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Strategic Decisions in the Configuration of the Health Care Supply Chain

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Para o Tiago, o Simão e o Miguel

Para o José António

Para os meus Pais

Pensa bem no teu plano
Recomenda o tucano!
[...]
Anda lá e tenta
Diz o pangolim magenta!
[...]
Nos teus pensamentos mergulha
Canta o bico de agulha!
[...]
Questiona, questiona e sempre questiona
Relembra o macaco-mona!
[...]
Dança quando chegares ao fim
Sugere o guaxinim!

“Bons conselhos de amigos animais”, Richard Zimler

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Resumo

Nas últimas décadas, os custos associados à saúde têm aumentado de forma significativa, à medida que mais pessoas acedem à prestação de cuidados, e o desenvolvimento e disseminação de novos tratamentos permitem que um maior número de doenças seja tratável. Conter os custos dos sistemas de saúde e, ao mesmo tempo, assegurar serviços de qualidade e sem falhas de segurança constitui, por isso, um importante desafio. Ao nível da cadeia de abastecimento existem oportunidades para, simultaneamente, melhorar a utilização de recursos e os processos, beneficiando o serviço prestado. Assim, tendo a complexidade da cadeia de abastecimento da saúde vindo a aumentar por influência das tendências no setor, o esforço para promover a sua melhoria deverá ser significativo e permanente.

Neste contexto, uma identificação clara de grupos de materiais (ou serviços), homogéneos em termos das competências que requerem da cadeia de abastecimento hospitalar, e a ligação desses grupos a estratégias operacionais da cadeia de abastecimento (definidas através de competências, processos e recursos operacionais) específicas e apropriadas, poderá facilitar a tarefa dos gestores aquando da seleção da estratégia a aplicar e da melhor forma para a implementar. Poderá ainda contribuir para aumentar a eficiência e a eficácia da cadeia, uma vez que favorece um melhor direcionamento de ações e dos esforços de gestão e financeiro (por exemplo, no que diz respeito à definição do nível e posicionamento de stocks de segurança).

No segundo capítulo desta dissertação, é feita uma síntese da literatura relacionada com o tema da segmentação da cadeia de abastecimento de materiais em contexto hospitalar, através da análise, conciliação e resumo de informação relacionada com as variáveis de segmentação utilizadas, os segmentos daí resultantes e as estratégias operacionais recomendadas para os diversos segmentos. Os resultados deste trabalho foram comparados com informação qualitativa obtida em dois centros hospitalares. As discrepâncias entre a informação proveniente das duas fontes poderão indiciar possíveis falhas na investigação ou nas práticas de gestão.

De seguida, no trabalho descrito no terceiro capítulo, efetuamos uma Análise de Agrupamentos[1] para segmentar os materiais (mais concretamente, os produtos farmacêuticos, materiais clínicos e dispositivos médicos) fornecidos pela cadeia de abastecimento hospitalar. A segmentação determinada baseia-se em características dos artigos consideradas como relevantes para distinguir as competências operacionais que os diferentes segmentos requerem da cadeia. No âmbito deste trabalho, propomos uma medida representativa da *criticidade* de um artigo em contexto hospitalar, relacionada com o serviço. Foi ainda estabelecida uma ligação entre os segmentos identificados (artigos *caros de uso específico*; artigos de *volume elevado e uso*

[1] Mais conhecida por *Análise de Clusters*.

frequente e generalizado; e artigos *críticos*) e as competências, processos e recursos operacionais da cadeia de abastecimento que têm sido recomendados para gerir artigos com as mesmas características.

No quarto e quinto capítulos apresentam-se modelos para apoiar a definição de estratégias na cadeia de abastecimento de artigos de *volume elevado e uso frequente e generalizado* em contexto hospitalar.

Num setor onde tradicionalmente as mudanças são difíceis de implementar e manter, e em que as decisões afetam múltiplos intervenientes, o desenvolvimento de *simuladores* simples para os processos de gestão da cadeia de abastecimento pode facilitar a observação e análise dos efeitos de decisões alternativas e a conciliação dos vários, e frequentemente conflituosos, interesses envolvidos. Assim, no quarto capítulo, a perspetiva de análise foca-se na cadeia de abastecimento hospitalar interna, e envolve o desenvolvimento e simulação de vários modelos de Dinâmica de Sistemas para analisar processos operacionais alternativos. Nomeadamente, são tratados os seguintes processos: controlo descentralizado dos stocks sem partilha de informação *versus* controlo centralizado dos stocks com alguma partilha de informação; possibilidade de entregas de emergência do Centro de Distribuição (CD), em caso de rutura de stock num serviço clínico; atribuição de prioridade à Urgência na alocação de stock do CD, no caso de o stock aí disponível não ser suficiente para satisfazer os pedidos de todos os serviços clínicos; fornecimentos laterais dos restantes serviços clínicos para a Urgência. Para além disso, analisaram-se os efeitos de algumas práticas de gestão, habituais em hospitais e com origem em razões comportamentais, nomeadamente, a tendência para acumular stocks para “se algo correr mal”.

No quinto capítulo desta dissertação, apresentamos uma abordagem para determinar o número, tamanho e composição de grupos de compra, para um conjunto de hospitais dispostos a cooperar, minimizando os custos partilhados da respetiva cadeia de abastecimento. Esta abordagem revela o impacto financeiro das várias alternativas de cooperação, para o grupo e para cada um dos participantes, abrindo caminho a processos de negociação sobre a distribuição dos custos e ganhos decorrentes da cooperação. A abordagem proposta, desenvolvida a partir de uma meta-heurística híbrida “Pesquisa de Vizinhança Variável[2] / Pesquisa Tabu”, resultou numa ferramenta flexível que pode ser aplicada a grupos de compras com caraterísticas diversas, nomeadamente, em termos das suas circunstâncias operativas e de mercado, e a cadeias de abastecimento com diferentes topologias e custos atípicos. Os resultados computacionais preliminares obtidos demonstram o potencial da abordagem desenvolvida, para a resolução de um conjunto alargado de problemas.

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[2] Conhecida através da sigla VNS.

Abstract

In the last decades, health care costs have increased as more and more people have access to services, additional diseases become treatable and related new treatments are developed and disseminated. Holding health care costs down, while assuring services quality and safety is therefore an important challenge. The health care supply chain entails opportunities for both better resource utilisation and processes enhancements, with a positive impact on service. Thus, as health care developments have in general increased its inherent complexity, there is a growing need for continuous and significant health care supply chain improvement.

A clear identification of groups of materials (or services) that are homogeneous in terms of the capabilities they require from the hospital system supply chain, and the linkage of these groups with specific adequate operational supply chain strategies (defined by associated operational capabilities, processes and resources) may facilitate the task of the managers when deciding which supply chain strategy to apply and how to implement it. This identification can also contribute to increase the efficiency and the effectiveness of the supply chain system, as it favours a better targeting of actions and managerial and financial (e.g., concerning safety stock levels) efforts.

In the second chapter of this dissertation, we synthesise the literature related to hospital materials supply chain segmentation, by analysing, reconciling and condensing information related to the segmentation variables used, the resulting segments, and the recommended operational strategies for those segments. The results of this effort are compared with qualitative information collected from two hospital systems. The discrepancies between the information collected from the two sources are indicative of research or managerial gaps.

Then, in the third chapter, we use Cluster Analysis to segment the items flowing in a hospital supply chain (pharmaceutical, medical and clinical materials). For the different items, this segmentation is based on the characteristics that are relevant in terms of the operational supply chain capabilities required by the different segments. In the course of this work, we proposed a service related proxy for hospital item *criticality*. The identified segments (namely, *expensive, specific use* items; *high volume, frequent and generalised use* items; and *critical* items) were linked to operational supply chain capabilities, processes and resources that have been recommended for their management.

The research work described in the fourth and fifth chapters concerns the development of models to support the definition of supply chain strategies for hospital *high volume, frequent and generalised use* items.

In a sector where traditionally changes are difficult to implement and sustain, and where multiple stakeholders are involved, the development of simple supply chain management process *simulators* can facilitate the observation and analysis of the effects of alternative decisions and the conciliation of the involved, often conflicting interests. Thus, in the fourth chapter, the focus was on the internal hospital supply chain, with the development of several System Dynamics models, to simulate and analyse alternative supply chain operational processes. These processes involved: decentralised inventory control with no information sharing *versus* centralised inventory control and some information sharing; the possibility of emergency deliveries from the Distribution Centre (DC) in case of a stock-out at a ward; giving (or not) priority to the emergency room (ER) in the allocation of inventory when the inventory on hand at the DC is insufficient to meet all requests; and/or the existence of lateral transshipments from the other wards to the ER. Furthermore, the effects of some usual behavioural-based hospital management practices, namely the "just-in-case" approach to inventory control, are analysed.

In the fifth chapter, we present an approach for recommending the number, size and composition of purchasing groups, for a set of hospitals willing to cooperate, while minimising their shared supply chain costs. This approach makes the financial impact of the various cooperation alternatives transparent to the group and to the individual participants, opening way to a negotiation process concerning the allocation of the cooperation costs and gains. The approach was developed around a hybrid "Variable Neighbourhood Search (VNS) / Tabu Search" metaheuristic, resulting in a flexible tool that can be applied to purchasing groups with different characteristics, namely different operational and market circumstances, and to supply chains with different topologies and atypical cost characteristics. Preliminary computational results show the potential of the approach in solving a broad range of problems.

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1 Introduction

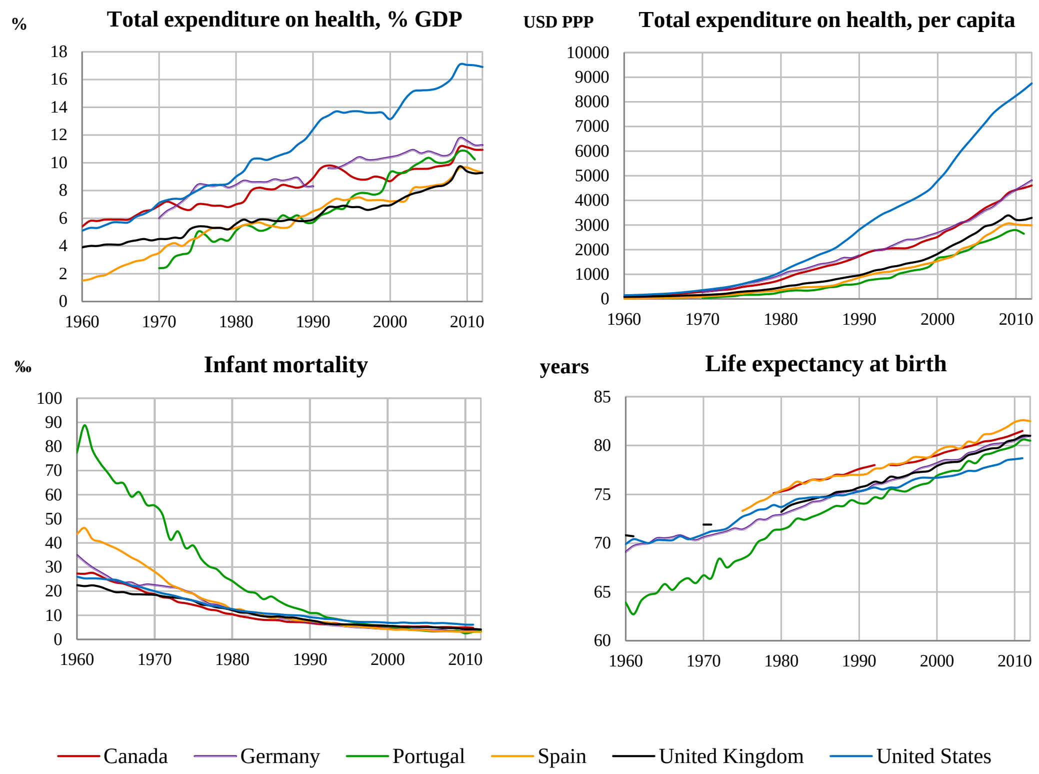
Subsection 1.1.1 of this chapter is based on part of the following published paper:

REGO, N., CLARO, J. & PINHO DE SOUSA, J. 2014. A hybrid approach for integrated healthcare cooperative purchasing and supply chain configuration. *Health Care Management Science,* 17**,** 303-320.

