- $Q_{ST_{m,f,t_j}}$: medical unit stockout quantity to deliver. In case $m \neq h$, it is an internal stockout to be transported from the pharmacy out of $RP_{m,f}$, otherwise it is an hospital pharmacy stockout quantity (external stockout).
- SR_{m,f,t_j}: scheduled receipts, the quantity (defined according to the lot size policy) already ordered on the basis of POR_{m,f,t_j}, which is going to be received by the medical unit *m* from hospital pharmacy. In the case *m=h*, it is the quantity to be received from suppliers.

3.2 AS IS AND TO BE INVENTORY POLICIES

3.2.1 Assumptions

The assumptions of the two processes can be summarised as follows:

1 TT_m and LT_f are constant, to simplify the interpretation of the results of the comparison.
2 Absence of backorders. In line with the current practices in healthcare (Nicholson, 2004), it is assumed that all lacking materials are immediately replenished at a fixed cost.

3.2.2 AS IS process

In the AS IS process, subprocesses b) and c) adopt the *Periodic review par level* servicing approach to issue orders. Materials (POL_{m,f,t_j}) are delivered each reorder period ($RP_{m,f}$) to restore the par level ($S_{m,f}$). When the orders arrive, they are called SR_{m,f,t_j} .

3.2.3 TO BE process

In the TO BE process, subprocesses b) and c) adopt the MRP method according to the traditional definition of the Association for Operations Management – APICS (see, for example Chase et al., 1998 and Segerstedt, 1996), but some slight variations are introduced due to the drug management framework. Materials (POL_{m,f,t_j}) are delivered each reorder period ($RP_{m,f}$) to fulfil requirements.

In particular, for a generic time bucket t_j, the main steps are the netting, lead time offsetting, and lot sizing (the bill of materials explosion until the low level code is not considered, under the hypothesis that purchased drugs do not need to be "assembled". For more details, see, for example, Hendrick and Moore, 1985.

In this process, thanks to the sharing of information assumption, the hospital pharmacy intervenes in the decision process having the complete control of hospital stocks. Then, the reorder period $RP_{m,f}$ should be defined by pharmacists on the basis of drugs availability in the central warehouse.

The formalization of the two subprocesses is described in what follows.

b) MRP for Medical Unit Inventory Management Process

Netting

After the physician round, the HIS aggregates the requirement from prescriptions Q_{p,m,f,t_j} for each m, f and t_j, thus obtaining the medical unit gross requirement GR_{m,f,t_j} ("the *master schedule*"). Taking into account the scheduled receipts (SR_{m,f,t_j}), the available on-hand inventory (AV_{m,f,t_j}) and the safety stock ($SS_{m,f}$), the net requirements (NR_{m,f,t_j}) is defined.

$$GR_{m,f,t_j} = \sum_p Q_{p,m,f,t_j} \tag{1}$$

$$POH_{m,f,t_j} = \begin{cases} max\left(AV_{m,f,t_j} - SS_{m,f} + SR_{m,f,t_j}; 0\right) & for\ j = 1 \\ max\left(POH_{m,f,t_{j-1}} - GR_{m,f,t_{j-1}} + SR_{m,f,t_j}; 0\right) & else \end{cases} \tag{2}$$

$$NR_{m,f,t_j} = max\left(GR_{m,f,t_j} - POH_{m,f,t_j}; 0\right) \tag{3}$$

Lead time offsetting

The MRP method adopts the backward scheduling to issue orders using TT_m .

If offsetting is not possible ($j \leq TT_m$) and there is a lack of drugs for administrations ($\sum_{j=1}^{TT_m} NR_{m,f,t_j} \geq SS_{m,f}$), the medical unit will need urgent deliveries consigned in packages ($Q_{ST\,m,f,t_j}$ with $m \neq h$).

Lot Sizing

Finally, requirement for each t_j is aggregated for each $RP_{m,f}$ according to the lot for lot sizing policy (in packages), in order to define the delivery plan ($POL_{\,m,f,t_{j-TT_m}}$). When orders are confirmed, $POR_{\,m,f,t_j}$ becomes SR_{m,f,t_j} (rolling approach). If there is no safety stock ($SS_{m,f}$) to restore, the formulation is the following:

Note that the transportation plan for a medical unit is characterized by:

- $c_{m,f,k}$: k^{th} time bucket at which the replenishment for the medical unit *m* and the drug *f* starts
- $c_{m,f,0}$: "immediate" urgent replenishment for the medical unit *m* and the drug *f*, which may happen when $j \leq TT_m$ (explained in the following paragraph)
- $C_{m,f}$: replenishment scheduling for the medical unit *m* and the drug *f*. $C_{m,f} = [c_{m,f,0}, c_{m,f,1}, c_{m,f,1+RP_{m,f}}, \dots, c_{m,f,k}, \dots, c_{m,f,K}]$

Then, $\forall j: t_{j-TT_m} \equiv c_{m,f,k}$

$$POL_{\,m,f,t_{j-TT_m}} = \left\lceil \frac{\left(\sum_{j}^{j+RP_{m,f}-1} GR_{\,m,f,t_j}\right)}{N_f} \right\rceil \quad (4)$$

$$POR_{\,m,f,t_j} = POL_{\,m,f,t_{j-TT_m}} \quad (5)$$

$$SR_{m,f,t_j} = POR_{\,m,f,t_j} \quad (6)$$

An intuitive numeric example of the physician prescriptions and medical unit MRP (without the urgency management) is provided in Figure 21.

c) MRP for Hospital Inventory Management process

In parallel with the medical unit warehouse management process (b), at the hospital pharmacy level the medical units requirement is aggregated, orders backward planned and delivered depending on LT_f, and stockouts are managed by means of urgent orders to suppliers ($Q_{ST\,h,f,t_j}$).

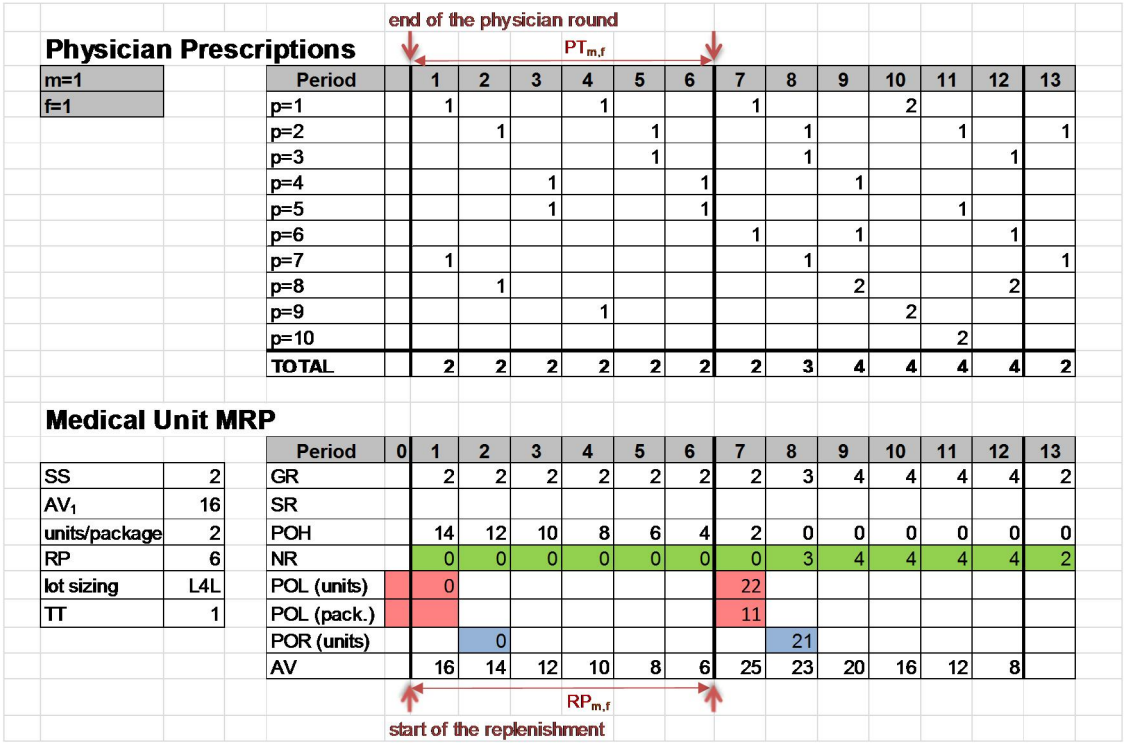

Figure 21 - Numerical example of physician prescriptions and medical unit MRP (without urgencies)

Urgency management (medical unit case)

Before deciding how much to deliver to medical units, it is important to consider what happens during TT_m.

The lead time offsetting is performed in order to plan the orders and, if needed, adopt urgent transportations to prevent for stock outs. Then, it is introduced a "*proxy quantity*", the quantity to release ($QTR_{m,f,t_{j-TT_m}}$), in order to test the feasibility of a planned order releases (POL_{m,f,t_j}) in dependence on the relationship between the requirement for the time bucket under computation t_j and the TT_m dimension.

If $NR_{m,f,t_j} > 0$:

$$QTR_{m,f,t_{j-TT_m}} = \begin{cases} NR_{m,f,t_j} & for\ j > TT_m \quad (i) \\ 0 & for\ j \le TT_m\ ,\ \sum_{j=1}^{TT_m} NR_{m,f,t_j} < SS_{m,f} \quad (ii) \\ \sum_{j=1}^{TT_m} NR_{m,f,t_j} - SS_{m,f} & for\ j \le TT_m\ ,\ \sum_{j=1}^{TT_m} NR_{m,f,t_j} \ge SS_{m,f} \quad (iii) \end{cases} \quad (7)$$

The three conditions respectively are:

(i) $j > TT_m$ and $QTR_{m,f,t_{j-TT_m}}$ is a requirement that may be ordinarily transported (aggregated to others) because it is needed after the replenishment time TT_m (but hospital pharmacy availability has to be checked);

(ii) $j \leq TT_m$ but $SS_{m,f}$ (before subtracted in the computation of the $POH_{m,f,0}$) can cover the requirement;

(iii) $j \leq TT_m$ and the requirement can be fulfilled ($SS_{m,f}$ is not enough). A urgent transportation is needed.

Then, while the case *(i)* is the "ordinary one", and it is more probable the higher is the service level, in the second and third cases, some adjustments to the quantity to transport to the medical unit have to be done considering that a portion of the safety stock is consumed, and, in the third case, a urgent replenishment related to the remaining part of materials required has to be planned.

In particular, the actions to undertake, respectively, are:

(ii) restore the used safety stock consumed ($SSR_{m,f}$) at the next medical unit warehouse replenishment;

(iii) activate an urgent procedure for the lacking materials and restore the $SS_{m,f}$ at the next transport ($SSR_{m,f}$).

Finally, the stock to restore because of the consumption of the $SS_{m,f}$ is:

- $SSR_{m,f}$: Safety Stock to restore at the next replenishment of the drug *f* for the medical unit *m*

$$SSR_{m,f} = \begin{cases} 0 & (i) \\ SS_{m,f} - \sum_{j=1}^{TT_m} NR_{m,f,t_j} & (ii) \\ SS_{m,f} & (iii) \end{cases} \tag{8}$$

About the **lot sizing** step, $\forall j: t_{j-TT_m} \equiv c_{m,f,k}$, it can be calculated:

$$POL_{m,f,t_{j-TT_m}} = \begin{cases} \left\lceil \frac{QTR_{m,f,t_{j-TT_m}}}{N_f} \right\rceil \equiv Q_{ST_{m,f,t_{j-TT_m}}} & for\ k = 0\ (j \leq TT_m) \\ \left\lceil \frac{\left(\sum_{j-TT_m=k}^{k+RP_{m,f}-1} QTR_{m,f,t_{j-TT_m}} + SSR_{m,f}\right)}{N_f} \right\rceil & else \end{cases} \tag{9}$$

The following flowchart helps readers to understand the modified algorithm to manage urgencies (Figure 22).