1.1 Research motivation

1.1.1 Context

In the last decades there has been, in most OECD countries, a continuous growth in health expenditures as a share of GDP (see some examples in Figure 1.1). Although this economic effort has been accompanied by significant improvements in health services (illustrated in Figure 1.1 by the evolution of Infant Mortality and Life Expectancy at Birth), there is a collective concern for control of costs and for systems efficiency.



Source: OECD (2014b)

Figure 1.1 Health care evolution, 1960-2012

In Portugal, hospitals are accountable for approximately 40% of total current expenditure on health, and more than 75% of it arises at public hospitals, i.e., hospitals included in the National Health Service, NHS (own calculations, using 2012 data from INE 2014). In 2010, 55% of the 231 hospitals in the country were state owned and concentrated 73% of all hospital beds (OECD 2013). Seven hospital systems represent more than 50% of total pharmaceuticals consumption by publicly managed hospitals (INFARMED 2012). In 2009 the supply costs accounted for 30% to 40% of their operational costs[3], this value being in line with the proportion observed at US hospitals (Burns and Lee 2008). Pharmaceuticals represent between 70% and 80% of these supply costs while medical-surgical materials represent between 20% and 25%.

1.1.2 Health care supply chain complexity

Health care supply chains are often described as *complex*. However, these descriptions are rarely supported by a clear explanation of how the involved *complexity* is defined. Our view on the *complexity* of heath care supply chains is contextualised by insights from the Complex Systems research field:

> *In contrast to simple systems, such as the pendulum, which has a small number of well-understood components, or complicated systems, such as a Boeing jet, which have many components that interact through predefined coordination rules (Perrow 1999), complex systems typically have many components that can autonomously interact through emergent rules. […] In management contexts, complex systems arise whenever there are populations of interacting agents (persons, organizations, or communities) that act on their limited and local information. That is, the agents and the larger system in which they are embedded operate by trading their resources without the aid of a central control mechanism or even a clear understanding of how actions of (possibly distant) agents can affect them.* (Amaral and Uzzi 2007: 1033)

A hospital supply system provides a great variety of services and products through a network that is composed by a few central departments and numerous, diverse and relatively autonomous point of care units (wards). These service lines (e.g., transplantation, cardiology, open-heart surgery, oncology, neurology, obstetrics and gynaecology, acute care, and paediatrics) operate as quasi-strategic business units for a hospital (Jack and Powers 2004). Frequently, decisions at the various points of the network are taken without considering their impact on the whole system. The hospital supply system is linked to various external organisations and entities whose actions have impacts on its behaviour (e.g., suppliers, group purchasing organisations, the Ministry of Health, authorities that approve pharmaceuticals and medical devices, nurses and physician professional bodies, etc.). The various stakeholders involved in the decision processes often have different perspectives of what "good" system

[3] Source: hospital systems Profit and Loss Accounts

performance is, and individuals' reactions to the system state (namely, to the information they obtain about that state) highly influence subsequent system performance. Additionally, hospitals are frequently non-profit organisations, and this introduces significant differences relatively to the performance evaluation logic at profit-oriented companies.

A health care supply chain must assure a high service level, as the occurrence of stock-outs has an impact on the confidence of the clients of the system, may cause delays, and lead to over-work to materials managers or pharmacists and health professionals (Vila-Parrish and Ivy 2013) and can, in extreme situations, threaten the patients' life.

In Table 1.1, we describe several types of complexity that can be observed in health care supply chains.

Table 1.1 Complexity in the health care supply chain

Type of complexity	Arises from…	Examples
structural	the number of components in the system and the network of interconnections between them	there is a great variety of services and products that flow through a network of diverse and relatively autonomous wards
combinatorial	the number of combinations (possibilities) to consider when making a decision	the number of possibilities when deciding the quantities that flow and how much and where to store in an existing hospital network is huge
behavioural	the type of behaviour that emerges due to the manner in which sets of components interact	individuals' reactions to the system state (namely, to the information they obtain about that state) influence system performance
evaluative	the competing perspectives of stakeholders who have different views of "good" system performance	health professionals may prefer higher inventory levels and a wider variety of available materials, while management wants to minimise inventory levels and standardise purchased materials
nested	the interaction between a complex "physical" domain and a complex "institutional" sphere	health care (supply chain) activities are embedded in an environment that is highly regulated by the government, health authorities, professional bodies, etc.
dynamic	the interactions among the agents over time	nurses and physicians make decisions based on the information they remember, their memory obviously being limited

Source: own examples, using the complexity categories of Mostashari and Sussman (2009)

1.1.3 Challenges

During the last decades, academics and consultants have repeatedly presented arguments and examples to support the idea that companies should not apply a “one-size-fits-all” strategy to manage multi-product supply chains. However, it may be challenging to link the desired supply chain capabilities (e.g., low cost, speed, high quality and/or flexibility, safety) to the actual operational processes and resources that are within the sphere of decision makers.

It is also clear that the supply chain of a hospital must gather all resources needed to assure the provision of a great variety of services through a network of diverse and relatively autonomous entities (mainly wards), this requiring managing the flows and inventories of a great diversity of materials, especially in the case of a general hospital.

There is therefore a need for the identification of hospital supply chain segments with specific requirements from the supply chain, and for the development of research focused on the supply chain management of those segments, while taking into account the complexity of the health care context.

1.2 Research questions and objectives

The health care supply chain can be analysed at quite different levels (see the multilevel stakeholder decomposition of the health care system presented by Fradinho et al. 2014). The work presented in this dissertation is positioned at the hospital level, sometimes mainly focusing in its internal supply chain, and sometimes considering the external supply chain in the analysis, and is directed at the materials that flow in the chain.

The developed research work aims at answering the following research questions:

RQ1: How do the characteristics of the services provided or materials supplied influence the capabilities required from a hospital materials supply chain?

RQ2: How can the required hospital materials supply chain capabilities be achieved? (i.e., which processes and resources are needed to attain those capabilities?)

RQ3: How are good hospital supply chain operational strategies (for differentiated types of materials) defined in terms of operational capabilities, processes and/or resources?

Given these research questions, the general objective of our research work is to obtain management knowledge to support the definition of hospital materials supply chain management strategies, while dealing with its underlying complexity and taking into account the objectives of the different groups / stakeholders involved (depending on the focus of the analysis, these may be wards, professional groups, the central hospital management or various cooperating hospitals), and facilitating the interaction/negotiation between those stakeholders during the choice process for the strategies.

This general objective involved the prosecution of the following operational objectives:

I.a) identify opportunities for hospital materials supply chain management enhancement through a better fit between operational strategies and services/items characteristics;

I.b) explain how the capabilities required for the materials supply chain of a hospital are influenced by characteristics of the services provided or of the items that flow through the supply chain;

I.c) develop a scheme to simplify hospital materials supply chain management through the identification of a manageable number of groups (segments) of homogeneous items (in terms of the capabilities required from the supply chain), linking those groups with specific operational capabilities and the necessary processes and resources;

II. taking the determined segments into account, develop (simulation or optimisation) models to assess different hospital materials supply chain operations strategies, at various levels of analysis (in the internal and/or external supply chain), while evaluating the impact of those strategies for different hospital supply chain players / stakeholders.

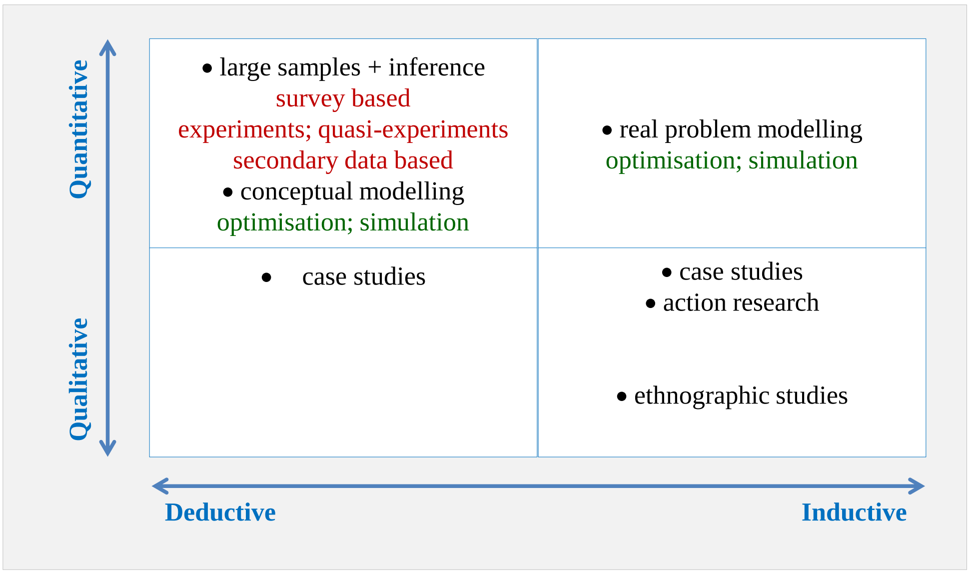
1.3 Research strategy

The research strategy adopted must assure internal consistency among the elements of the research project: research questions, prior work, research design, and theoretical contributions (Edmondson and Mcmanus 2007).

In terms of *prior work,* the hospital supply chain segmentation topic, addressed in chapters 2 and 3, can be considered between the *nascent* and the *intermediate* levels of the continuum of theory in management, as proposed by Edmondson and Mcmanus (2007), since little health care specific related theory exists. The same applies to hospital supply chain dynamics, the topic addressed in chapter 4. Accordingly, in our work, some insights from operations strategy are considered (in chapters 2 and 3) and contributions from similar/related analysis in other contexts (e.g., in manufacturing) are taken into account (in chapters 2, 3, and

4). In what concerns the topic studied in chapter 5, the theory development can be viewed as more evolved (at the *intermediate* level), as the topic "Group Purchasing Organisations", particularly in health care, has already received some research attention.

Figure 1.2 displays various research methods that can be used in the operations and supply chain management field. As defined by Hyde (2000), *inductive* reasoning is a theory building process, starting with observations of specific instances, and seeking to establish generalisations about the phenomenon under investigation; *deductive* reasoning is a theory testing process that starts with an established theory or generalisation, and seeks to see if the theory applies to specific instances. The other axis of the matrix, relates to the type of data: *qualitative* or *quantitative*, collected and analysed. Either type of data or a combination of the two can be used for inductive or deductive research (see e.g., Hyde 2000, Größler and Milling 2007, Größler 2008, Barratt et al. 2011). For simplification reasons, *case studies* and *action research* have been classified as qualitative, although they frequently include some level of quantitative analysis.



Source: adapted from "Using modeling to drive education policy" (Sturtevant and Contardo 2014) using insights from Swamidass (1991), Handfield and Melnyk (1998), Karen and Gyöngyi (2006), Barratt et al. (2011), Chatha et al. (2015) and *Journal of Operations Management* editorial description (Guide and Mikko 2015)

Figure 1.2 Research methods in the field of operations and supply chain management

The particular research methods applied to develop the work described in each of the following four chapters are presented in detail in each chapter. As explained next, an essentially inductive approach is transversal to the four chapters.

The work in the next two chapters takes into account or departs from the specific case of real hospital systems. It is based on a content analysis of the literature and of the interviews and, although it starts deductively (using a few categories derived from operations strategy), it is mainly inductive. This work touches the domain of conceptual methods (see Meredith 1993), as it represents an effort to expand existing descriptive hospital supply chain segmentation schemes into an *explanatory framework*.

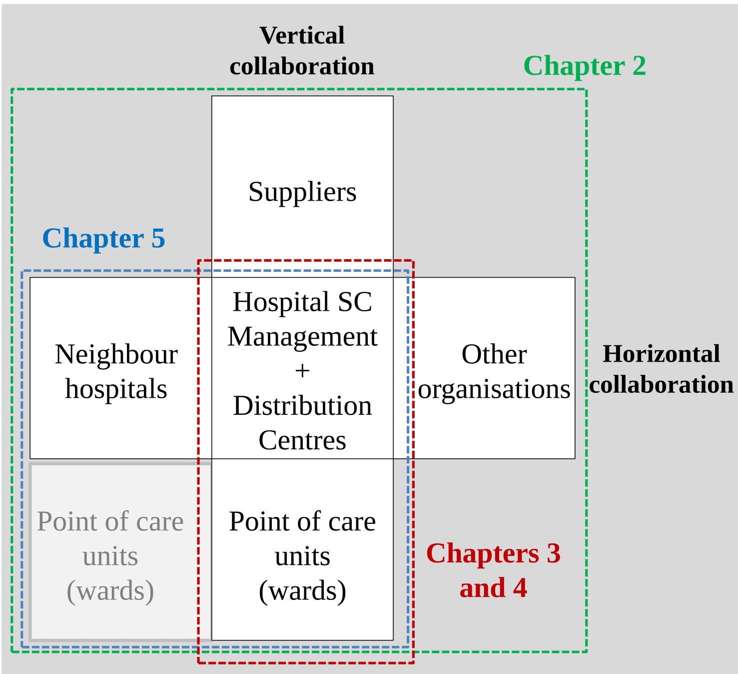
Despite the fact that systems and decisions affecting business processes can be "modelled", the analysis of empirical data is crucial for the development and validation of models (Boyer and Swink 2008). According to these authors, models seldom cover some complex social and behavioural elements involved in operations and supply chain management. Our research work was grounded on empirical data collected from two real hospital systems. In chapters 4 and 5, the solutions to specific problems are sought, and specific situations serve as the basis for the developed models. Therefore, our approach involves *inductive modelling* (Größler and Milling 2007, Größler 2008), even if some insights obtained through the run of the developed models may be generalised in a way resembling *inductive theory building* (Größler 2008). In the scope of this work, models are, as defined by Schwaninger and Grösser (2008), sufficiently accurate representations of real systems, in which the constituent variables and their functional relationships, including the underlying assumptions, are formalised and therefore made transparent.

Given the current research stage of the analysed topics (between nascent and intermediate), and following the recommendations by Edmondson and Mcmanus (2007):

- our research questions are open-ended;
- the qualitative information is collected through open-ended inquiries and some quantitative archival data is also collected;
- qualitative data analysis is performed using content analysis, and quantitative data analysis uses exploratory statistical methods or simulation/optimisation;
- the goal of data analysis is pattern identification and exploration of new propositions, and
- the theoretical contributions "integrate previously separate bodies of work" and often constitute an "invitation for further work on the issue or set of issues opened up by the study".

In Figure 1.3, we compare the scope of the research work described in each of the following chapters, in terms of the parts of the hospital materials supply chain considered under analysis. Thus, in chapter 2, the whole hospital supply chain is considered; in chapters 3 and 4, the analysis is more focused at the internal supply chain; in chapter 5, the analysis includes the internal supply chain and horizontal cooperation in the external supply chain, namely, supply chain cooperation involving groups of neighbour hospitals.

Chapter 2 explores the hospital materials supply chain segmentation theme linking possible segments to possible operational supply chain strategies (at all the supply chain stages) recommended for those segments. Its scope is therefore necessarily broad. The findings of this chapter, containing much of the literature review that supports the work described in chapter 3, are then used to inform the work of the following chapters. In this chapter, the analysis is directed to the segmentation of the materials that flow in the internal supply chain of a hospital system. Then, in chapters 4 and 5, the analysis is directed to operational strategies that have been recommended for one of the segments identified on chapter 2. In chapter 4 this means the analysis of issues related to collaboration within the hospital internal supply chain (namely, information sharing between echelons and lateral transshipments between wards), and in chapter 5 an analysis of collaboration among neighbour hospital systems is performed (through the formation of group purchasing organisations).



Source: adapted from the "The scope of collaboration" (Barratt 2004)

Figure 1.3 Scope of the developed work

The developed research work is strongly related to inventory management. According to Silver (1981: 629), “the three key questions that inventory management attempts to answer on an item-by-item basis are: (i) How often should the inventory status be determined, that is, what is the review interval? (ii) When should a replenishment order be placed? (iii) How large should the replenishment order be?”, both if in a single or a multi-echelon situation.

On the other hand, while discussing the definition of Supply Chain Management, Mentzer et al. (2001) imputed its origins to the seminal work of Forrester (1958) because of its emphasis on the interrelationships among the flows (e.g., of materials and information) the organisations engaged in the supply of a product (being these internal or external to a company) exchange, having identified the phenomena currently known as the "bullwhip effect" (see Lee et al. 1997a). As a result of their literature review around Supply Chain Management definitions, Mentzer et al. (2001) conclude that as a management philosophy it has a systems approach to viewing the supply chain and a strategic orientation toward cooperative efforts to synchronise and converge intrafirm and interfirm operational and strategic capabilities with a focus on customer value. The authors do also emphasise the central role information sharing plays in Supply Chain Management.

Since the perspective of our work is not on the determination of the best review periods, ordering levels or replenishing periods, but, on the link between required strategic operational capabilities and the processes and resources recommended to attain them (in chapters 2 and 3), on the impact of the chain structure, information sharing levels and decision rules on the system (in chapter 4) and on the cooperation between neighbour hospitals (in chapter 5), we consider that our research goes beyond the inventory management topic and can be classified under the Supply Chain Management umbrella.

1.4 Outline of the dissertation

This dissertation is organised following the logic of a succession of articles. Thus, although there are some links between the chapters and, to avoid unnecessary repetitions, there are references to information presented on precedent chapters, in general, each of the chapters is self-contained, resulting in specific research contributions.

The remaining chapters of this dissertation are organised as follows:

- **Chapter 2 - A synthesis of hospital materials supply chain segmentation frameworks**. This chapter reviews and integrates the relevant literature related to supply chain segmentation (in general terms and in a hospital materials supply chain context) with qualitative information collected from two hospital systems, and identifies literature (and management practice) gaps. The emphasis is put on the identification of segmentation variables, typical supply chain segments and operational capabilities suggested for those segments, and processes and resources that may contribute to achieve the recommended capabilities.
- **Chapter 3 – Hospital supply chain segmentation – a classification scheme**. In this chapter, we use quantitative Cluster Analysis to define an empirical classification scheme of the items that flow through a hospital system supply chain, as a way to

identify a limited number of homogeneous groups, requiring different operational supply chain strategies. To operationalise the classification scheme, we propose a measure for hospital supply chain items criticality. Finally, we present a cross-reference between the identified segments and the operational capabilities, and the corresponding operational processes and resources (recommended by the literature and by the interviewed managers) for the materials' segments with characteristics that are common to the segments determined.

- **Chapter 4 – A System Dynamics based simulation of alternative supply chain strategies for hospital *high volume, frequent and generalised use* items.** This chapter presents a System Dynamics (SD) simulation analysis of some alternative operational strategies for one of the segments identified in the previous chapter (*high demand, frequent and generalised use items*). The simulated alternatives are based on the specific characteristics of a hospital setting.
- **Chapter 5 - A hybrid approach for integrated health care cooperative purchasing and supply chain configuration.** This chapter presents an innovative and flexible approach, developed around a hybrid Variable Neighbourhood Search (VNS) / Tabu Search metaheuristic, for recommending the number, size and composition of purchasing groups, in the case of a set of hospitals willing to cooperate, while minimising their shared supply chain costs.
- **Chapter 6 – Conclusions.** This chapter concludes the dissertation, presenting the key contributions of the produced research and suggesting paths for further developments.

2 A synthesis of hospital supply chain segmentation frameworks

2.1 Introduction

A prerequisite for supply chain management is that a strategy exists for the supply chain as a whole (Aronsson et al. 2011). Butler et al. (1996) have put the question "*Can hospitals effectively implement different operations strategies among different patient care services?*" in their list of questions requiring further research. Dobrzykowski et al. (2014), in their structured analysis of operations and supply chain management research in health care between 1982 and 2011, referred to the research agenda suggested by Butler et al. (1996) and did not identify any answer to the aforementioned question. The authors have also concluded that a more holistic understanding of how health care organisations operate and how their performance can be improved is needed. In a guest editorial making an overview of supply chain management in health services, de Vries and Huijsman (2011) identified the topic of strategy design – namely, the problematic around the lean-agile dichotomy – as requiring further research.

Academics and consultants have presented arguments and examples to support the idea that companies should not apply "one-size-fits-all" strategies to manage multi-product (and hence, multi-service) supply chains. Accordingly, several frameworks recommending specific supply chain strategies fitted to particular materials supply chain segments (e.g., depending on the characteristics of the products or services supplied) have been developed (as reviewed in the next two sections). The proliferation of such frameworks and the coexistence of numerous alternative/parallel approaches may be confusing from the point of view of a supply chain manager, even though most of the more important contributions can, from a practical point of view, be conciliated and integrated. Furthermore, it may be challenging to link the desired supply chain capabilities (e.g., low cost, speed, high quality, and/or flexibility) to the actual operational processes (e.g., inventory control policies or Information and Communication Technologies (ICTs) choice) and resources (e.g., capacity decisions). The result of our work is a condensed and conciliated overview of these frameworks in a hospital materials supply chain context, linking the supply chain capabilities recommended in the various approaches to the operational processes and resources suggested to enable them.

The supply chain of a hospital must assure the provision of a great variety of services, and gather all resources needed to do so, which involves managing the flows and inventories of a great diversity of materials. Moreover, the fact that ambiguous, and usually not clearly formalised, parallel segmentation schemes are used in health care results in conflicting priorities, goals, and performance metrics (Lillrank et al. 2010).

Since "[…] *there have been numerous calls for broader-based research* [in operations strategy], *particularly on services and on supply chain* […]" (Boyer et al. 2005: 446) from within the operations strategy research field, we look at hospital supply chain segmentation using an operations strategy lens, by adopting a *strategic fit* perspective, which considers that certain operations management strategic configurations/forms are more or less appropriate for certain business competitive strategies and environmental contexts (Boyer et al. 2005), and a *process* and *resource view* (see e.g., Van Mieghem 2015) of supply chain operations, thus, assuming a link between an organisation's performance and its processes, resources and resulting capabilities.