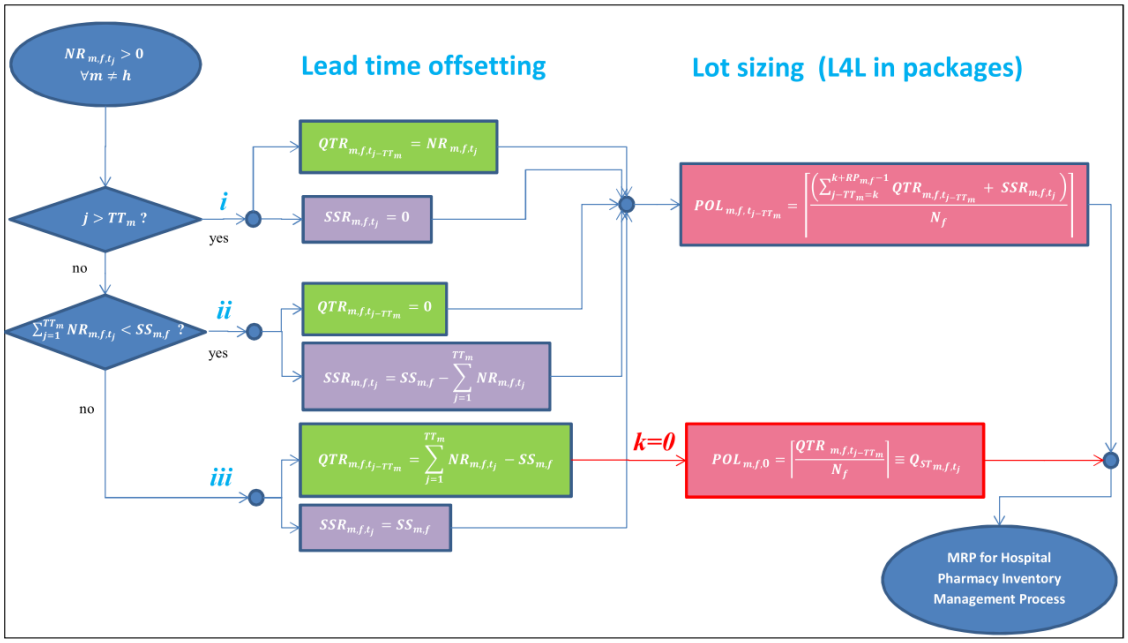

Figure 22 - From medical unit net requirements to hospital pharmacy delivery plan.

4. COST PERFORMANCE MEASURES

In an attempt to describe the behaviour of the HMM, the main evaluation criteria adopted in literature is the economic one, besides a few clinical measures, such as the pharmacokinetic failure (Wong et al., 2003), service level (Kelle et al., 2012), or usage of safety stocks (Liao and Chang, 2011).

Starting from the different contributions available, it is proposed a cost function that takes into account the overall cost of the HMM sustained by a hospital in adopting an inventory management policy for a time horizon *T*.

The values of the parameters introduced in the equation are computed in the case study reported in Chapter 6.

The cost function components ("*cost items*") are defined in what follows.

4.1.ORDERING COST

Ordering cost is the cost related to the issue of an order:

$$C_{O_{m,f,t_j}} = or_m * \delta_{O_{m,f}}(t_j) \tag{10}$$

where:

- or_m: ordering cost for each drug *f* order, independent of the quantity and code, but dependent on the medical unit *m* procedures. In the case of medical units and pharmacy, the ordering activity deals with requirement evaluations, decisions about the order quantity and order form filling. Moreover, for the hospital pharmacy, budget control, materials admission and quality control, and payments are considered.
- $\delta_{O_{m,f}}(t_j)$: Dirac delta, taking into account the existence of requirements for a drug f in the medical unit *m* during the time bucket t_j.

  $\delta_{O_{m,f}}(t_j) = \begin{cases} 1 \ if \ POL_{m,f,t_j} > 0 \\ 0 \ else \end{cases}$

4.2.PURCHASING COST

In literature, the cost of purchasing drugs is usually not subjected to quantity/time discount (an exception is Liao and Chang, 2011). Here it is the considered as proportional to the unit price of the material and the purchased quantity.

$$C_{P_{m,f,t_j}} = SR_{m,f,t_j} * P_f, \qquad m = h \tag{11}$$

where:
- P_f: unit price for a drug package.

4.3.WAREHOUSING COST

For Kelle et al. (2012) and Liao and Chang (2011), the drug-holding cost is proportional to the price of the drug and the holding cost rate. Dellaert and van de Poel (1996) suppose that it is always proportional to the product price, and thus split it into three components:
- physical system cost (or housing cost),
- holding cost (proportional to the interest rate),
- wasting cost (which occurs when items are no longer fit for use).

According to this general formalization, the warehousing cost is computed as follows:

$$C_{W_{m,f,t_j}} = AV_{m,f,t_j} * \left[ps_m + h * P_f + \mu * (d_m + P_f)\right] \tag{12}$$

where:
- ps_m: physical system cost (housing cost), related to the physical storage of a package (energy, space, amortisation, security, etc.).
- h: holding cost rate, for financial and insurance costs.
- μ: stock decay rate, expressing the deterioration that occurs during the stay in the warehouse.
- d_m: disposal cost per unit of package, for reverse logistics activities.

4.4.HANDLING COST

This is the cost associated with the handling of a drug code (pick and place):

$$C_{H_{m,f,t_j}} = pc * SR_{m,f,t_j} \tag{13}$$

where:
- pc: handling costs per unit of package.

4.5.TRANSPORTATION COST

Liao and Chang (2011) consider transportation cost as proportional to the number of trips needed for the quantity to be transported, depending on the transportation capacity of each vehicle in a given time period. Without loss of generality, taking also into account that this activity is outsourced very often (becoming a variable cost), each consignment to medical unit assumed to be carried out at a cost proportional to the time needed to accomplish it and can be delivered outright:

$$C_{T_{m,t_j}} = DT_m * tr * \delta_{T_m}(t_j), \quad \forall\, m \neq h \tag{14}$$

where:

- DT_m: delivery time, time needed to transport drugs from the hospital pharmacy to the medical unit, with $DT_m < TT_m$.
- tr : cost of transportation expressed in value per time bucket.
- $\delta_{T_m}(t_j)$: Dirac delta taking into account the transportation cost only if at least one drug replenishment is planned for the medical unit *m*.

$$\delta_{T_m}(t_j) = \begin{cases} 1 \;\; if \;\; \exists f: \;\; SR_{m,f,t_j} > 0 \\ 0 \;\; else \end{cases}$$

4.6.DISTRIBUTION COST

The drug distribution cost encompasses the handling and transportation costs for the materials:

$$C_{D_{m,t_j}} = \sum_f C_{H_{m,f,t_j}} + C_{T_{m,t_j}} \tag{15}$$

Finally, the stockout costs, as assumed by Kelle et al. (2012), are considered independent of the size of the shortage, because they are managed as they emerge (no orders batch is made).

4.7.INTERNAL STOCKOUT COST

This is the cost to manage a stockout at the medical unit level:

$$C_{IS_{m,f,t_j}} = in_m * \delta_{IS_{m,f}}(t_j) \tag{16}$$

where:

- in_m: cost of urgent delivery from hospital pharmacy to medical unit *m* [€/code].
- $\delta_{IS_{m,f}}(t_j) = \begin{cases} 1 \;\; if \;\; Q_{ST_{m,f,t_j}} > 0, \quad \forall\, m \neq h \\ 0 \;\; else \end{cases}$
- $C_{IS_{m,f,t_j}} = 0, \quad m = h.$

4.8.EXTERNAL STOCKOUT COST

This is the cost to manage a stockout at the hospital pharmacy level:

$$C_{ES_{h,f,t_j}} = \left(ex + Q_{ST_{h,f,t_j}} * P_f\right) * \delta_{ES_{h,f}}(t_j) \quad (17)$$

where:

- ex: cost of urgent delivery from suppliers for each requested code. This is also dependent on intangible aspects, such as the relevance of the drug for patient care and survival or the immediate availability of drugs for pharmacokinetic reasons.
- $\delta_{ES_{h,f}}(t_j) = \begin{cases} 1 & if \ Q_{ST_{m,f,t_j}} > 0, \quad m = h \\ 0 & else \end{cases}$

4.9.TOTAL COST

The HMM total cost (C) for the observation time T is thus:

$$C = \sum_{t_j} \sum_m \left[\sum_f \left(C_{O_{m,f,t_j}} + C_{P_{m,f,t_j}} + C_{W_{m,f,t_j}} + C_{ES_{m,f,t_j}} + C_{IS_{m,f,t_j}}\right) + C_{D_{m,t_j}}\right] \quad (18)$$

This function will be evaluated in both the TO BE ($C^{TO\ BE}$) and the AS IS process ($C^{AS\ IS}$).

5. DESIGN AND IMPLEMENTATION OF HMM SIMULATION MODEL

5.1 SIMUALTION FRAMEWORK

Dean et al. (1999) state that the simulation is particularly useful decision making in hospital pharmacy management and technology evaluation, providing managers with a tool to explore a wide range of potential solutions and to prevent the introduction of inappropriate changes.

A discrete event simulation of the three subprocesses described in chapter 3 has been implemented using *Arena Rockwell* simulation software. The TO BE and AS IS simulators are feed by several *Microsoft Excel* spreadsheets and export data to them, in order to perform the inventory management policies of both the AS IS and TO BE processes and collect simulation outputs. The whole simulation framework, in the case of the TO BE process, is shown in Figure 23.

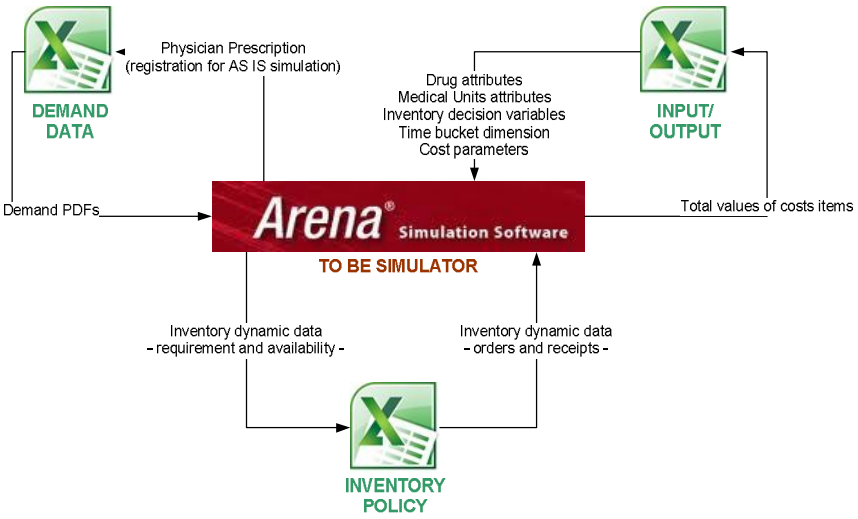

Figure 23 - Simulation framework – TO BE process.

Simulations Input and Output are reported below.

Simulation Input

The simulation takes as input (from a data entry spreadsheet reported in Figure 24):

- Drug attributes, as described in chapter 3;
- Medical units attributes, as described in chapter 3;
- Inventory variables, as described in chapter 3;
- Cost parameters, as described in chapter 4;
- Duration of a time bucket t_j;
- Daily drug demand Probability Distribution Functions (PDFs), for each drug-medical unit pair.

Simulation Output

The simulation gives as output:

- Inventory build-up diagram for each drug-medical unit pair;
- Total values of each cost item at each supply chain echelon (medical units and hospital pharmacy) and the total HMM cost C, as described in chapter 4.