In the scope of this chapter and chapter 3, *configurations* are classification schemes - i.e., typologies and taxonomies - establishing a link between structure and strategy[4]. Configurations have been used in a strategic management context for years (as can be seen in a review and synthesis of related literature performed by Miller 1986). The terms *classification scheme, taxonomy,* and *typology* have been used interchangeably in much of the related management literature (Doty and Glick 1994), and that has also been the case when the topic is supply chain segmentation. According to Hambrick (1984), a *taxonomy* is a classification scheme derived from quantitative (numeric) empirical data, and a *typology* is a classification scheme derived conceptually or from non-numeric empirical information. Complementary, Rich (1992) defines *taxonomy* as an empirically derived, hierarchical system, built of sets of similar groups (taxa) that are built into ever larger and increasingly subsuming groups (such as species are classified in genus, genus in families, families in orders, etc.), and *typology* as the classification of data into types based on the theoretically derived, and more or less intuitively categorised, qualities of observed phenomena. Summing up, Doty and Glick (1994) define *classification scheme* and *taxonomy* as a classification system that categorises phenomena into mutually exclusive and exhaustive sets with a series of discrete decision rules, and *typology* as a conceptually derived interrelated set of ideal types, each of which represents a unique combination of the organisational attributes that are believed to determine the relevant outcome(s). A more detailed description of the use of classification on organisational analysis and of the debate between Typologists and Taxonomists was presented by Meyer et al. (1993).

We perform an inventorying, comparison, and whenever possible, integration of the literature proposing or describing segmentation schemes, i.e., taxonomies or typologies, applicable to hospital materials supply chains, by focusing on identifying the proposed segmentation variables, the resulting segments and the operational strategies (i.e., capabilities, processes and resources) recommended for those segments.

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[4] The term *configuration* has been used with a different meaning in this dissertation, e.g., when integrated in the expression *supply chain configuration*.

In the scope of this work, the *hospital supply chain* encompasses the internal hospital supply chain (composed by the hospital wards, where services are provided and materials are consumed, and the hospital distribution centre(s) that serve them), the hospital suppliers, and other hospitals or health services collaborating with the focal hospital in terms of direct materials or services exchanges, with the purpose of providing care at the hospital level. This definition is organisation, and not process, centred, and it includes both vertical (e.g., between the hospital and its suppliers) and horizontal (e.g., between wards or between neighbour hospitals) organisational relationships (see Harland 1996a, Barratt 2004).

The analysis of the hospital materials supply chain segmentation frameworks was preceded and framed by an analysis of supply chain segmentation frameworks proposed in the context of other industries or without specifying an industry, but generally developed under the conceptual reference of a manufacturing context. The underlying supply chains are designated simply as *supply chains*.

Although there has been previous research under the topic of supply chain segmentation (e.g., Tang and Gattorna 2003, Lovell et al. 2005, Godsell et al. 2011), we did not find any explicit definitions of *supply chain segment* or *supply chain segmentation*. Curiously, at the Supply Chain Management Terms and Glossary of the Council of Supply Chain Management Professionals, the following entry is available: "*Segmentation: In marketing, it is the identification and classification of groups of buyers within a market who share similar needs and who demonstrate similar buyer behaviour*." (Vitasek 2013)

In fact, supply chain segmentation derives from the marketing concept of market (or customer) segmentation. A comprehensive and clarifying discussion of the market segmentation concept and its relation with supply chain strategy was made by Godsell (2008: 30-39).

Some of the previous supply chain segmentation studies recommend the diversification of the supply chain strategy according to the needs of different groups of customers. However, this is difficult to apply in a hospital setting since there are various types/layers of clients: the patients, the health professionals, the payers. In addition, frequently the hospitals are non-profit organisations. In this context, we can define a hospital supply chain segment as a group of materials or services with some common characteristics that are relevant in explaining (and predicting) supply chain performance variations influenced by diversified supply chain strategies.[5] Supply chain segmentation is thus the determination of supply chain segments.

[5] Adapted from the following sentence in the review by Wind and Cardozo (1974, p.155): "*A market segment is simply a group of present or potential customers with some common characteristic which is relevant in explaining (and predicting) their response to a supplier's marketing stimuli*."

This work contributes to the systematisation and conceptual integration of the literature related to the supply chain segmentation topic, and highlights the links between desired operational capabilities and the processes and/or resources that can support those capabilities, namely on a hospital materials supply chain context.

The literature related to the supply chain segmentation topic is vast, as described in section 2.3. On the contrary, although the amount of literature on health care supply chain management has grown fast (Dobrzykowski et al. 2014), the topic of health care or hospital supply chain segmentation is still under-explored. In this chapter, we review and synthesise research on hospital materials supply chain segmentation, contribute to its conceptual integration by providing a framework for literature analysis, and identify related research gaps.

This chapter is organised as follows. In the next section, we describe the research methods followed. Then, we present a literature review on materials supply chain segmentation in other industries (section 2.3), and in a hospital context (section 2.4). In section 2.5, we present a preliminary analysis of the qualitative information obtained from two hospital systems. In section 2.6, we compare, summarise and discuss all the information collected, identify some literature (and management practice) gaps, and indicate lines for further research. In section 2.7, we summarise the work developed, the main research gaps identified throughout the study and link the findings of the chapter to the remainder of the dissertation.

2.2 Methods

In this chapter we synthesise and integrate hospital materials supply chain related literature and qualitative data obtained through interviews to supply chain managers at two general hospital systems. Two different sources of qualitative information were considered because the amount of previous studies addressing the topic of hospital materials supply chain segmentation is still limited. Since we examine methodologically dissimilar data and whether they corroborate each other, the performed interviews were used as a method of data triangulation in an approach analogous to *public health triangulation* (see Rutherford et al. 2010). The integration of various types of information (i.e., information from the literature and the views of those involved in the problematic being analysed) on research syntheses in a public health context had already been suggested and exemplified by Oliver et al. (2005). As the authors describe, we have also *juxtaposed findings* from the synthesis of the literature with those from the views of supply chain managers, and have *compared* them to look for aspects referred by the managers but not treated in the literature and vice-versa.

The method of synthesis used was the *framework synthesis* (Barnett-Page and Thomas 2009, Thomas and Harden 2008) based on the *framework approach* (Miles and Huberman 1994, Pope et al. 2000).

Figure 2.1 summarises the method followed to develop the work described in this chapter:

- We have reviewed the literature related to supply chain segmentation on other industries and, in a more detailed and comprehensive way, on hospital contexts. Only the research works focusing on the segmentation of the materials supply chain have been included in our sample, which involved an *a priori* analysis of all research works proposing supply chain segmentation schemes in a hospital context to exclude those that segmented the services (the *materials – services* dichotomy was used before by de Vries and Huijsman (2011) to categorise research on a health care context as the authors specified the *element of exchange*, one of the dimensions[6] of the framework proposed by Croom et al. (2000) for the categorisation of literature on Supply Chain Management).
- Simultaneously, we collected qualitative information from two general hospital systems, with the main objective of finding out *if* and *how* the materials supply chain management was affected by the type of services provided and by the characteristics of the items that flow through the system.

[6] The other dimension is the *level of analysis*: *dyadic level*, *chain level* or *network level*.

- Then, the information obtained from the literature and from the practice was systematically compared and integrated in order to enumerate the variables usually considered relevant to segment a hospital materials supply chain, to identify typical hospital materials supply chain segments and the strategies recommended for each type of segment, to list the supply chain operational capabilities that are associated to each strategy, and to bring up the processes and resources recommended to obtain them (the used framework of analysis is explained in detail in section 2.4).
- Finally, the results of the analysis of the information collected have been discussed with the main goal of identifying research gaps and corresponding possible future paths of knowledge development.

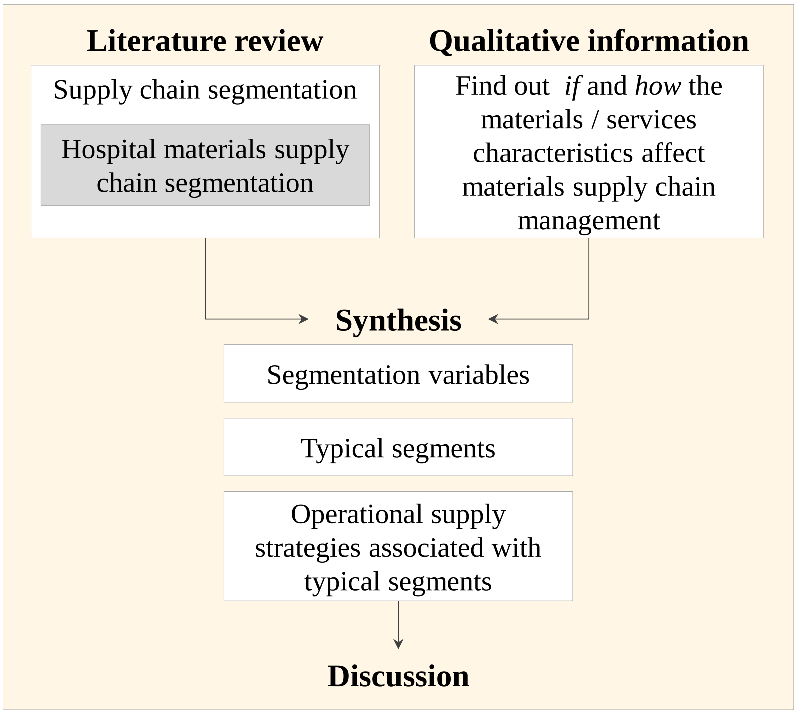

Figure 2.1 Work development scheme

For the purposes of this work, we are interested in the studies that link different supply chain segments to specific supply chain strategies. When addressing the literature related to supply chain segmentation in general, which is very oriented to manufacturing settings, we present an integrative view supported mainly by milestone research.

The selection of the relevant research related to hospital materials supply chain segmentation to be analysed in detail (see section 2.4) was performed by:

- first, searching referential databases, namely, MEDLINE/PubMed, Web of Science, Scopus, and Google Scholar, using combinations of appropriate search words (i.e., health care OR healthcare OR hospital*, AND supply chain* OR supply network*, AND strategy OR segmentation);

- alternatively, which has been more decisive, following the citations of relevant papers, or looking at works that cite them;
- all papers or other research documents considered potentially significant were examined concerning their relevance in relation to our research objectives, through the reading of their abstracts, or, when necessary, the skimming of the whole document.

Four research works were selected through this process for detailed analysis (presented in section 2.4). Two of them are theses from the Master of Engineering in Logistics of the Massachusetts Institute of Technology (DeScioli 2005, Cheng and Whittemore 2008). These works provide valuable insights because the authors have analysed several real hospital cases. The remaining works are papers published at scientific peer-reviewed journals.

In what concerns the collection of qualitative information about real hospital supply chains, we interviewed the CEOs, and supply chain and pharmacy managers of two hospital systems: a general hospital system composed by three hospitals (Hospital System 1, HS1), and a general, teaching and research hospital system (Hospital System 2, HS2). Table 2.1 exhibits some of the characteristics of these two hospital systems. The selected hospital systems are large general hospitals, thus providing a wide variety of services that use very diverse materials. Additionally, they are generally recognised as providing good quality care and as being well managed (namely, in the supply chain area).

Table 2.1 Characteristics of the studied hospital systems

	Hospital System 1	**Hospital System 2**
Type	general	general, teaching
Number of inpatient beds	550	1100
Number of employees	3200 (1020 nurses + 760 doctors)	5200 (1950 nurses + 1200 doctors)
% of cost of materials consumed on total operational costs	29%	36%

Source: data from the 2012 Financial Statements of the hospital systems, involving own calculations when necessary; the values in the table are approximate

First, two group unstructured interviews with the CEOs and the executive supply chain directors of each of the hospital systems were conducted by two members of the research team. The main objectives of these interviews were to understand the global strategy of the hospital systems and the top leadership involvement with supply chain management issues. These group interviews, that took approximately one hour each, were not recorded. Instead, written notes were taken and compared.