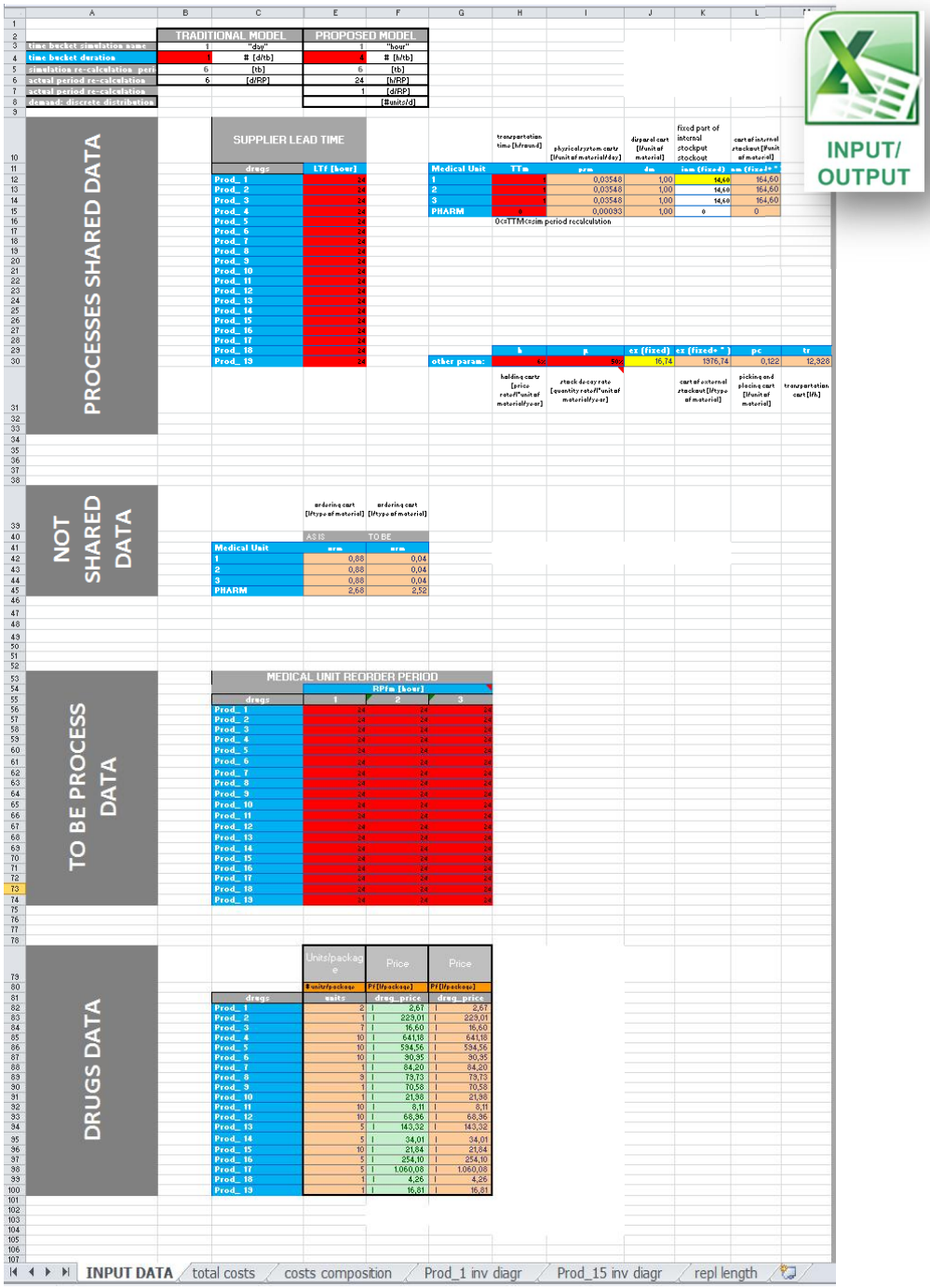

Figure 24 - Data entry - Excel spreadsheet

5.2 PROCESSES MODELLING

The main **entity** type that flows throughout the simulation model is information. The simulation is built on the MRP classical record and its feeding information, as an ensemble of matrices and vectors, where the data about gross requirement, materials availability, scheduled receipts and so on are recorded for each drug code, medical unit and time bucket, during the simulation.

The **processes** modelled - graphically gathered in boxes (see Figure 25) - are the ones identified in chapter 2:

a) Patient management;
b) Medical unit inventory management;
c) Centralized inventory management.

Moreover, a simulator block (called "Engine box") is designed in order to compute the cost items defined in chapter 4 and transfer the simulation data to an external decision support system, implemented in *Microsoft Excel*, as shown in Figure 23.

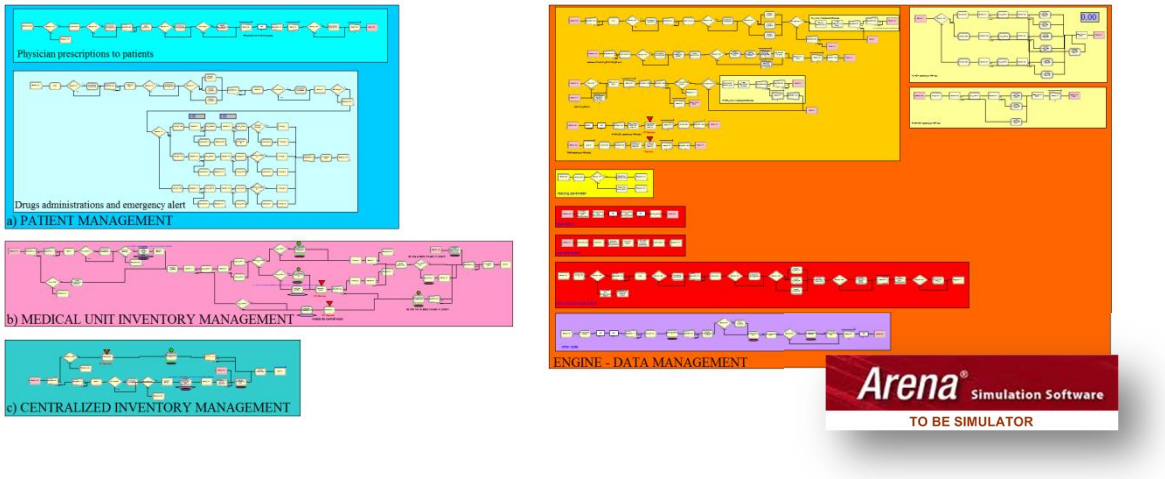

Figure 25 -TO BE process modelling, screenshot from Arena Rockwell

a) Patient management

Drug requirement modelling

On the basis of known demand PDFs for each pair drug-medical unit, a **Monte Carlo Simulation** (MSC) is carried out in order to randomly generate daily demands.

Under the assumptions of uniform usage of drugs along the period of consumption, a requirement is allocated to each t_j in order to avoid demand concentrations only on few time buckets (that would favour the TO BE process performances).

The resulting plan corresponds to the aggregation of the prescriptions delivered by the physician at the beginning of t_1, after his ward round, and each time a new round ends (each $PT_{m,f}$). No real locked planning period is given because the physician prescriptions had an immediate effect on requirement. In

this way, the model can simulate the worst running condition in which requirement continuously changes over the time.

The drug requirement variability over the time at each medical unit and for each drug is part of the hospital framework that the TO BE and the AS IS processes share. The requirement dynamics is designed in the TO BE process and reproduced in the AS IS process.

Details about MSC implementation

An example of MCS is given in the case of 57 couples of medical unit-drug demand PDFs.
Having defined:

- $f \epsilon F = \{1,\ldots, 19\}$
- $m \epsilon M = \{1,2,3,h\}$
- *row= 1,…, 57*: set of *m,f* couples managed by the simulator. In particular:
  - *row=1,…19* are related to *m=1*
  - *row=20,…,38* are related to *m=2*
  - *row=39,…,57* are related to *m=3*
- *conteggioCol=1,…,6*: set of time buckets in which the administrations prescribed by physicians during their word wound fall.
- *k=0.1, 0.2, … ,1*: multiplied by 10, it is the set of deciles of a PDF.

The following matrices are defined:

- *dem(row,k)*: matrix of the Cumulative Distribution Functions (DCFs) of the daily demand of the couples *m,f*. The element *(row,k)* of the matrix represents the maximum quantity of the drug code *f* in the medical unit *m* (related to a *row* and expressed in number of units) which has the *k*-probability of being requested in one day. In expressions (one row in Table 5):

$$Probability(quantity \leq dem(row,k)) = k \qquad (19)$$

m	f	DISCRETE CUMULATIVE DISTRIBUTION OF THE DAILY DEMAND [# units/day]									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1	1	48	96	132	168	210	252	294	366	438	684

Table 5 - Example: *row=1* in *dem(row,k)* matrix.

- *Daily_Demand (row, conteggioCol)*: matrix of the daily demand of drugs for each couple *m,f* (for this special matrix a time bucket lasts 1 day).
- *MRP_GR(row, conteggioCol)*: matrix of gross requirement (GR_{m,f,t_j}), the aggregation of the prescriptions made by physicians during their round for each *m,f,*t_j.

The *DISCrete* function of the implementation language *SIMAN* (available in *Arena Rockwell*) is used. It is structured as follows:

- *DISCrete(Prob1,Value1,Prob2,Value2, . . . [,Stream])*

where:

- o *$Prob_i$:* Cumulative probability
- o *$Value_i$*, Value associated with probability *$Prob_i$*

This function generates a random number between 0 and 1. SIMAN then searches the probabilities, *$Prob_i$*, until it finds one larger than the random number. The *$Value_i$* associated with that probability is returned. The *DISCrete* function adopted and the assignment to the output matrix is shown in Figure 26.

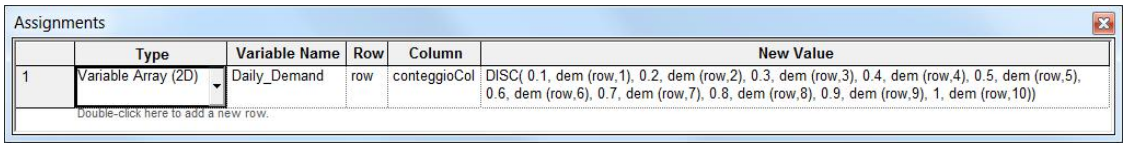

Figure 26 - *DISCrete* function to generate daily demand for each couple *m,f*. Assignment to the matrix *Daily_Demand (row, ConteggioCol)*.

The procedure is repeated for each value of *conteggioCol* and the results are stored in the matrix *Daily_Demand (row, conteggioCol)*. This means that the stochastic daily demand of drugs for 6 days (the biggest value of *conteggioCol*) has been found.

Under the assumption of uniform usage of drugs along the day, the daily demand obtained, opportunely elaborated according to the chosen time bucket dimension t_j, reproduce GR_{m,f,t_j}, that is the administrations' plan coming from prescriptions at each physician round ($PT_{m,f}$). Than, the gross requirements matrix *MRP_GR(row,conteggioCol)* is filled.

The possibility to change the time bucket dimension makes the simulator flexible in terms of $PT_{m,f}$ duration, from the frequent visits that happen during an ordinary hopsitalization, to the weekly or monthly prescriptions for chronic diseases in ambulatory services.

Gross requirements are registered in the *Excel spreadsheet* during the TO BE process and re-used in the AS IS process.

During the simulation, when $PT_{m,f}$ passes, MSC is repeated in order to re-enact the physician prescriptions and the changing events that can happen to prescriptions (patient discharge and new arrivals, patient reactions to therapies, etc.).

Drug administration

Each unit of drug is modelled as a single entity. Buffers are constituted by medical units' and pharmacy warehouses. According to the administrations schedule, the units are withdrawn from the medical unit warehouse at the end of each t_j .

There is no variability in the administrations, as the variability of prescriptions is continuously taken into account by the system.

If a stockout occurs ($Q_{ST_{m,f,t_j}}$), a urgent procedure is activated in order to satisfy a patient requirement.

b) and c) Medical units and hospital pharmacy inventory management

Drug orders

In the hospital pharmacy, drug orders are received from suppliers and delivered to medical units on the basis of the POL_{m,f,t_j}. Replenishment (TT_m) and provisioning (LT_f) lead times are constant, modelled as simple delays.

5.3 DATA MANAGEMENT BOX

The "Engine box" is the way in which the simulator interact with the external Decision Support System, not only dedicated to the data entry (Figure 24) but, as before anticipated, to carry out inventory policy calculations of chapter 3, cost calculations and complete data export for further analysis.

Regarding the costs items computation:

- C_P, purchasing costs, are counted when drugs arrive at the hospital pharmacy warehouse;
- C_W, warehousing costs. The inventory level for each items and place of storage is checked and each end of time bucket.
- C_{ES} and C_{IS}, stockouts costs, are computed each time a stock out is recovered.
- C_O, ordering costs, are sustained when an order is delivered,
- C_D, distribution costs. The handling cost are valorised when a drug package is taken from pharmacy warehouse; the transportation cost is attributed to the medical unit of destination when packages arrive.

6. DATA COLLECTION AND ANALYSIS

In order to compare the two previously described processes, the proposal (TO BE) and the traditional one (AS IS), the drug demand distributions and values of the cost parameters defined in Chapter 4 has been obtained through data collection at a regional university acute hospital comprising 1500 beds and 30 medical specialties. However, because demand and cost parameters differ from hospital to hospital depending on the catchment area, type of resources, HIS, and procedures, the design of experiments (Chapter 7) takes into account their variation with the aim to generalise the study results.

6.1 DRUG REQUIREMENTS

The following drug data were extracted from the HIS for the year 2012:

- List of hospital pharmacy orders
- List of medical units requests
- Daily medical units consumption
- Material prices
- List of wasted materials

55,000 medical unit consumption records were examined, related to 900 items used in the hospital.

The Pareto's Law is a known selective management principle that has been used, among others, as a method for drug classification (McLaughlin and Olson, 2012; Srinivasan, 2008).

The Pareto analysis was carried out on the drug annual cost expenditure of the hospital in order to define the drug sample to use in the simulation model (excluding drugs typically subjected to planning techniques, namely the ones used in oncology and infectious disease care). 19 drugs were selected, which constitute 50.8% of the total drug expenditure. With the same method, there were selected the three medical units where these drugs were mainly used.

From the collected data, for each medical unit-drug pair (57 pairs), it was derived the PDF of the daily demand (Table 6).

Table 6 - CDF of daily demand for each couple medical unit-drug. Number of units per package of drug code.

m	f	DISCRETE CUMULATIVE DISTRIBUTION OF THE DAILY DEMAND [# units/day]										# units/ package
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	
1	1	48	96	132	168	210	252	294	366	438	684	2
1	2	0	0	0	0	0	0	0	0	0	0	1
1	3	0	6	6	12	12	12	18	24	36	48	1
1	4	0	0	0	0	6	6	6	6	12	18	1
1	5	6	12	12	12	24	24	48	60	60	150	1
1	6	0	0	0	0	6	12	18	48	198	252	1
1	7	0	0	0	0	0	0	0	0	0	0	1
1	8	0	6	6	6	12	12	18	24	36	54	1
1	9	0	0	0	0	0	18	18	18	18	48	1
1	10	0	0	0	0	0	6	6	6	12	12	1
1	11	6	12	18	24	30	30	30	42	48	60	10
1	12	0	0	0	6	6	6	6	12	12	30	10
1	13	0	0	0	0	0	0	18	150	198	252	5
1	14	0	0	0	0	0	0	6	6	6	18	5
1	15	6	6	12	12	12	12	18	18	30	54	10
1	16	0	0	0	0	0	0	0	0	0	0	5
1	17	0	0	0	0	0	0	0	6	12	18	5
1	18	6	6	12	12	18	24	30	30	42	66	1
1	19	0	0	0	0	0	0	0	0	0	0	1
2	1	30	54	60	72	84	102	114	150	192	300	2
2	2	0	0	0	0	0	0	6	6	6	12	1
2	3	0	0	0	0	6	6	6	12	12	18	1
2	4	0	0	0	0	0	0	0	0	0	0	1
2	5	6	6	6	6	18	18	18	102	102	180	1
2	6	0	0	0	0	0	0	0	0	0	0	1
2	7	0	0	0	0	0	0	0	0	6	6	1
2	8	0	0	12	12	18	18	24	24	36	60	1
2	9	0	0	0	0	0	0	0	0	0	0	1
2	10	0	0	0	0	0	0	0	0	0	6	1
2	11	18	24	24	24	24	24	24	24	48	54	10
2	12	0	0	0	0	0	6	6	6	6	12	10
2	13	0	0	0	0	0	0	0	0	6	6	5
2	14	0	0	0	0	0	0	0	0	0	0	5
2	15	0	0	0	0	0	0	0	0	0	6	10
2	16	0	0	0	0	0	0	0	0	0	0	5
2	17	0	0	0	0	0	0	0	0	0	0	5
2	18	6	6	12	12	18	18	24	24	36	60	1
2	19	0	0	0	0	0	0	0	0	0	0	1
3	1	12	24	36	54	90	114	144	192	270	480	2
3	2	0	0	0	0	0	0	0	0	0	0	1
3	3	6	6	12	12	18	18	24	30	42	72	1
3	4	0	0	0	0	0	0	0	0	0	6	1
3	5	0	0	0	0	6	6	6	6	12	12	1
3	6	0	6	6	6	6	12	12	12	18	24	1
3	7	0	0	0	0	0	0	0	0	0	6	1
3	8	0	0	0	0	0	0	0	0	0	42	1
3	9	0	0	0	0	0	0	0	0	0	0	1
3	10	0	0	0	0	6	6	6	6	12	24	1
3	11	0	6	6	12	12	12	18	18	24	48	10
3	12	0	0	6	6	6	12	12	18	24	36	10
3	13	0	0	0	0	0	0	0	0	0	6	5
3	14	0	0	0	0	0	0	0	0	0	0	5
3	15	0	0	0	0	6	6	18	18	42	78	10
3	16	0	0	0	0	0	0	0	0	6	6	5
3	17	0	0	0	0	0	0	0	0	0	0	5
3	18	0	0	0	0	0	6	6	6	6	12	1
3	19	0	0	6	6	6	6	6	6	6	12	1

6.2 COST PARAMETERS

Activity Based Costing (ABC) has been recommended for hospital cost accounting (Chan, 1993), even if experimentations concerning the hospital structure as a whole are limited (Cinquini et al., 2009).

Time-driven ABC (TDABC) is an improved version of the ACB by Kaplan and Anderson (2004) which requires that providers estimate only two parameters for each process activity: the cost of each of the resources used in the process and the quantity of time needed to carry out the activity (Kaplan and Porter, 2011).

In this thesis, following the ABC premise that products consume activities, activities consume resources, and resources consume costs (Gupta and Galloway, 2003), an algorithm is presented in order to compute the cost parameters defined in chapter 4 using data collected on the field (from the above mentioned hospital). In this case, the "products" (or cost objects) are the unit inventory costs (cost parameters under analysis), the "activities" are the tasks performed in the HMM process, and the "resources" are the personnel, equipment, energy and materials needed to carry out the activities. Some indirect cost, moreover, have to be addressed to activities. The unitary cost of resources is computed, taking into account the maximum value of the resource cost driver (full capacity of the resource, that is mainly the time available).

The customisation of the or_m cost parameters is made to be representative of the AS IS and TO BE processes:

- for the *medical units* in the TO BE process, stock level evaluation, computation of the quantity to require from the pharmacy, and its validation by pharmacists are faster than in the AS IS process, because the quantity to be ordered (POL_{m,f,t_j}) is directly elaborated, with less time spent by nurses and pharmacists. The required time is drastically reduced, so the distinction between ${or_m}^{AS\ IS}$ and ${or_m}^{TO\ BE}$ has been made;
- for the *hospital pharmacy*, the time to define the quantity needed and deliver the order is shorter in the TO BE than the AS IS process as well, thus ${or_h}^{AS\ IS}$ and ${or_h}^{TO\ BE}$ have to be computed.

Table 7 - Value of the cost parameters calculated by means of the Time-Driven ABC.

COST PARAMETER		VALUE	UNIT OF MEASURE
P.1	${or_h}^{AS\ IS}$	3,82	€/code
P.2	${or_m}^{AS\ IS}$	0,88	€/code
P.3	pc	0,12	€/package
P.4	tr	0,22	€/transportation/min
P.5	ps_h	0,0000006	€/unit of material/min
P.6	ps_m	0,0000246	€/unit of material/min
P.7	in_m	150,00	€/type of material
P.8	ex	2800,00	€/type of material
P.9	d_m	1,00	€/unit of material
P.1	${or_h}^{TO\ BE}$	2,52	€/code
P.2	${or_m}^{TO\ BE}$	0,04	€/code
	h	6%	cost of money/€/package/year
	μ	50%	waste rate/€/package/year

The cost parameters values resulting from the analysis are reported in Table 7**Errore. L'origine riferimento non è stata trovata.**.

In what follows, the details about the designed algorithm (Figure 27) and a description for each step are provided.

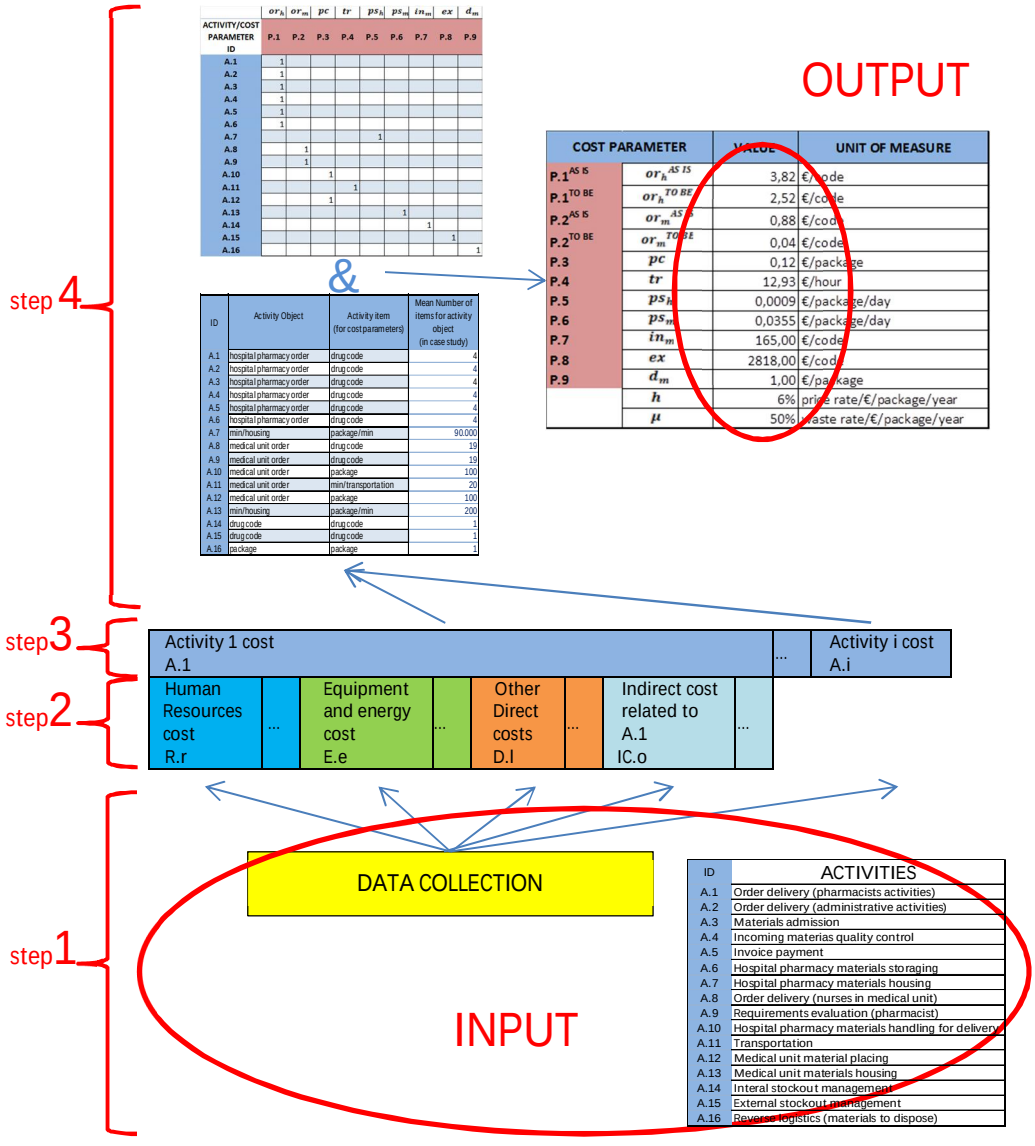

Figure 27 - Steps to compute the cost parameters.

6.1.1 Details about TDABC implementation

Notation:

Main TDABC indices:

- *i*: activity , with $i \in A$, for example the "Order delivery" made by pharmacist
- *x*: resource class, with $x \in X$
- q: cost parameter, with $q \in P$.

Activities

- *A*: set of activities of HMM process, *A={A. i}*.
- $activity\ cost_i$: activity cost, depending on resources implied in the activity execution, in the example, the cost to perform the delivery of an order.
- $activity\ object_i$: the type of object the activity refers to. In the example, the object is a hospital pharmacy order.