Then, the various supply chain and pharmacy managers of the two hospital systems were asked *if* and *how* the hospital system materials supply chain management was affected by the characteristics of the items that flow in the system and by the type of services provided. The guide for the interviews can be seen in Appendix 2.2.

Although a guide was developed, the interviews were semi-structured, and therefore not completely standardised, since the questions wording could vary depending on the interviewer-respondent interaction, and questions could be sequenced or segmented differently for different respondents; moreover, conversation paths that had not been anticipated in the guide could be explored, or questions could be omitted for particular interviewees (see Miles and Huberman 1994: 37-38). As can be observed in the guide, there was a predominance of *what* and *how* questions. The issues addressed were mainly derived from our previous experience with health care supply chain management topics and from an exploratory investigation of related literature. Six interviews, taking approximately one hour each, were conducted. These interviews were audio-recorded and transcribed.

The content analysis of both the selected research works and the interviews started deductively, taking into account the predefined categories of the conceptual framework developed for the analysis (see details in section 2.4), but was deepened inductively, through conventional content analysis that raised the second order categories (see Hsieh and Shannon 2005). That is, we did not consider preconceived categories for the segmentation variables, the supply chain capabilities or the supply chain processes and resources; instead, categories were derived from the data.

2.3 Supply chain segmentation

The theme of supply chain segmentation has received contributions from several research streams. In this section, we identify them and the related key concepts or insights that we consider relevant in a supply chain context.

The earlier implementations of supply chain segmentation ideas were based on simple inventory classification schemes, namely the well-known ABC inventory classification, first described in the 1950s by a General Electric manager (Dickie 1951), and involving the ranking of items depending, most frequently, on their demand value. The ABC inventory classification based on a single criterion has evolved to the development of multi-criteria approaches and/or the development and application of diverse classification techniques. Examples of the available approaches can be found in two recent literature reviews analysing item classification research: a) Bacchetti and Saccani (2012) take a spare parts management perspective, but include works referring more generally to low demand items and some of the most-known general approaches to item classification, and b) van Kampen et al. (2012) take a more general production and operations management perspective.

Multi-product (and/or multi-service) supply chains segmentation, suggested by Fuller et al. (1993) and still an influent and proficuous theme, and inventory items classification are closely interconnected. These topics are also linked to the vast literature related to the expansion and integration of the lean and agile manufacturing paradigms in the total supply chain and with research related to push and/or pull systems or concerning the positioning of the decoupling point (previously designated as *order penetration* point). These inter-connected areas have been identified by Nag et al. (2014) as the main streams of research on the formation of supply chain inventory strategy, and thus the authors explain the rationale behind each of them, and describe some of the related seminal studies. Research on the lean and/or agile paradigms was reviewed by Naim and Gosling (2011), and in part also by Nakano and Akikawa (2014) whose review is concentrated on the numerous empirical studies using the Strategy–Structure–Processes–Performance paradigm - that is, empirical studies based on the proposition that firms that have achieved proper *fit/ alignment* among supply chain strategy, structure, and processes are expected to perform better than competitors that lack such alignment.

Besides having been included in the reviews of Nag et al. (2014), Naim and Gosling (2011) and Nakano and Akikawa (2014), research related to supply chain segmentation, following the influential article by Fisher (1997), has also been more specifically reviewed by Basnet and Seuring (2014). However, having been published as a working paper and presumably still in process, in its current version, it generally only provides information about the number of papers included in the review where an analysed category was observed, without providing details about which are the corresponding references. Furthermore, the authors have ignored the fact that, when researchers from the network of an influential research school publish work building on and expanding previous research from that same school, these works will naturally have several aspects in common (e.g., the segmentation variables, that Basnet and Seuring (2014) designate as *contingency categories*), which makes a mere reference counting misleading. A detailed description of how literature that is relevant in the scope of our work has evolved in the context of predominant research schools (namely, the *lean-agile* and the *strategic alignment* schools) was presented by Godsell et al. (2011).

For the purposes of this work, we are interested in the studies that link different supply chain segments to specific supply chain strategies. In the next paragraphs, we summarise the main research contributions on the topic (a detailed summary of the papers considered more relevant is presented in Appendix 2.1). Then, in the next section, we present a more detailed and comprehensive review on the theme, focusing specifically on hospital materials supply chain contexts.

Fisher (1997) recommended that the supply chain strategy should be fitted to the characteristics and demand predictability of the product. Thus, a physically efficient supply chain strategy should be adopted for functional products with predictable demand, and a market responsive supply chain strategy should be adopted for innovative products with unpredictable demand. This framework has received considerable attention and supported numerous subsequent studies.

The *lean* thinking paradigm, pioneered by Toyota, advocates eliminating unnecessary steps, aligning all steps in an activity in a continuous flow, recombining labour into cross-functional teams dedicated to that activity, and continually striving for improvement as a mean to reduce human, space, tools, and time utilisation, and thus, overall expense (Womack and Jones 1994).

The *agile* thinking paradigm implies breaking out of the mass-production mould, often associated with lean manufacturing, producing much more highly customised products, and delivering them when and where the customer wants (Sheridan 1993).

Lean concepts work well where demand is relatively stable, and hence predictable, and where variety is low, while, in contexts where demand is volatile and the customer requirement for variety is high, a much higher level of agility is required (Agarwal et al. 2006).

Leanness and agility can sometimes be combined with the strategic use of a *decoupling point* – i.e., the point in the material flow stream where order-driven and forecast-driven activities meet (Mason-Jones et al. (2000) based on Hoekstra and Romme (1992)). Since the decoupling point coincides with an important stock point from which the customer is supplied

(Mason-Jones et al. (2000) based on Hoekstra and Romme (1992)), it acts as a buffer between a lean approach upstream, where production output is smooth, and an agile approach downstream, where fluctuating customer orders or product variety are observed, creating a *leagile* supply chain (term and concept introduced by Naylor et al. 1999). The positioning of the decoupling point is closely related to *postponement* (see e.g., Pagh and Cooper 1998), i.e., moving product differentiation (at the decoupling point) closer to the end customer (Naylor et al. 1999). Apart from the postponement of product differentiation, postponement strategies may involve purchasing postponement, delaying the forward movement of inventories, and/or maintaining inventories in centralised locations (Yang et al. 2004a). Determining the location of the decoupling point(s) is therefore a key challenge in supply chain design.

In Table 2.2 we present a comparison of lean, agile and *leagile* supply chains, separating the product/market characteristics that justify the recommendation for each of these types of supply chain strategy from the operational processes, resources or capabilities associated with each of them.

Agility may require firms to hold inventory buffers for key components to hedge against supply disruptions, *adaptability* may require firms to evaluate the needs of end customers, and not merely immediate customers; and *alignment* may require firms to share information and knowledge freely with suppliers and customers (Nag et al. 2014, referring to the article by Lee 2004).

In Table 2.3, we list the *segmentation variables* – i.e., characteristics used to assign products to supply chain segments - that were recommended by some of the most influential researchers in the area to distinguish between products that should have differentiated supply chain strategies in manufacturing contexts. Some of these variables are interrelated, and to mark that fact, in the table, they are listed in contiguous places and separated by a dashed line. This list aims at representing the variety of variables that are used. The relationship between the relevance of each variable and the number of researchers that have recommended or used it in the past is not linear since some approaches have been developed and furthered by important knowledge schools, and originated numerous research papers (e.g., the approaches following the work of Christopher and Towill 2000). Furthermore, the choice of segmentation variables depends on the objectives of the segmentation process, and it is expectable that different variables are used when the researchers consider different perspectives of the supply chain. Actually, the objective of our review has been to capture that diversity of point of views.

Table 2.2 Comparison of lean, agile and *leagile* supply chains

	Distinguishing attributes	**Lean supply chain**	**Agile supply chain**	***Leagile* supply chain**
Product/ market characteristics	Typical products	Commodities	Fashion goods	Product as per customer demand
	Market demand	Predictable	Volatile	Volatile and unpredictable
	Product variety	Low	High	Medium
	Product life cycle	Long	Short	Short
	Customer drivers	Cost	Lead-time and availability	Service level
	Market winners	Cost	Service level	Cost Service level
	Market qualifiers	Quality Lead-time	Cost Quality Lead-time	Quality Lead-time
	Profit margin	Low	High	Moderate
	Dominant costs	Physical costs	Marketability costs	Both
	Stock-out penalties	Long term contractual	Immediate and volatile	No place for stock-out
Operational capabilities, processes or resources	Purchasing policy	Buy goods	Assign capacity	Vendor Managed Inventory (VMI)
	Information enrichment	Highly desirable	Obligatory	Essential
	Forecast mechanism	Algorithmic	Consultative	Both/either
	Lead time compression	Essential	Essential	Desirable
	Eliminate waste[7]	Essential	Desirable	Arbitrary
	Rapid reconfiguration	Desirable	Essential	Essential
	Robustness	Arbitrary	Essential	Desirable

Source: adapted from the table built by Agarwal et al. (2006) to summarise information from Naylor et al. (1999), Mason-Jones et al. (2000), Olhager (2003) and Bruce et al. (2004)

Even though a product *contribution margin* (suggested by Fisher 1997), *profit margin* (suggested by Lee 2002) or *value density* (suggested by Lovell et al. 2005) are closely linked to its *cost* and/or *price*, the observation of Table 2.3 draws the attention to the fact that, contrary to what may have been expected, the *product cost*, *value* or *price* has not been directly recommended as a segmentation variable in any of the analysed[8] studies, which contrasts with the traditional use of the ABC classification scheme to assess the logistical importance that should be assigned to products.

[7] In the original, *muda* (i.e., transportation, inventory, motion, waiting, over-processing, over-production and defects).
[8] The analysed studies can be seen in Appendix 2.1.

Table 2.3 Segmentation variables recommended to segment manufacturing supply chains

Segmentation variable	Author(s)
inventory cost	Lee (2002)
contribution margin*/ profit margin	Fisher (1997), Lee (2002)
unit value /cost /price	
product value density	Lovell et al. (2005)
physical size and/or weight	
physical complexity	Lamming et al. (2000)
demand volume/level	Christopher and Towill (2000), Lee (2002), Olhager (2003), Lovell et al. (2005)
demand volume stability	Naylor et al. (1999)
demand uncertainty/ variability/ volatility/ predictability	Fisher (1997), Mason-Jones et al. (2000), Christopher and Towill (2000), Lee (2002), Olhager (2003), Lovell et al. (2005)
uncertainty (e.g., technological, in customer needs, in legal standards)	Yang et al. (2004a, 2004b)
demand variety stability	Naylor et al. (1999)
product variety	Fisher (1997), Christopher and Towill (2000), Lee (2002), Olhager (2003)
ease of replacement/ existence of substitutes/ uniqueness	Lamming et al. (2000)
innovation level/ life cycle length/ obsolescence risk	Fisher (1997), Mason-Jones et al. (2000), Christopher and Towill (2000), Lamming et al. (2000), Lee (2002)
end-of-sale markdown	Fisher (1997)
stock-out risk/ costs	Mason-Jones et al. (2000), Lee (2002)
make-to-order lead time	Fisher (1997)
supply uncertainty	Lee (2002)
time window for delivery	Christopher and Towill (2000)
number of potential suppliers/ number of supply sources	Lee (2002)
modularity (in product development or cycle)	Yang et al. (2004a, 2004b)

$* \; contribution\ margin = \frac{price - variable\ cost}{price}$

Several empirical studies have tested the validity of the model proposed by Fisher (1997) or derived models. The following studies concluded for full or partial validation of those models:

- Based on survey responses from 128 Swedish manufacturing companies, Selldin and Olhager (2007) found significant relationships between product and supply chain types, as well as concerning the impact of alignment on performance, and concluded that alignment between the type of product and the type of supply chain is important since it is significant for delivery speed, delivery dependability, and cost performance.
- Analysing survey responses from 604 manufacturing firms in China, Qi et al. (2009) concluded that an agile strategy is markedly more associated with innovative products than a lean strategy, and that groups of companies with emphasis on lean, agile or a combination of the two strategies have substantially best financial and operational performance than the group with a traditional strategy, due to their emphasis on supply

chain capabilities. Using data from the same sample, Qi et al. (2011) concluded that if a company primarily uses overall cost leadership as its competitive strategy, it should increasingly emphasise a lean supply chain strategy; if it focuses more on differentiation, it should concentrate more on an agile supply chain strategy. Moreover, they concluded that in an unstable environment, improving lean capabilities without improving agile capabilities will not suffice to achieve cost advantages, and that a lean strategy has a much greater impact on performance in a stable environment than in a volatile environment, while an agile strategy is much more effective in a volatile environment than in a stable environment.