Resources

- *X*: set of resource classes, $X = \{X.x\} = \{R.r, E.e, D.l, IC.o\}$.
- *R*: set of human resources working at the HMM process, *R={R. r}*.
- *E*: set of equipment and energy need for the HMM process, *E={E.e}*.
- *D*: set of other direct costs related to the HMM process (different from *R* and *E*), *D={D. l}*.
- *IC*: set of indirect costs addressable to activities of the HMM process, *IC={IC.o}*.
- $capacity\ of\ resource_x$: amount of resource driver (intensity, transaction or duration driver) that the resource *x* can afford in a period of time. To the scope of this thesis, the full practical capacity (Kaplan and Porter, 2011) of resources is considered. For example, in the case of a human resource, it is considered as 80% of its yearly working time (the resource driver is the time), for a manual transpallet it is 10% of its yearly availability time.
- $capacity\ cost\ rate_x$: cost of the resource *x* for unit of driver (consumption).
- $expenses\ attributable\ to\ resource_x$: cost of the resource for a period of time. For example, one yearly salary of a human resource or yearly amortization cost for an equipment.

Cost parameters

- *P*: set of cost parameters of the HMM process (presented in chapter 4), *P={P.q}*.
- $cost\ parameter\ value_q$: the value of the *q*-th cost parameter, with $q \in P$.

Relationship among activities and resources

- δ_{ix}: dirac delta, which takes into account the usage of the resource class *x* to accomplish the activity *i*:

$$\delta_{ix} = \begin{cases} 1 & if\ x\ is\ used\ for\ the\ activity\ i \\ 0 & else \end{cases} \quad (20)$$

- $resouce\ usage_{ix}$: amount of resource *x* driver (time) used to perform the activity *i*.
- $activity\ resource\ cost_{ix}$: resource *x* cost to perform the *i* activity, depending on resources consumption.
- $activity\ resource\ class\ cost_{iX}$: activity *i* cost, depending on the class of resource *X*.

Relationship among activities and cost parameters

- $activity\ item_i$: component of the activity object which corresponds to the unit of measure of the related cost parameter. For example, in case the activity is "order delivery" by pharmacists, while the activity object is the "hospital pharmacy order", the activity item is the "drug code" because the activity is related to the "ordering cost", which is measured in euro per drug code.
- $item\ amount_i$: average number of items comprised in in the activity object. In the previous case, the average amount is 4 drug codes.
- δ_{iq}: dirac delta, which takes into account the dependence of the cost parameter *q* on the activity *i*.

$$\delta_{iq} = \begin{cases} 1 & if\ q\ is\ dependent\ on\ the\ activity\ i \\ 0 & else \end{cases} \quad (21)$$

Step 1: Data collection

The considered activities (and the related ID) are listed in the Table 8. Because of the different research objective as in the first part of the thesis, some simplifications related to the processes described in chapter 2 are made. The affinities between the chosen activities and the notation given in chapter 2 are shown in the third column of Table 8.

Table 8 - Activities of the HMM process and their affinity with HMM notation of chapter 2

ID	ACTIVITIES	Affinity with HMM notation
A.1	Order delivery (pharmacists activities)	c.1
A.2	Order delivery (administrative activities)	c.1
A.3	Materials admission	c.3
A.4	Incoming materias quality control	c.3
A.5	Invoice payment	c.3
A.6	Hospital pharmacy materials storaging	c.1
A.7	Hospital pharmacy materials housing	c.1
A.8	Order delivery (nurses in medical unit)	b.1
A.9	Requirements evaluation (pharmacist)	b.2
A.10	Hospital pharmacy materials handling for delivery	c.2
A.11	Transportation	c.2
A.12	Medical unit material placing	b.1
A.13	Medical unit materials housing	b.1
A.14	Interal stockout management	b.1
A.15	External stockout management	c.1
A.16	Reverse logistics (materials to dispose)	c.2

The list of activities helped in identifying the resources involved in their accomplishment. In order to define their load and cost, the following data were collected:

- Profit and loss account;
- Number, price, lifespan, and power (where available) of the equipment to handle, store, and transport the materials in the hospital pharmacy and medical units;
- Number, salary, and availability of human resources and time needed to order, accept, handle, store, and transport the materials in the hospital pharmacy and medical units;
- Time spent by resources (equipment and personnel) to perform the activities;
- Hospital layout.

Moreover, for activities shifting from the AS IS to the TO BE process, resources and consumption estimations were made.

Step 2: Capacity cost rate computation and resources-activities association

Step 2 deals with the association of resources and other costs to the activities in place. In formulas, it is expressed by the binary variable δ_{ix}.

The table below reports the existent dependencies (Table 9).

Table 9 - Dependence of Cost Parameters on Hospital Activities (α_{ix})

ID	R.1	R.2	R.3	R.4	R.5	E.1	E.2	E.3	E.4	E.5	E.6	E.7	E.8	D.1	D.2	D.3	D.4	IC.1	IC.2	IC.3	IC.4	IC.5	IC.6
A.1			1									1							1	1	1	1	1
A.2				1								1							1	1	1	1	1
A.3	1																		1	1			1
A.4			1																1	1			1
A.5				1															1	1	1	1	1
A.6	1							1											1	1			1
A.7						1	1											1					
A.8					1								1									1	1
A.9			1									1							1	1	1	1	1
A.10		1										1							1	1		1	1
A.11					1						1												
A.12					1																		
A.13									1	1				1									
A.14															1								
A.15																1							
A.16																	1						

Cost of human resources (R) and equipment (E)

Moreover, the unit cost of resources (also called resource capacity cost rate) is found.

The cost of each resource, divided by its practical capacity as a percentage of theoretical capacity (Kaplan and Anderson, 2004), results in the cost rate of the resource (per unit of consumption). This is not the usual way of treating ABC, but this research does not aim at evaluating the capacity of a specified number of resources needed for inventory management. The objective, instead, is to consider the activities related to HMM as variable unit costs (cost parameter). When multiplied by scale factors characterising an inventory policy (for example, volume of material requested and transported), they allow to make comparisons among policy performances.

$$capacity\ cost\ rate_x = \frac{expenses\ attributable\ to\ resource_x}{capacity\ of\ resource_x} \quad (22)$$

Other Direct Costs (D)

The considered direct costs are energy (attributable to storing and holding of materials), internal and external stockout and disposal costs. These last three $capacity\ cost\ rate_x$ were directly estimated by the hospital management.

Indirect costs (IC)

One of the main features of the ABC analysis is the ability to avoid the "peanut butter" method, making an effort to address the indirect costs pro-quota to the cost object (activity or process) who enjoys for them. Naturally, the way to allocate the indirect cost (overheads, support activities) is the cost driver.

The considered indirect costs are cleaning, heating and lighting of offices and warehouses, the cost of the pharmacy director and the cost of the part of the HIS used for HMM.

The cost data mainly came from the profit and loss account. The cost drivers were defined to find the unit indirect cost, which was finally reported in cost per minute.

Step 3: Activity cost computation

The data collection also concerned the duration time (that is the amount of the activity driver) for each activity (Then, taking into account the unit cost per activity before calculated, the cost for each activity object was found by means of the following equation:

$$activity\ recource\ cost_{ix} = resource\ usage_i * capacity\ cost\ rate_x * \delta_{ix} \quad (25)$$

$$activity\ cost_i = \sum_x activity\ recource\ cost_{ix} \quad (26)$$

Another view is given if the total cost for each class of resource is computed, for example, for human resources:

$$activity\ resource\ class\ cost_{iR} = \sum_k activity\ recource\ cost_{ik} \quad (27)$$

The results are shown in Table 11 for the AS IS process.

Obviously, to the contrary of the classical TDABC procedure, at this point it is useless adding all $activity\ cost_i$ because they have different cost objects.

Table 10). The Time-Driven ABC is adopted and, as a simplification of the problem, all resources that take part to the accomplishment of an activity are used for the same time. The last three activities do not have a duration because they were directly estimated by hospital management:

$$resource\ usage_{ix} \equiv resource\ usage_i \quad \forall x: \delta_{ix} = 1 \quad (23)$$

$$resource\ usage_i = 1 \qquad for\ i = 14, 15, 16 \quad (24)$$

Then, taking into account the unit cost per activity before calculated, the cost for each activity object was found by means of the following equation:

$$activity\ recource\ cost_{ix} = resource\ usage_i * capacity\ cost\ rate_x * \delta_{ix} \quad (25)$$

$$activity\ cost_i = \sum_x activity\ recource\ cost_{ix} \quad (26)$$

Another view is given if the total cost for each class of resource is computed, for example, for human resources:

$$activity\ resource\ class\ cost_{iR} = \sum_k activity\ recource\ cost_{ik} \quad (27)$$

The results are shown in Table 11 for the AS IS process.

Obviously, to the contrary of the classical TDABC procedure, at this point it is useless adding all $activity\ cost_i$ because they have different cost objects.

Table 10 - Duration time for each activity ($resource\ usage_i$).

i	*resource usage* $_i$	
ID	AS IS Activity time [min]	TO BE Activity time [min]
A.1	10	1
A.2	8	8
A.3	5	5
A.4	5	5
A.5	8	8
A.6	10	8
A.7	1	1
A.8	50	1
A.9	10	1
A.10	30	15
A.11	20	20
A.12	20	20
A.13	1	1
A.14		
A.15		
A.16		

Table 11 - $activity\ resource\ class\ cost_{iX}$ and $activity\ cost_i$ for the AS IS process.

A.i	*activity resource class cost* $_{iX}$				*activity cost* $_i$
ID	R HUMAN RESOURCES	E EQUIPMENTS AND ENERGY COSTS	D OTHER DIRECT COSTS	IC INDIRECT COSTS	Activity Total Cost (for Activity Object)
A.1	€ 4,62	€ 0,03	€ -	€ 0,67	€ 5,32
A.2	€ 1,52	€ 0,02	€ -	€ 0,54	€ 2,07
A.3	€ 0,89	€ -	€ -	€ 0,21	€ 1,10
A.4	€ 2,31	€ -	€ -	€ 0,21	€ 2,52
A.5	€ 1,52	€ -	€ -	€ 0,54	€ 2,05
A.6	€ 1,78	€ 0,04	€ -	€ 0,42	€ 2,23
A.7	€ -	€ 0,02	€ -	€ 0,04	€ 0,06
A.8	€ 10,65	€ 0,04	€ -	€ 0,66	€ 11,36
A.9	€ 4,62	€ 0,03	€ -	€ 0,67	€ 5,32
A.10	€ 6,21	€ 0,08	€ -	€ 1,63	€ 7,92
A.11	€ 4,26	€ 0,05	€ -	€ -	€ 4,31
A.12	€ 4,26	€ -	€ -	€ -	€ 4,26
A.13	€ -	€ 0,00	€ 0,00	€ -	€ 0,00
A.14	€ -	€ -	€ 150,00	€ -	€ 150,00
A.15	€ -	€ -	€ 2.800,00	€ -	€ 2.800,00
A.16	€ -	€ -	€ 1,00	€ -	€ 1,00

Step 4: Activity cost per item computation

This is the last step, the dependencies among activities and cost parameters are drawn (Table 12). In formulas, it is represented by the binary variable δ_{iq}.

The conversion from $activity\ cost_i$ to activity cost per each item (which links activities to the cost parameters) is made, obtaining the cost parameter value. In detail, the average value of the volume of items related to each activity object ($item\ amount_i$) was collected, as in Table 13.

Finally, the cost parameters are computed:

$$cost\ parameter\ value_q = \sum_i \frac{activity\ cost_i}{item\ amount_i} * \delta_{iq} \quad (28)$$

The value of the cost parameters are gathered in Table 7. Naturally, different cost parameters are found for the AS IS and TO BE process when the related activities differ. Moreover, h and μ were directly collected on the field.