- Using data on the bicycle industry, and solving models considering different sourcing decisions and appropriate competitive priorities for each product type with a multi-echelon inventory optimisation commercial program, Harris et al. (2010) concluded that if a product is mostly functional, a supply chain strategy focused on efficiency should be adopted; on the other hand, if the product is mostly innovative, a market responsive strategy should be chosen. They have also concluded that Fisher's framework is correct for both the most stable end and the most variable end of the product spectrum, providing a sound foundation upon which supply chain alignment research can build.
- Using 295 responses to a survey of US and European manufacturing firms, and secondary financial data, Wagner et al. (2012) concluded that the higher the supply chain fit (i.e., the strategic consistencies between the products' supply and demand uncertainty and the underlying supply chain design), the higher the Return on Assets (ROA) of the firm, and that *firms with a negative misfit* (i.e., firms that designed their supply chains to support responsiveness while the products' supply and demand is quite certain and the products are predictable) show a lower performance than *firms with a positive misfit* (i.e., firms that designed their supply chains to support efficiency while the products' supply and demand is rather uncertain and the products are unpredictable).

On the contrary, Lo and Power (2010) concluded that there is a lack of empirical support to those models. Their results, based on 107 responses to a survey of manufacturing companies in Australia, indicate that the association between product nature and supply chain strategy as articulated in Fisher's model is not significant. The authors found that a hybrid strategy (pursuing both efficiency and responsiveness) is employed by most organisations irrespective of the nature of the primary product they supply.

Although the final conclusions of the aforementioned studies were divergent, they are not completely contradictory, and their results are in accordance with our perspective. In fact, most of the studies recognise that companies may combine more than one typical supply chain strategy (i.e., efficient and responsive, or lean and agile) when in a multi-product situation. As stated by Christopher and Towill (2002), "… quite different pipelines may function alongside each other, each needing appropriate operating and management skills". It seems also clear that, for more innovative products or in unstable environments, responsive or agile strategies are preferred, and, for more functional products or in stable environments, efficient or lean strategies are preferred. More doubts surround the products that combine characteristics of both the typical functional and innovative extremes of the classical dichotomy. Finally, it is also important to consider that, in many situations, efficient and responsive, or lean and agile, strategies are combined for one product through a clever positioning of the decoupling point.

2.4 Hospital materials supply chain segmentation

There were some early references to the idea of segmenting supply chains in a health care context. For example, Harland (1996b) refers a case study in a health care context which provided empirical support for the need for a portfolio of differentiated supply network strategies to serve end-customer segments. There have also been attempts to adapt the ABC inventory classification to a hospital context by adding a measure of item criticality, which originated the ABC-VED (Vital/ Essential/ Desirable) classification scheme (Thawani et al. 2004).

In Table 2.4, we present a content analysis of the research related to the segmentation of hospital materials supply chains. This content analysis was performed as described in section 2.2 and bounded by a *framework of analysis* (Miles and Huberman 1994) with the following key components (the corresponding schematic representation is presented in Figure 2.2):

- the *segmentation variables* used to partition the supply chain, and the resulting *segments*;
- the *strategies* recommended for each segment, defined in terms of the corresponding *operational capabilities*, equivalent to the *competencies* as defined by Van Mieghem (2015), and the *processes* and *resources* that support them (Van Mieghem 2008, 2015).

Having general hospitals as a background for our research, we looked at the hospital materials supply chain segmentation question assuming a *top-down* and *outside-in* perspective (see Van Mieghem 2015), that is, we started by figuring out what the best customer value proposition mix (defined in terms of operational capabilities) for each supply chain segment would be, and then, a link between those capabilities and specific operational processes and resources was sought. However, the results from our analysis can also be useful for someone with a *bottom-up*, *inside-out* point-of-view (see Van Mieghem 2015), i.e., starting by the identification of the resources and processes of the supply chain (for example, when designing the supply chain for a specialised/focused hospital).

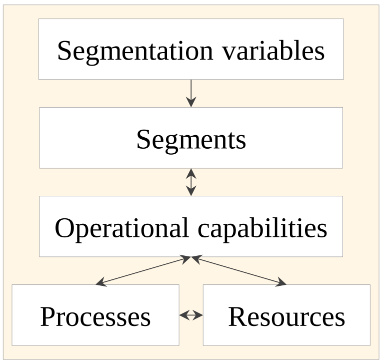

Figure 2.2 Framework for the analysis of literature on hospital materials supply chain segmentation

In the following paragraphs, we provide the key highlights about the research works analysed in detail in Table 2.4.

DeScioli (2005) argues that various hospital supply chain policies should be defined depending on the characteristics of the products considered, and proposes alternative policies for some conceptually defined groups of products. However, due to the lack of related information in the products master file, the author does not use all the segmentation variables suggested to segment the various products of the hospitals object of analysis, nor does he describe the empirical foundations of the recommended policies for each segment. Moreover, the proposed policies have little differences from one segment to another, and were not validated.

Danas et al. (2006) propose a multi-attribute approach to classify medicines[9] consumed by hospitals, assuming that the method will be used to define the inventory management strategy of a set of neighbour hospitals. The authors have not implemented or validated the approach recommended. This method has the disadvantage of demanding an important *a priori* assessment effort from hospital supply chain managers and health professionals. This makes the method difficult to implement and maintain. Gebicki et al. (2013) give an account of having experienced difficulties when trying to use part of the classification scheme proposed by Danas et al. (2006) to classify drugs at a real hospital.

[9] The authors use also the term *drugs* to designate the materials they address.

The ABC-VED analysis, described by Thawani et al. (2004) and applied to the pharmaceuticals of some hospitals, mainly in India (an example of such applications is described by Gupta et al. 2007), has the advantage of being easy to understand conceptually, but has the disadvantage of putting an emphasis on the ranking of the materials, which results in a simplification (by aggregation) of the available information about the materials characteristics. Additionally, this approach requires an exhaustive *a priori* classification of all items relatively to their criticality, which in many practical situations is difficult.

The research by Cheng and Whittemore (2008) is rich in terms of the diversity of possible segmentation variables in a hospital supply chain identified, and the authors consider both pharmaceuticals and medical/surgical supplies in their analysis. However, the relevant supply chain segments are determined through bivariate analysis of the association between some of the segmentation variables suggested, using scatter charts, which, from a statistical point of view, is simplistic. Moreover, the authors do not describe the analysis of possible relations between all pairs of variables, and the existence of correlations among more than two variables was not investigated. Furthermore, there is still need for evidence or arguments that support some of the supply chain strategies they recommended for specific segments, namely considering the whole supply chain, since some of the proposed strategies were not fully supported in terms of the required volume for their applicability or could be beneficial to the hospital at the expense of its suppliers.

Table 2.4 Previous research related to hospital materials supply chain segmentation

Authors /Type of material /Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
DeScioli (2005) /pharmaceuticals and medical supplies /case study: 2 hospitals implementing automated point of use (APU) systems in the USA	• product unit price • demand volume[10] • demand variability[10] • physical size • criticality (non-critical, critical, highly-critical)	(high or low unit cost + large or small physical size) + highly critical	not explicitly named	ensuring very high availability + minimising inventory value + minimising storage space + security	• very frequent review period (at least daily), particularly for high cost or large items • tight control (closed door storage)[11] • very high (99,9%) service level[12]
		(high or low unit cost + large or small physical size) + critical	not explicitly named	ensuring availability + minimising inventory value + minimising storage space + security	• very frequent review period (at least daily), particularly for high cost or large items • tight control (closed door storage)[11] • high (99,5%) service level[12]
		high unit cost + large physical size + non critical	not explicitly named	minimising inventory value + minimising storage space + security	• very frequent review period (at least daily) • tight control (closed door storage) [11] • normal (98 - 99%) service level[12]
		low unit cost + small physical size + non critical	not explicitly named	reducing material handling time for medical staff	• Economic Order Quantity (EOQ) and capacity define order frequency • decrease medical staff handling time: open shelf system[13] • normal (98 - 99%) service level

[10] Although recommended as a segmentation variable, it was not considered for segment description purposes because the author simultaneously proposed a (s, Q) inventory policy considered to be optimal for all demand volumes and variabilities.
[11] Closed cabinets (requiring authorisation before deployment, e.g., APU systems).
[12] (s, Q) inventory policy to ensure product availability at a given service level and optimised costs; the author recommends that in future research both the hospital's cost and distributor's cost should be considered in developing the proper order quantity and the objective should be to minimise the cost of the entire channel, not just one member within the channel
[13] Interviewees estimated APU systems login increases picking time from 5 – 10 seconds to 20 – 30 seconds (DeScioli, 2005, p. 44).

Authors /Type of material /Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Danas et al. (2006) /pharmaceuticals /2 consecutive focus groups (involving researchers + 3 doctors and researchers + pharmacists) /processes recommended assume the implementation on a set of neighbour hospitals	• criticality (critical, important, not important, depending on danger of loss of life, quality of treatment, and replacement with other treatment) • supply characteristics: lead time, # of potential suppliers, replacement • inventory problems: price, space required, special storage condition, expiry date • usage rate: over stocking, frequency of use	A: very important[14] (includes critical materials)	not explicitly named	very high availability[15] flexibility[15,16]	• stocked in each clinic that uses them and at every hospital pharmacy as safety stocks
		B: important[14] (includes critical materials)	not explicitly named	high availability[15] flexibility[15,16]	• stocked in each clinic that uses them but the safety stock is distributed among hospitals in the same geographical area and managed virtually
		C: less important[14]	not explicitly named	availability[15] low cost[15]	• stocked only in each clinic that uses them, making each clinic responsible for the stock management
		D: not important[14]	not explicitly named	low cost[15]	• supplied in a JIT basis in each clinic that requires them • no safety stock
Gupta et al. (2007), using the classification scheme described by Thawani et al. (2004) /pharmaceuticals /190 bed military hospital in India (all 325 medicines under section one of priced vocabulary)	• unit cost × demand (ABC classification) • criticality (V: Vital, E: Essential, D: Desirable)	I (AV+BV+CV+AE+AD)	not explicitly named	cost containment availability	• monitor by top management • bring down the number of AD items
		II (BE + CE +BD)	not explicitly named	availability of BE and CE items	• manage by middle management
		III (CD)	not explicitly named	not stated	• manage at lower management level

[14] Items (pharmaceuticals) are classified using a tree-based classification system that combines the various segmentation variables.
[15] Operational capabilities are not explicit; the ones in the table were derived by us from explicitly recommended processes.
[16] The more upstream in the supply chain inventories are stored, the higher their flexibility.