Table 12 - Dependencies among activities and cost parameters (β_{iq})

	$cost\ parameter_q$								
	or_h	or_m	pc	tr	ps_h	ps_m	in_m	ex	d_m
ACTIVITY/COST PARAMETER ID	P.1	P.2	P.3	P.4	P.5	P.6	P.7	P.8	P.9
A.1	1								
A.2	**1**								
A.3	1								
A.4	**1**								
A.5	1								
A.6	**1**								
A.7					1				
A.8		**1**							
A.9		1							
A.10			**1**						
A.11				1					
A.12			**1**						
A.13						1			
A.14							**1**		
A.15								1	
A.16									**1**

Table 13 - Type and amount of item for each activity.

			item amount $_i$
ID	Activity Object	Activity item (for cost parameters)	Mean Number of items for activity object (in case study)
A.1	hospital pharmacy order	drug code	4
A.2	hospital pharmacy order	drug code	4
A.3	hospital pharmacy order	drug code	4
A.4	hospital pharmacy order	drug code	4
A.5	hospital pharmacy order	drug code	4
A.6	hospital pharmacy order	drug code	4
A.7	min/housing	package/min	90.000
A.8	medical unit order	drug code	19
A.9	medical unit order	drug code	19
A.10	medical unit order	package	100
A.11	medical unit order	min/transportation	20
A.12	medical unit order	package	100
A.13	min/housing	package/min	200
A.14	drug code	drug code	1
A.15	drug code	drug code	1
A.16	package	package	1

7. DESIGN AND ANALYSIS OF EXPERIMENTS

This section focuses on the design of experiments aimed at evaluating the HMM cost savings of the TO BE process as compared to the AS IS under different scenarios, by means of the following performance index:

$$\%€_{saving} = \frac{C^{AS\ IS} - C^{TO\ BE}}{C^{AS\ IS}} \quad (29)$$

Both management parameters and hospital factors (see paragraph 1.1) are considered as input parameters changing in the processes, and four experiments are shown to assess the proposal performances:

A. Case study;
B. Under the variation of ${RP_{m,f}}^{AS\ IS}$ and $LS_{m,f}$;
C. Under the variation of the drug demand variability;
D. Under the variation of the least controllable cost parameters.

The common setting parameters and hypotheses of these experiments are as follows:

1. $PT_{m,f}$ and ${RP_{m,f}}^{TO\ BE}$ are equal and coincident ($1\ day\ \forall\ m, f$)
   One of the main topics of the supply chain integration is the replenishments synchronization: identical review interval and/or sharing of information across echelons, indeed, can allow for responsiveness and risk sharing among actors, avoiding wastes related to higher stock level or penury costs (Holweg et al., 2005). Then, according to replenishments synchronization theory, the TO BE process requires $PT_{m,f} \geq {RP_{m,f}}^{TO\ BE}$, which means that the requirement can change less frequently than provisioning. The system is set in the worst condition: when requirement changes, stocks are reviewed and replenishments occur ($PT_{m,f} = {RP_{m,f}}^{TO\ BE}$).
2. $TT_m = 1\ hour = 1\ time\ bucket\ \forall m$
   This duration has been measured in several hospital pharmacies with manual workforce, without considering some faster handling (for example, automated warehouses) or transportation systems (pneumatic conveying, automated guided vehicles, etc.).
   Moreover, in the TO BE process, because the medical unit replenishment occurs TT_m time buckets afterwards physician round and considering the assumption number 1, the medical unit

safety stocks should cover the variability of demand during TT_m. Prescriptions are recorded at the beginning of specific time buckets (at the end of physician rounds) and administrations happen at the end of each t_j, which lasts 1 hour, the TT_m duration is non-influential on the consumption rate as new orders are fulfilled in time for the first administrations. As a result, in the following experiments, the medical units under the TO BE process do not need to maintain safety stocks while they are fed by the hospital pharmacy.

3. $LT_f = 1\,day \;\; \forall f$
   In the same way as for the medical unit (assumption 1), to be most efficient, it should be $LT_f \leq {RP_{m,f}}^{TO\,BE}$ at the hospital pharmacy level. This means that, during the time between two replenishments to medical units, the hospital pharmacy has time to restock its warehouses. Again, the TO BE system is set in the worst conditions: immediately after medical unit replenishments and based on the requirement of the next time buckets, orders to suppliers are backward-planned and delivered when needed, being fulfilled when new replenishments have to be organised. In such a way, the hospital pharmacy blind period is LT_f ($LT_f = {RP_{m,f}}^{TO\,BE}$). In contrast, the AS IS process has a blind period equal to ${RP_{m,f}}^{AS\,IS}$ plus the LT_f of suppliers.
4. $S_{m,f}$ and AV_{m,f,t_1} values $\forall f, m$.
   While par levels ($S_{m,f}$) for the AS IS process are set to cover average demand and its variability according to the service level $LS_{m,f}$, initial stocks AV_{m,f,t_1} for both processes are selected to cover the requirement of the first blind period:
   - in the AS IS process, it is equal to the par level $S_{m,f}$;
   - in the TO BE process, it is equal to the $SS_{m,f}$ in the pharmacy and, taking into account the same initial circumstances for both processes, equal to the average demand and its variability in ${RP_{m,f}}^{TO\,BE}$ in the medical units' warehouses.

The simulation length was 1110 days (approximate 3 years). Three replications were provided to compensate for the effects of extractions over the time of the Monte Carlo simulation and thus accurately estimate the drug demand distributions.

When the parameters were changed, moreover, the same seed was used at each replication to compare systems under the same conditions.

7.1 EXPERIMENT A

In the case study, as in many other hospitals, the maximum service level was requested at each echelon of the supply chain and orders (from medical units and hospital pharmacy) were issued about twice a week (each 3 days). The parameter setting is as in Table 14, while the mean results are reported in Table 15, in which the advantage of adopting the TO BE process in the case study is shown.

Table 14 – Experiment A. Design of experiment

Factor	Level
$\boldsymbol{LS_{m,f}}$ [%]	100%
$\boldsymbol{RP_{m,f}}^{\boldsymbol{AS\ IS}}$ [day]	**3**

Table 15 – Experiment A. Results

	Mean	Standard Deviation
$\boldsymbol{\%€_{saving}}$ **[%]**	3.69	0.07

The simulation length, along with the number of repetitions, ensured that the real demand variability over time was accurately reproduced during the simulation runs (the standard error, with a confidence level of 95%, was 0.20 (Chung, 2004)).

Examining the expenditure distribution on the cost items for both processes (Table 16), as expected, the main cost was related to purchasing (C_P). Obviously, the amount of drugs consumed in both processes was the same, but there was a difference in the purchased quantity. Indeed, in the AS IS process materials were purchased on the basis of forecasts (expressed by the par level concept) but part of them was not used because not prescribed to patients. To the contrary, in the TO BE process it was bought only what was really needed, safety stocks were kept only in the pharmacy warehouse and the warehousing time was shorter (these were also the reasons of the savings in warehousing cost C_W). Anyway, purchasing savings accounted for 27.39% of total savings.

The TO BE process shown a little increase in the handling cost (C_H) because all needed drug codes in medical units had to be taken from the pharmacy at each $RP_{m,f}{}^{TO\ BE}$, while the transportation costs (C_T), considered in the model as directly proportional to the number of deliveries, tripled in the TO BE process.

Finally, the TO BE process had no stock-outs events while in the AS IS one, although warehouses were fully provisioned, some internal and external stockouts occurred.

According to the cost formulation of chapter 4, the total cost attributed to the two echelons (hospital pharmacy and medical units) was computed. In particular, ordering, purchasing, warehousing, handling

and external stockout costs were attributed to the first one, while to the second one ordering, warehousing, handling, transportation and internal stockout costs were charged. The cost comparison shown evident advantages both in the medical units (68.90% cost savings, see Figure 28), and in the hospital pharmacy (1.77% cost reduction). Finally, an example of inventory build-up diagram for a drug code at the two echelons is presented in Figure 29 and Figure 30

Table 16 – Experiment A. HMM costs distribution and TO BE cost savings for Each Cost Item

Cost item	C_O Ordering	C_P Purchasing	C_W Warehousing	C_H Handling	C_T Transp.	C_{IS} Int.Stockout	C_{ES} Ext.Stockout
AS IS expenditure distribution [%]	0.23	95.41	3.79	0.35	0.09	0.05	0.07
TO BE expenditure distribution [%]	0.21	98.01	1.11	0.37	0.30	0.00	0.00
$\%€_{saving}$ [%]	**9.03**	**1.06**	**71.82**	**- 0.33**	**- 200.42**	**100.00**	**100.00**

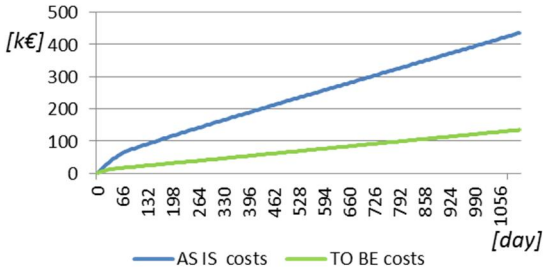

Figure 28 - Experiment A. Medical unit costs of the AS IS and TO BE Processes over Time ($\forall m \neq h$).

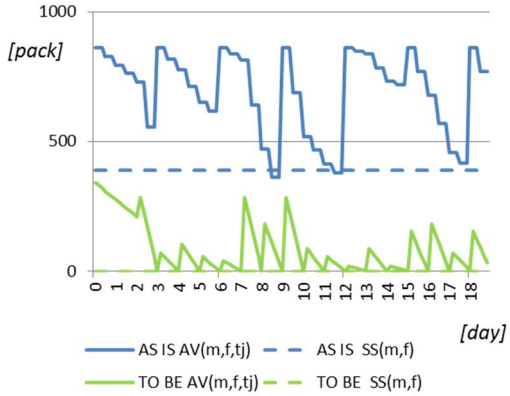

Figure 29 - Experiment A. Inventory Build-up Diagram of AS IS and TO BE Processes. f=1 and m=1.

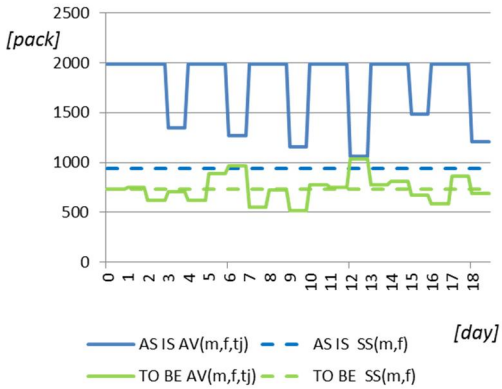

Figure 30 - Experiment A. Inventory Build-up Diagram of AS IS and TO BE Processes. *f*=1 and *m*=h.

7.2 EXPERIMENT B

The first generalisation in the process performance comparison was made by analysing the behaviours of the HMM system under the variation of the input parameters of Experiment A (Table 17).

The variation of $RP_{m,f}{}^{AS\ IS}$ was oriented to configure a number of scenarios with which many hospitals can identify, that is, the case in which the frequency of replenishments occurs about once a week ($RP_{m,f}{}^{AS\ IS} = 6$) or, at the other extreme, once a day ($RP_{m,f}{}^{AS\ IS} = 1$). This last value is particularly important because it allows to evaluate the performance of the TO BE process under the same $RP_{m,f}$ as the AS IS process.

The variation of $LS_{m,f}$, on the other hand, was taken into account to assess the potential for a reduction in safety stocks and par levels compared to the full warehouses shown in Figure 30. Such a variation was tested in both the TO BE and AS IS processes. As previously mentioned, a reduction in $LS_{m,f}$ in this thesis does not correspond to a decrease in the quality of care provided to patients, because urgent procedures are activated and the drugs are always delivered on time. Obviously, such urgency is managed at higher costs (C_{ES} and C_{IS}), which reflect the increase in the organisational complexity required to cope with the issue. Instead of considering service level as a system requirement (as made, for example, by Nicholson et al.. 2004), the critical ratio of the newsboy model was adopted to set $LS_{m,f}$, thus minimising the cost incurred in the case of overage or underage of items with respect to the quantity demanded (Graves et al., 1993).

$$LS_{calc} = \frac{C_{underage}}{C_{underage}+C_{overage}} \tag{30}$$

where:

- $C_{underage}$: unit cost of underage, that is, the difference between the penalty cost for not having the requested material and the cost not incurring in purchasing the material.
- $C_{overage}$: unit cost of overage, that is, the sum of holding costs for the remaining inventory (purchased, but not sold at the end of the period) and the cost to purchase the material (at the end of the period, non-retrievable).

This expression is applied when the product's useful life lasts only one planning period (Graves et al., 1993), with many different extensions being made (Khouja, 1999). The formulation is here readapted to a multiple period probabilistic demand framework, while excluding the purchasing cost, since the material can be later used if not requested in the reorder period $RP_{m,f}$:

- $C_{underage}{}_{m,f,RP_{m,f}}$: unit cost of underage for medical unit *m*, drug *f*, and generic reorder period $RP_{m,f}$. It is the cost borne in the management of internal stockouts. Since the cost structure of chapter 4 considers an internal stockout cost for each code, independently of the lacking quantity, it was used a dummy stockout quantity as the one that falls between 95% up to 100% (the last 5-th percentile) of the CDF in the blind period ($DQs_{m,f,RP_{m,f}}$ with $m \neq f$). The same hypothesis was made for external stockout costs in the hospital pharmacy (m=h).
- $C_{overage}{}_{m,f,RP_{m,f}}$: unit cost of overage for medical unit *m*, drug *f*, and generic review period $R_{m,f}$. It is the cost to keep one package of material, not used in the period of time, in the medical unit warehouse. In the cost structure, it corresponds to the unit warehousing cost because the ordering and distribution costs are independent of the quantity replenished at each time period except for the handling costs.

The expressions are thus:

$$C_{underage_{m,f,RP_{m,f}}} = \begin{cases} \frac{in_m}{DQS_{m,f,RP_{m,f}}} & \forall f, \forall m \neq h \\ \frac{ex}{DQS_{m,f,RP_{m,f}}} & \forall f, m = h \end{cases} \quad (31)$$

$$C_{overage_{m,f,RP_{m,f}}} = \left[ps_m + h * P_f + \mu * (d_m + P_f)\right] * R_{m,f} \quad \forall f, \forall m \quad (32)$$

The factors-levels table below (Table 17) summarises the setting of the parameters for experiment B, while $LS_{calc_{m,f}}$ formula adoption in the AS IS process gave the results of Table 18.

Table 17 – Experiment B. Design of experiment

Factors	Levels
$\boldsymbol{LS_{m,f}}$ **[%]**	$\begin{cases} 100\% \\ LS_{calc_{m,f}} \end{cases}$
$\boldsymbol{RP_{m,f}}^{\boldsymbol{AS\ IS}}$ **[days]**	$\begin{cases} 1 \\ 3 \\ 6 \end{cases}$

Table 18 – Mean and Standard Deviation of $\boldsymbol{LS_{calc_{m,f}}}$ in the AS IS Process, with $\boldsymbol{RP_{m,f}}^{\boldsymbol{AS\ IS}} = 3$

Warehouse	Mean [%]	Standard Deviation [%]
Medical Units	95.50	9.0
Hospital Pharmacy	99.99	0.5

First of all, just looking at the cost performance of the AS IS process under the variation of the service levels $LS_{m,f}$ (Table 19), it results that $LS_{calc_{m,f}}$ works better than $LS_{m,f} = 100\%$ when ${RP_{m,f}}^{AS\ IS} > 1$. Indeed, in these two cases it was not optimal to completely fill the warehouses to avoid stockouts, because there was a trade-off between stockout and keeping costs, which could force the system to lower stocks. When ${RP_{m,f}}^{AS\ IS} = 1$ the situation was inverted because the time horizon was not large enough to test the compensation of effects when more than one "demand" event is taken from the demand distribution. However, in this specific, but rather rare case, filling the warehouses was more convenient.

The $LS_{calc_{m,f}}$ formula did not obtain such a significant advantage in the case of the TO BE process, where it was about 0.04%.

Finally, the cost savings of the TO BE process on the AS IS in the experiment B are presented in Figure 31. In particular, $\%€_{saving}$ is always positive, also when $LS_{calc\,m,f}$ is adopted, and it is the higher the longer is $RP_{m,f}^{AS\ IS}$.

Table 19 – Experiment B. Behaviour of the AS IS process

$RP_{m,f}^{AS\ IS}$ levels	Average % of savings of $LS_{calc\,m,f}$ on $LS_{m,f}$ = 100% in the AS IS model [%]
1	-0.42
3	0.32
6	1.60

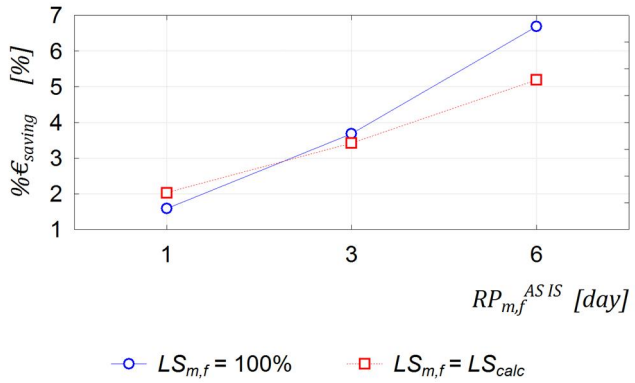

Figure 31 - Experiment B. Percentage of savings for the TO BE Process Compared to the AS IS Process ($\%€_{saving}$). $LS_{m,f}$ * $RP_{m,f}^{AS\ IS}$. Repeated Measures Analysis of Variance. Sigma-restricted Parameterisation. Effective Hypothesis Decomposition. ***Fisher (2,12)=271.14 p=0.00000.***

7.3 EXPERIMENT C

The second generalisation introduced with respect to the case study was the variation in drug demand PDF that could be experienced by hospitals. Indeed, a hospital dedicated to chronic diseases has a stable demand over the time, while an emergency care centre with many medical specialties is characterised by higher variability.

The drug demand variability is measured as the coefficient of variation (D) of the sum of the medical unit drug demand variables. Two new demand scenarios to test the cost performances of the proposal were introduced. Moreover, the same levels of the AS IS reorder periods as in experiment B were retained, and $LS_{calc_{m,f}}$ was used to set the safety stock, using the worst-case scenario in terms of TO BE savings (Table 21).

Table 20 – Experiment C. Design of experiment

Factors	Levels
$\boldsymbol{D}$ **[%]**	$\begin{cases} 48\% \ (D_{high}) \\ 0\% \ (D_{average}) \\ -30\% \ (D_{low}) \end{cases}$
$\boldsymbol{RP_{m,f}^{AS\ IS}}$ **[day]**	$\begin{cases} 1 \\ 3 \\ 6 \end{cases}$
$\boldsymbol{LS_{m,f}}$ **[%]**	$LS_{calc_{m,f}}$

The effects of demand variability on stock levels are clear if the following two inventory build-up diagrams are graphically compared (Figure 32 and Figure 33).

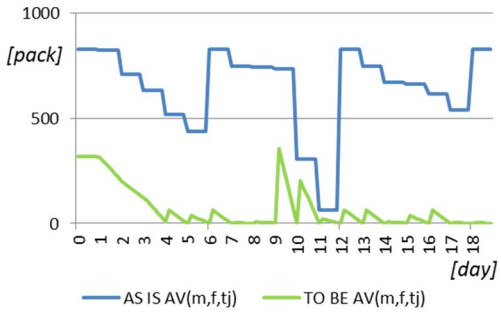

Figure 32 - Experiment C. Inventory Build-up Diagram of AS IS and TO BE processes. D_{high} and $RP_{m,f}^{AS\ IS} = 6$, with $f = 1$ and $m = 1$

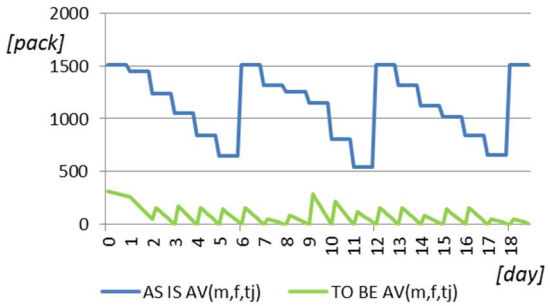

Figure 33 - Experiment C. Inventory Build-up Diagram of AS IS and TO BE processes. D_{low} and $RP_{m,f}^{AS\ IS} = 6$, with $f = 1$ and $m = 1$

With reference to Figure 34, as expected from the literature, a higher demand variability was better managed with a look-ahead instead of look-back approach, and the TO BE process allowed best cost performances over the AS IS process, while the effect of the $RP_{m,f}^{AS\ IS}$ hospital choice remained a key element. Indeed, the management of higher variability can be done by focusing on information about requirements or increasing the frequency of checks and replenishments. Moreover, when the demand was stable (for D_{low}, the overall medical unit variability coefficient was 0.19), the proposed scenario remained advantageous.

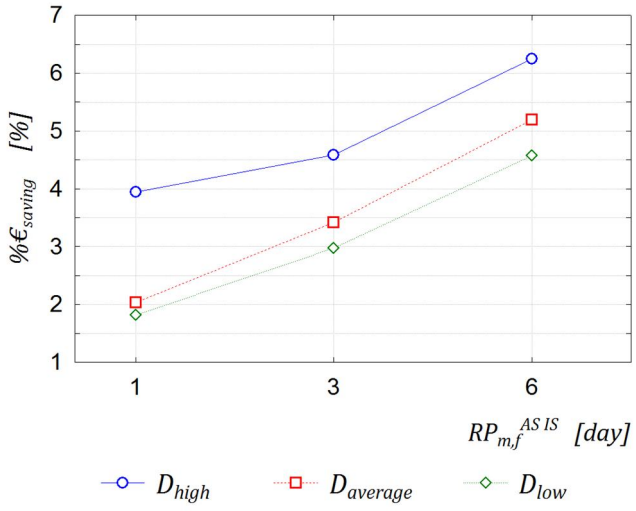

Figure 34 - Experiment C. Percentage of Savings in the TO BE Process Compared to the AS IS ($\%€_{saving}$). $D_{level} * RP_{m,f}^{AS\ IS}$. Repeated Measures Analysis of Variance. Sigma-restricted Parameterisation. Effective Hypothesis Decomposition. *Fisher(4,18) = 33,153 p = 0,00000.*

7.4 EXPERIMENT D

The final analysis took into account the variability of cost parameters, focusing on external stockouts (ex) and pharmacy ordering costs in the AS IS process ($or_h{}^{AS\ IS}$) with respect to other factors that are more controllable by the hospital:

1. ex is the most uncertain cost because it depends on intangible aspects besides logistics costs;
2. or_h is highly dependent on supply chain management and governmental regulations.

The same levels used for $LS_{m,f}$ and $RP_{m,f}{}^{AS\ IS}$ in experiment B were maintained.
The levels chosen for the mentioned factors are shown in Table 21.

Table 21 – Experiment D. Design of experiment

Factors	Levels
$\boldsymbol{or_h{}^{AS\ IS}}$ **[%]**	$\begin{cases} 30\%\ (or_{high}) \\ 0\%\ (or_{average}) \\ -30\%\ (or_{low}) \end{cases}$
$\boldsymbol{ex}$ **[%]**	$\begin{cases} 30\%\ (ex_{high}) \\ 0\%\ (ex_{average}) \\ -30\%\ (ex_{low}) \end{cases}$
$\boldsymbol{RP_{m,f}{}^{AS\ IS}}$ **[day]**	$\begin{cases} 1 \\ 3 \\ 6 \end{cases}$
$\boldsymbol{LS_{m,f}}$ **[%]**	$LS_{calc_{m,f}}$

Given that the combination $or_{average}$ - $ex_{average}$ represents the baseline, it was expected that, in case of or_{high}, the TO BE process would be more convenient because the cost function is proportionally linear to the factor; when $ex = ex_{high}$, the performance was not easily predictable in association with the equation of LS_{calc} (30).

The results are presented in Figure 35. As in the previous experiment, the higher was the $RP_{m,f}{}^{AS\ IS}$, the higher were the savings, and $\%€_{saving}$ was always positive. In particular, the savings in adopting the TO BE process were the highest when $or_h{}^{AS\ IS}$ and ex increased, with the opposite result when they both decreased. However, the variation range between the two extremes was smaller (maximum 12.00% loss when passing from the minimum to maximum savings in case $RP_{m,f}{}^{AS\ IS} = 1$), which suggests that, by using $LS_{calc_{m,f}}$, the processes are rather robust to cost variations.