Authors /Type of material /Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Cheng and Whittemore (2008) /pharmaceuticals and medical supplies /case study: 3 hospitals in the USA typology, although there was some graphical bivariate variable analysis	• unit price • handling characteristics • physical size and weight • shelf life (expiry date) • criticality (materials to be delivered to critical wards) • demand location / dispersion (# of locations where demand occurs) • demand level • demand frequency (# of transactions) • demand variability	extremely critical wards (Emergency Room, Operating Room, some Intensive Care Units)	ward oriented minimum safety stock	high availability[15]	• wards should store their own safety stock for emergency use
		high unit cost +low (weekly) demand ($\Rightarrow$ high opportunity cost)	flexible, customer-responsive supply chain (agile supply chain) • make-to-order or assemble to order (pack-to-order) • centralised inventory[17] with frequent distribution	decreased lead times, increased supply chain flexibility $\Rightarrow$ minimised uncertainty	• faster transportation + centralised inventory to lower the inventory level • IT infrastructure to enable visibility of the entire supply chain
		high demand level[18] + low unit cost	lean supply chain, fragmented inventory	low cost[15]	• if demand is expectedly stable, periodic replenishments with fragmented inventory[19] (i.e., decentralised inventory location)
		high demand frequency + high demand level	horizontal cooperation	reduced supply chain costs	• shared distribution networks and warehouses among neighbour hospitals
		high demand dispersion + high demand level	virtually centralised inventory (in analogy with the supply chain of convenience stores)	low cost (low inventory and low logistics costs) high service levels high customer satisfaction with fresh products	• information sharing: point-of-use sales data (POS), sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules; this information can be assessed by the professionals throughout the hospital. • real-time central database, with demand information + inventory levels in all locations

[17] Centralised inventory $\Rightarrow$ risk pooling advantages.
[18] Measured by average weekly demand.
[19] According to the author, this may increase the storage space needed in the hospital but will save staff efforts and transportation costs; on the other hand, by setting up a cross-functional supplier association, it would be necessary to enable supplier-customer coordination and development.

2.5 Analysis of the qualitative information collected from two hospital systems

As explained in section 2.2, we performed a conventional (or inductive) content analysis (see Hsieh and Shannon 2005) of the transcriptions of the interviews with materials supply chain and pharmacy managers. The interview excerpts of parts containing respondents' mentions to characteristics of items or services with an impact on materials supply chain management, i.e., with specific requirements from materials supply chain management, were coded according to that characteristic. We have also coded the references to supply chain capabilities, processes or resources recommended for specific item or service characteristics. It is important to note that the interviewees were asked if all the items or services had the same requirements from materials supply chain management and to explain how the identified differences occurred (as can be observed in Appendix 2.2) – the interview questions did not suggest any specific materials, services or characteristics. The emphasis is put on the impact of materials or service characteristics on materials supply chain since the managers interviewed are responsible for materials supplies and movements (and not for services organisation).

There was a consensus among the respondents that there was an influence of both the items and the services characteristics on materials supply chain management requirements and the item or service characteristics that they referred are organised in Appendix 2.3 and Appendix 2.4, respectively.

The item characteristics that the respondents referred as influencing materials supply chain management were: unit cost, demand volume, shelf life/ expiry date, demand variability, demand dispersion/ material specificity (use in a specific care unit vs. use in the whole hospital), existence of substitutes, criticality/ urgency, variety, physical size, and storage conditions.

The service characteristics that the respondents referred as influencing materials supply chain management were: demand volume, demand variability, criticality/ urgency, unit cost (of the consumed materials), use of (patient) specific materials, variety (of the consumed materials), innovation (of the services or of the involved materials), physical size or weight (of the involved materials), and traceability requirements (of the involved materials).

There is a close relationship between the characteristics that were pointed out by the hospital systems managers relatively to the items and those pointed out relatively to the services, and vice-versa, as can be observed in the following excerpts of interview transcripts[20] (several more examples can be found in Appendix 2.3 and Appendix 2.4):

[20] The original statements, in Portuguese, can be read in Appendix 2.3.

> [After having characterised material logistical requirements at the Emergency Rooms (ERs), Emergency Operating Rooms (EORs), Intensive Care Units (ICUs) and Operating Rooms (ORs)] *The remaining materials are... ordinary, protection materials, materials for wounds, drainage, the materials that are typical of the medical care provided at inpatient care, such as diapers, clothes… These materials do not need the same worries.* (Supply Chain Manager, HS2)

> *[…] for example, prostheses [...] or [devices] that are for a given patient. For example, the neuro-stimulators for Parkinson surgeries. This is something that has to be articulated, normally… naturally, with the Services. The Service knows when a Parkinson surgery, during which a neuro-stimulator will be implanted, is expected, when it was scheduled, and asks, in due time before, for that neuro-stimulator to that patient to be acquired, and the neuro-stimulator is registered for that patient*. (Supply Chain Director, HS2)

Thus, items are frequently described as having certain characteristics mainly because of the characteristics of the services that will consume them, and services are mentioned as requiring differentiated supply chain management due to the characteristics of the items that are consumed for their provision.

The fact that, when asked if different services had different supply chain requirements, hospital supply chain managers based their answers on the impact of the services on materials flows could be expected, since their professional activity is mainly based on assuring the provision of the needed materials to the various services. More relevant is the fact that the characterisation of the materials is frequently made depending on the type of service that will consume them (e.g., special worries are described relatively to the materials consumed at critical wards).

The respondents' descriptions of some of the supply chain operational processes that the hospital systems use to deal with the requirements of some services/items in terms of supply chain capabilities are presented in Appendix 2.5. Statements referring the emergency room (ER), emergency operating room (EOR), intensive care unit (ICU), operating room (OR), hemodynamics (stents) (i.e., a ward that consumes high unit cost, high variety materials), medicine inpatient care, or high unit cost medicines provided at ambulatory care have been obtained. The specific operational processes referred can be seen in subsection 2.6.4.

In Table 2.5, we list the characteristics associated with the wards used as an example of materials supply chain management specificities by the respondents. It must be noted that the interviewees were asked if there were services with characteristics that had specific supply chain requirements, and not to characterise each of the hospital systems' wards or services.

Table 2.5 Characteristics associated with the wards used as example of supply chain management specificities by the respondents (materials supply chain managers)

Service/ ward	Characteristics associated by the respondents
medicine inpatient care	high demand volume, low unit cost materials
surgery inpatient care	high demand volume
inpatient care	low criticality/ urgency
ophthalmology and ambulatory surgery operating rooms	high demand volume, small size materials
outpatient care	low demand volume materials, low materials demand variability, low criticality/ urgency
emergency rooms	high demand variability/ demand difficult to predict on a daily basis, high criticality/ urgency, narrow time window
emergency operating rooms	high criticality/ urgency
intensive care units	high criticality/ urgency
operating rooms	high criticality/ urgency
orthopaedics	high unit cost materials, high weight materials
neurosurgery	high unit cost materials, high weight materials, use of (patient) specific materials, with traceability requirements
ambulatory care	high unit cost materials
cardiovascular surgery (including hemodynamics)	use of (patient) specific materials, high unit cost materials, high materials variety, innovation (in the hospital system under analysis), with traceability requirements
gastric surgery	use of (patient) specific materials, with traceability requirements
central OR	high unit cost materials

2.6 Synthesis and discussion

2.6.1 Introduction

In the next subsections, we compare the qualitative information obtained from the analysed hospital systems, organised in Appendix 2.3, Appendix 2.4 and Appendix 2.5, with the information obtained from the literature. In particular, the following aspects are addressed:

- the potential segmentation variables identified used or recommended on previous research (as described in section 2.4) are compared with those identified in the respondents answers (as described in section 2.5);
- the characteristics associated to each of the wards/specialties that the respondents used to exemplify the impact of the type of service delivered on the hospital system materials supply chain management, when asked if there were services with characteristics requiring specific supply chain features;
- the referred associations of specific levels of segmentation variables to define typical supply chain segments are compared with those present in the literature.

Throughout these analyses, the interviewees are coded as described in Table 2.6.

Table 2.6 Codes used to identify the respondents

Respondent function	Respondent hospital system
SCD – Supply Chain Director	HS1 – Hospital System 1
SCM – Supply Chain Manager	HS2 – Hospital System 2
PUD – Purchasing Director	
PHD – Pharmacy Director	

2.6.2 Segmentation variables

The segmentation variables determine why the segments differ, as the materials that flow in the supply chain are partitioned in such a way that materials or services that are similar along the chosen segmentation variables are aggregated. Since different variables naturally result in different segments, their appropriate selection is crucial in a supply chain segmentation process. As stated by Tang and Gattorna (2003), the supply chain segments' resulting from a segmentation process should be distinct, sizeable and actionable. The variables chosen to segment a hospital supply chain should be those that are more important to determine the application of diversified supply chain management practices to the various segments, so that the resulting segmentation scheme is "*sound (i.e., needs based) and implementable"* (Bonoma and Shapiro 1984: 259). The choice of the segmentation variables to use must also take into account the objectives of the segmentation process. Moreover, frequently a compromise between the theoretically desirable variables and those that are practically obtainable has to be made.

In Table 2.7, we list the potential hospital materials segmentation variables referred in previous literature or by the hospital supply chain managers interviewed. Variables that have some level of similitude or coincidence in terms of their underlying concepts are separated by a dashed line.

Some of the segmentation variables more frequently used, or at least referred as being relevant, in the previous literature are coincident with those identified in the literature related to industrial supply chains (see Table 2.3), namely:

- demand volume/level,
- demand uncertainty/variability/predictability,
- physical size and/or weight, and
- number of potential suppliers.

Some previous researchers consider *physical size/weight* as a potential hospital supply chain segmentation variable, but they do not manage to implement it on their research, mainly because of the lack of related information in the hospitals' materials master files (see references to this problem in DeScioli 2005, Cheng and Whittemore 2008, and Danas et al. 2006). Given the fact that most materials supplied by a hospital supply chain are relatively small and light when compared with those flowing through other supply chains, we do not think that this is a major limitation. To support our argument, we can, for example, observe that the strategies recommended by DeScioli (2005) (see Table 2.4, p.32) are not significantly affected by the *physical size* of the materials, being apparently only determined by their *criticality* and *unit cost*.

The *number of potential suppliers* can be a relevant variable from a strategic point of view. The analysed literature does not describe how the supply chain strategy should be modified depending on the number of potential suppliers for the materials. In the studied hospital systems, the concentration of purchases in one or two suppliers per material was indicated as a condition for the implementation of VMI. Frequently, the existent concentration resulted from a strategic decision and not from a market condition.

Table 2.7 Hospital materials segmentation variables: references in previous literature and in respondents' answers

Segmentation variable	Authors or respondents
unit value/ cost/ price	DeScioli (2005), Danas et al. (2006), Gupta et al. (2007), Cheng and Whittemore (2008) SCD, HS1; SCD, HS2; SCM, HS2
demand volume/level	DeScioli (2005), Gupta et al. (2007), Cheng and Whittemore (2008) SCD, HS1; SCD, HS2; PHD, HS2; SCM, HS2
demand frequency	Danas et al. (2006), Cheng and Whittemore (2008)
demand uncertainty/ variability/ predictability	DeScioli (2005), Cheng and Whittemore (2008) SCD, HS1; SCD, HS1*; SCD, HS2*
demand location/ dispersion	Cheng and Whittemore (2008) SCM, HS2; SCD, HS1; SCD, HS2
(patient) specificity	SCD, HS1; SCD, HS2; SCM, HS2
variety	SCD, HS2
physical size and/or weight	DeScioli (2005), Cheng and Whittemore (2008) SCM, HS2; SCD, HS1
shelf life or expiry date	Danas et al. (2006),Cheng and Whittemore (2008) SCD, HS1; SCD, HS2
criticality	DeScioli (2005), Danas et al. (2006), Gupta et al. (2007), Cheng and Whittemore (2008) PHD, HS1; SCM, HS2**
special storage condition or handling characteristics	Danas et al. (2006), Cheng and Whittemore (2008) SCD, HS2; PHD, HS1; PHD, HS2; SCM, HS2
with traceability requirements	PUD, HS1; SCD, HS2
number of potential suppliers	Danas et al. (2006)
ease of replacement/ existence of substitutes	Danas et al. (2006) SCD, HS1
innovation level	SCD, HS1

* Referred relatively to the services delivered at the ER
** The respondent gave some examples of materials requiring fewer worries than those used in ERs or ICUs (i.e., item criticality was associated to the ward consuming the item).