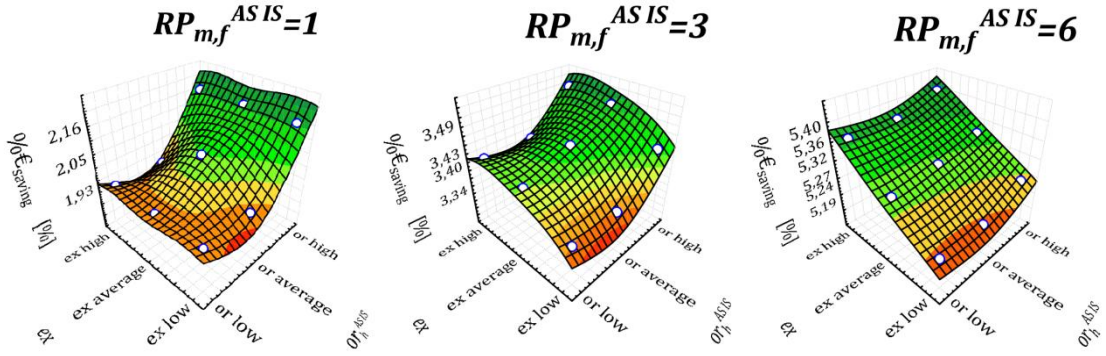

Figure 35 - Experiment D. Percentage of Savings in the TO BE Process Compared to the AS IS ($\%€_{saving}$).

CONCLUSIONS

This thesis proposes an integrated approach to hospital data management, with the aim at developing and demonstrating the advantages of a look-ahead inventory policy applied on hospitals materials, basing pharmacy orders to suppliers on requirements of physicians' prescriptions coming from CPOE and, then exploiting the advantages of stock centralization. Moreover, with a holistic approach to HMM process, it shows how to increase patient safety thanks to clinical information traceability, while freeing personnel from time-consuming managerial tasks.

With these objectives, a streamlined HMM process has been designed, implemented in a BPM suite and verified in terms of completeness and usability by hospital personnel. Then, the MRP algorithm has been customised for a hospital framework, a comprehensive cost performance indicator has been developed, the proposed process (TO BE) and the traditional one (AS IS) have been designed by means of a discrete event simulation.

To test the performances of the proposal, HMM data from a medium-scale hospital have been collected and total HMM costs in both processes have been compared, while making variations to the main parameters. Under non-restrictive assumptions, the savings ranges from 2% to 7% of the total cost, what means that significant benefits can be achieved in optimising hospital operations. Moreover, because the proposed process has been tested under worst-case setting scenarios, further experiments may be carried out to define the highest savings in the case study.

Analysing the results of the simulations, it has been found that the traditional AS IS process can also achieve economic advantages by seeking a balance between underage and overage material costs rather than filling warehouses to prevent stockouts; the longer is the replenishment period, the more expensive is the HMM process, while the higher is the drug demand variability, the greater is the convenience of a look-ahead approach. Furthermore, there has been little influence on the total cost performance when external stockouts and pharmacy ordering costs varied.

Further studies should aim to explore the effect of stochastic supplier lead-times on the performances of the proposed system. Resources capacities and load conditions should also be taken into account (MRP II) to optimise the frequency and scheduling of HMM activities if a particular hospital wants to adopt the proposal.

Finally, it is worth to note that different policies can be chosen according to the material demand profiles. Indeed, while drug prescriptions and administrations should always be recorded for patient safety and monitoring or governmental regulations, other materials, such as "general goods" devices (for example, bandages or gloves), do not need such details on demand and consumption. For this reason, in order to assess the overall system saving, hybrid inventory management policies, embracing both the look-back and look-ahead approaches and with different reordering periods, should be analysed when the proposal is under evaluation by a particular hospital.

LIST OF ACRONYMS

ABC	Activity-Based Costing
ATC	Anatomic-Therapeutic-Chemical
BPM	Business Process Management
BPML	Business Process Modeling Language
BPMN	Business Process Modeling Notation
CDF	Cumulative Distribution Function
CPOE	Computer Physician Order Entry
CS	Consignment Stock
HIS	Hospital Information System
HMM	Hospital Materials Management
ICA	Contra-Indication and Allergies
IHE	Integrating the Healthcare Enterprise
IT	Information Technology
FIFO	First In-First Out
JIT	Just In Time
MSC	Monte Carlo Simulation
MRP	Material Requirements Planning
PCM	Patient-Centred Management
PDF	Probability Distribution Function
PMR	Patient Medical Record
POQ	Period Order Quantity
RP	Reorder Period
TDABC	Time-Driven Activity Based Costing

NOTATION

LIST OF INDICES AND SETS

$\boldsymbol{f}$	drug code, with $f \in F$
$\boldsymbol{F}$	set of list of drugs used in a hospital, with $f \in F$
$\boldsymbol{h}$	hospital pharmacy, with $h \in M$
$\boldsymbol{m}$	medical unit, with $m \in M$
$\boldsymbol{M}$	set list of medical units, with $M = \{1, \dots, m, \dots, h\}$
$\boldsymbol{o}$	indirect cost addressable to activities of the HMM process, with $IC.o \in IC$
$\boldsymbol{p}$	medical prescription for a patient, with $p \in PP$
$\boldsymbol{PP}$	set of prescriptions made by physicians, with $p \in PP$
$\boldsymbol{t_j}$	time bucket, with $t_j \in T$
$\boldsymbol{T}$	observation time, with $T = \{t_1, \dots, t_j, \dots, t_J\}$

LIST OF INDICES AND SETS FOR CHAPTER 6 only

$\boldsymbol{A}$	set of activities of HMM process, with $A = \{A.i\}$
D	set of direct costs (different from E and R)related to the HMM process, with $D = \{D.l\}$
$\boldsymbol{e}$	equipment and energy need for the HMM process, with $E.e \in E$
E	set of equipment and energy need for the HMM process, with $E = \{E.e\}$

$\boldsymbol{i}$	activity of HMM process, with $A.i \in A$
$\boldsymbol{IC}$	set of indirect costs addressable to activities of the HMM process, $IC = \{IC.o\}$
$\boldsymbol{k}$	human resource working at the HMM process, with $R.r \in R$
$\boldsymbol{l}$	direct cost (different from *E* and *R*) related to the HMM process, with $D.l \in D$
$\boldsymbol{P}$	set of cost parameters of the HMM process, with $P = \{P.q\}$
$\boldsymbol{q}$	cost parameter of the HMM process, with $P.q \in P$
$\boldsymbol{r}$	human resources working at the HMM process, with $R.r \in R$
R	set of human resources working at the HMM process, with $R=\{R.r\}$
$\boldsymbol{x}$	resource class, with $X.x \in X$
$\boldsymbol{X}$	set of resource classes, with $X = \{X.x\} = \{R.r, E.e, D.l, IC.o\}$

LIST OF ABBREVIATIONS

$\boldsymbol{activity\ cost_i}$	activity cost, depending on resources implied in the activity execution
$\boldsymbol{activity\ object_i}$	the type of object the activity refers to
$\boldsymbol{activity\ resource\ class\ cost_{iX}}$	activity *i* cost, depending on the class of resource *X*
$\boldsymbol{activity\ resource\ cost_{ix}}$	resource *x* cost to perform the *i* activity, depending on resources consumption
$\boldsymbol{AV_{m,f,t_j}}$	available quantity
$\boldsymbol{C}$	total cost of HMM
$\boldsymbol{capacity\ cost\ rate_x}$	cost of the resource *x* for unit of driver
$\boldsymbol{capacity\ of\ resource_x}$	amount of resource driver (intensity, transaction or duration driver) that the resource *x* can afford in a period of time
$\boldsymbol{C_{D_{m,t_j}}}$	distribution cost
$\boldsymbol{C_{ES_{h,f,t_j}}}$	external stockout cost
$\boldsymbol{C_{H_{m,f,t_j}}}$	handling costs
$\boldsymbol{C_{IS_{m,f,t_j}}}$	internal stockout cost
$\boldsymbol{C_{m,f}}$	replenishment scheduling, with $C_{m,f} = [c_{m,f,0}, c_{m,f,1}, c_{m,f,1+RP_{m,f}}, \dots, c_{m,f,k}, \dots, c_{m,f,K}]$
$\boldsymbol{c_{m,f,0}}$	immediate urgent replenishment, with $c_{m,f,0} \in C_{m,f}$
$\boldsymbol{c_{m,f,k}}$	k^{th} time bucket at which a replenishment starts, with $c_{m,f,k} \in C_{m,f}$
$\boldsymbol{C_{O_{m,f,t_j}}}$	ordering cost
$\boldsymbol{cost\ parameter\ value_q}$	value of the *q*-th cost parameter
$\boldsymbol{C_{overage_{m,f,RP_{m,f}}}}$	unit cost of overage
$\boldsymbol{C_{P_{m,f,t_j}}}$	purchasing cost
$\boldsymbol{C_{T_{m,t_j}}}$	transportation cost
$\boldsymbol{C_{underage_{m,f,RP_{m,f}}}}$	unit cost of underage
$\boldsymbol{C_{W_{m,f,t_j}}}$	warehousing cost
$\boldsymbol{d_m}$	disposal cost per unit of package
$\boldsymbol{D_{level}}$	coefficient of variation of the sum of the medical unit drug demand variables; levels of the factor *D* are: D_{high} , $D_{average}$ and D_{low}
$\boldsymbol{DT_m}$	delivery time

$\boldsymbol{\delta_{T_m}(t_j)}$	dirac delta, taking into account the existence of transportations
$\boldsymbol{\delta_{ES_{h,f}}(t_j)}$	dirac delta, taking into account the existence of external stockout
$\boldsymbol{\delta_{iq}}$	dirac delta, taking into account the dependence of the cost parameter *q* on the activity *i*
$\boldsymbol{\delta_{IS_{m,f}}(t_j)}$	dirac delta, taking into account the existence of internal stockout
$\boldsymbol{\delta_{ix}}$	dirac delta, taking into account the usage of the resource class *x* to accomplish the activity *i*
$\boldsymbol{\delta_{O_{m,f}}(t_j)}$	dirac delta, taking into account the existence of orders
$\%€_{saving}$	Percentage of cost savings of the TO BE process compared with the AS IS one.
$\boldsymbol{ex}$	cost of external urgent delivery from suppliers for *f*
$\boldsymbol{ex_{level}}$	levels of the factor ex are: ex_{high} , $ex_{average}$ and ex_{low}
$\boldsymbol{expenses\ of\ resource_x}$	cost of the resource for a period of time
$\boldsymbol{GR_{m,f,t_j}}$	gross requirement
$\boldsymbol{in_m}$	cost of internal urgent delivery from hospital pharmacy for each *f*
$\boldsymbol{item\ amount_i}$	average number of items comprised in the $activity\ item_i$
$\boldsymbol{LS_{calc_{m,f}}}$	$LS_{m,f}$ calculated by means of a modified version of the critical ratio of the newsboy model
$\boldsymbol{LS_{m,f}}$	service level
$\boldsymbol{LT_f}$	supplier lead time
$\boldsymbol{\mu}$	stock decay rate
$\boldsymbol{N_f}$	number of units of drug contained in a package
$\boldsymbol{NR_{m,f,t_j}}$	net requirement
$\boldsymbol{or_{level}}$	levels of the factor ${or_h}^{AS\ IS}$ (or_{high} , $or_{average}$ and or_{low})
$\boldsymbol{or_m}$	ordering cost for each *f*
$\boldsymbol{pc}$	handling costs per unit of package
$\boldsymbol{ps_m}$	physical system cost (part of warehousing)
$\boldsymbol{POH_{m,f,t_j}}$	projected on hand quantity
$\boldsymbol{POL_{m,f,t_j}}$	planned order releases

$\boldsymbol{POR}_{m,f,t_j}$	planned order receipts
$\boldsymbol{PT}_m$	time between two physician rounds
$\boldsymbol{Q}_{p,m,f,t_j}$	administration quantity
$\boldsymbol{Q}_{ST_{m,f,t_j}}$	medical unit stockout quantity
$\boldsymbol{QTR}_{m,f,t_{j-TT_m}}$	quantity to release
$\boldsymbol{resouce\ usage}_{ix}$	amount of resource *x* driver used to perform the activity *i*.
$\boldsymbol{RP}_{m,f}$	review period
$\boldsymbol{S}_{m,f}$	par level
$\boldsymbol{SR}_{m,f,t_j}$	scheduled receipts
$\boldsymbol{SS}_{m,f}$	safety stock
$\boldsymbol{SSR}_{m,f}$:	safety stock to restore
$\boldsymbol{tr}$	cost of transportation expressed in value per time bucket
$\boldsymbol{TT}_m$	internal replenishment lead time

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