Variables like *unit value, unit cost* or *price*, frequently mentioned as relevant to segment the materials flowing in a hospital supply chain, are not brought up in manufacturing contexts as frequently as could be expected (at least, not directly). They have been considered indirectly though, through the references to some unit cost dependent variables, such as the *usage value* (from ABC classification schemes), the *contribution margin*, the *profit margin* or the *product value density* (see Table 2.3).

Other variables present in the health care related literature are frequently used in studies related to specific industries or materials: the *shelf life or expiry date* are important in the food industry and in the management of blood supply, and *criticality* is frequently mentioned relatively to the inventory management of spare parts (e.g., Porras and Dekker 2008, Braglia et al. 2004).

Although identifying the materials with limited *shelf life* or *expiry date* is essential to the operational management of these items on a day-to-day basis[21], this is not an important feature to distinguish the materials that flow in a hospital in terms of the type of supply chain strategy that should guide their management. The operational management of materials with limited shelf life or expiry date can be substantially improved through the adoption of adequate information and traceability systems. It must, however, be noted that the use of systems to track materials in the health care supply chain is very important also when the materials involved do not impose significant shelf life or expiry date constraints. The use of such systems improves patient safety, facilitates recalls and returns of medical devices, medicines and other materials, and prevents pharmaceuticals counterfeiting, illegal importations and grey market (Bellman 2003). It also improves the security of items with high unit costs or legal control requirements (e.g., narcotic analgesics).

Criticality has consensually been considered relevant by authors addressing topics related to the segmentation of hospital supply chains (see Table 2.7), but it is frequently not explicitly taken into account in the operationalization of hospital inventory policies, as accounted by DeScioli (2005) and Cheng and Whittemore (2008) about the hospitals they analysed. Furthermore, as far as we are aware, its practical or empirical use to segment hospital supply chains has been very limited (as in the case of some VED analysis, see e.g., Gupta et al. 2007), due to lack of information related to the evaluation of items criticality on available hospitals records. In fact, researchers have repeatedly recommended that hospital product master files should be updated to include some item criticality evaluation (see, e.g., DeScioli 2005, Danas et al. 2006). Furthermore, previously recommended approaches depend on an extensive, time-consuming, and most probably sometimes subjective and difficult *a priori* classification of the materials according to their criticality by health professionals. For example, Gebicki et al. (2013) reported that the use of the criticality classification proposed by Danas et al. (2006) proved to be difficult to apply in real settings as in many situations it was not clear whether a

[21] At Hospital System 2, withdraws due to losses and exceeded expiry dates represented 0,076% of total pharmaceuticals consumption in 2012 (Source: hospital system 2012 Financial Statement).

treatment could be replaced or whether it was necessarily critical, or completely not important. Therefore, it would be important to develop criticality assessment methods that could be more easily used in practice, and hence, more useful for hospital supply chain managers.

Finally, some of the variables suggested to segment a hospital supply chain are less common in studies addressing other industries (Table 2.3):

- demand location/dispersion,
- demand frequency,
- special storage conditions or handling characteristics, and
- ease of replacement/existence of substitutes.

The type of *storage conditions* or *handling characteristics* required are relevant for facility and equipment planning, investment and management, or more operational supply chain issues such as assuring the control of the required conditions during transportation and storage. The monitoring of some of these conditions can be done using information and traceability systems, e.g., Radio-Frequency Identification (RFID) (see e.g., Wicks et al. 2006). According to the qualitative information collected, the storage conditions may not be very important to distinguish between pharmaceuticals since, for example, in one of the analysed hospital systems, almost all handled pharmaceuticals require the same storage conditions (protection from light and temperature between 2 and 8 ºC) and only a very limited, and thus, easily identifiable, number of pharmaceuticals (less than fifteen) requires very low temperatures (between -20 and -30 ºC) (see Appendix 2.3, p.228).

The *existence of substitute products* can be a relevant variable from a strategic point of view, but the analysed literature does not describe how it should influence the supply chain strategy. The hospital supply chain managers interviewed did not comment the topic in a detailed way either.

2.6.3 Supply chain segments

The segments proposed in the literature to segment supply chains in manufacturing settings are usually strongly influenced by the *functional – innovative* products dichotomy, i.e., products with long life cycles and low demand uncertainty versus products with short life cycles and high demand uncertainty (see Appendix 2.1).

We have identified the characteristics of the supply chain segments recommended in the reviewed studies, as described in Table 2.8. DeScioli (2005) and Cheng and Whittemore (2008) associate these characteristics in a bivariate manner. The approach proposed by Danas et al. (2006) is multi-attribute, but the authors do not provide details about how to apply the classification categories of some variables in practical situations, and therefore the logic behind the characteristics of the suggested segments is difficult to understand. In the table, we also identify some associations of variables the respondents used to exemplify their arguments. It must be noted that they were not asked to segment the hospital materials supply chain in a comprehensive way.

DeScioli (2005) and Cheng and Whittemore (2008) placed critical and/or urgent items (e.g., those consumed at critical services) on autonomous segments and Gupta et al. (2007) has classified "vital" pharmaceuticals in the most important segment independently of other variables. It can also be noted that many of the references in the literature or by the interviewees give an important role to the *unit cost*, which is not the case in manufacturing contexts.

Table 2.8 Dominant characteristics of the hospital supply chain segments recommended in the reviewed studies and association of characteristics referred by the respondents

		Dominant segment characteristic			
		Criticality	**Unit cost**		**Demand**
	Combined with	high	high	low	high volume
Demand	high volume			Cheng and Whittemore (2008) SCD, HS1; SCM; HS2	
	low volume		Cheng and Whittemore (2008)		
	high frequency				Cheng and Whittemore (2008)
	high demand dispersion				Cheng and Whittemore (2008)
Other	low variety			SCD, HS1	SCD, HS1
	large physical size/ heavy weight		DeScioli (2005) SCD, HS1		
	small physical size			DeScioli (2005)	SCM, HS1
	special storage requirements		SCM, HS2		
	narrow time window	SCM, HS2			
	long service processing time		SCD, HS1		
	short processing service time				SCD, HS1
	independent of other variables	DeScioli (2005), Gupta et al.(2007), Cheng and Whittemore (2008)			

2.6.4 Operational strategies associated with typical supply chain segments

Table 2.9, Table 2.10, Table 2.11 and Table 2.12 contain the operational capabilities for some typical hospital materials supply chain segments recommended in the literature and by the respondents, and the operational processes and/or resources suggested to achieve them. This effort of synthesis was not always easy because there were descriptions of the operational processes or resources to tackle the characteristics of specific segments without mentioning the operational capability that they were intended to achieve. Since the variety of operational capabilities listed is high, to improve the tables' readability, we categorised them under four themes: service, cost, time, and space related. There are, however, strong connections between operational capabilities included in different tables (e.g., *responsiveness*, which was considered under the time related operational capabilities label, is also much related to service).

The following *operational capability – segment* matches are worth emphasising because they have been referred by several researchers and hospital supply chain managers:

- *low cost/ cost efficiency* has been recommended for *high demand volume materials* that have *low unit cost* (Cheng and Whittemore 2008) or *high demand dispersion* (Cheng and Whittemore 2008);
- *high availability* has been recommended for *critical materials* (DeScioli 2005, Danas et al. 2006, Gupta et al. 2007), including materials consumed at critical wards – e.g., ERs and ICUs (SCM, HS2; SCD, HS1; Cheng and Whittemore 2008);
- *responsiveness* (SCM, HS2) and *flexibility* were recommended for *critical materials* (Danas et al. 2006);
- *tight control* or/and *security* have been recommended for *high unit cost materials* (SCM, HS2; DeScioli 2005), namely those provided to patients at ambulatory care services (SCD, HS1).

Finally, it must be noted that some desirable hospital supply chain capabilities may not be included in the tables simply because they are not recommended to a specific supply chain segment, being instead transversal to the whole supply chain – some types of *quality* and surely *safety* will be in this group.

Table 2.9 Cost related operational capabilities, and corresponding operational processes and/or resources recommended for typical hospital materials supply chain segments in the previous literature or by the respondents

Operational capability	Type of segment	Operational processes and/or resources	Author(s) or Respondent
low cost/ cost efficiency	less important	stock only in each clinic that uses them; the clinic is responsible for stock management	Danas et al. (2006)
	not important	JIT supply in each clinic that requires them; no safety stock	Danas et al. (2006)
	low unit cost + high demand	lean supply chain; if demand is expectedly stable, periodic replenishment with decentralised inventory location (this may increase the storage space needed, but decreases staff efforts and transportation costs)	Cheng and Whittemore (2008)
	high demand + high demand dispersion	virtually centralised inventory; information sharing throughout the hospital: POS data, sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules	Cheng and Whittemore (2008)
	vital + A	monitored by top management	Gupta et al. (2007)
cost containment/ optimised resource utilisation	high unit cost medicines (ambulatory care)	demand information sharing with the supplier, VMI, RFID	SCD, HS1
	high unit cost, high variety (e.g., stents)	consignment, demand information sharing with the supplier and VMI, two alternative suppliers, registration of consumption to the patient	SCM, HS2
	high demand + high demand frequency	horizontal cooperation: shared distribution networks and warehouses among neighbour hospitals	Cheng and Whittemore (2008)
	critical materials	frequent review period	DeScioli (2005)
reduced supply chain costs	high unit cost	frequent review period virtually centralised inventory; information sharing throughout the hospital: POS data, sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules	DeScioli (2005) Cheng and Whittemore (2008)
minimised inventory value	high demand + high demand dispersion materials high demand + high demand dispersion materials	frequent review period virtually centralised inventory; information sharing throughout the hospital: POS data, sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules virtually centralised inventory; information sharing throughout the hospital: POS data, sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules	DeScioli (2005) Cheng and Whittemore (2008) Cheng and Whittemore (2008)
	high demand + high demand dispersion materials	virtually centralised inventory; information sharing throughout the hospital: POS data, sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules	Cheng and Whittemore (2008)

Table 2.10 Service related operational capabilities, and corresponding operational processes and/or resources recommended for typical hospital materials supply chain segments in the previous literature or by the respondents

Operational capability	Type of segment	Operational processes and/or resources	Author(s) or Respondent
(very) high availability/ service level	critical	inventory policy that assures high service level	DeScioli (2005)
	(very) important (including critical)	stock in each clinic that uses them; keep a safety stock at every hospital pharmacy or distributed among neighbour hospitals and managed virtually	Danas et al. (2006)
	vital + A	monitored by top management	Gupta et al. (2007)
	consumed at extremely critical wards (ER, OR, ICUs)	wards should store their own safety stock	Cheng and Whittemore (2008)
	consumed at ERs, EORs and ICUs	storage of specific materials only in the services; daily replenishment; inventory virtual pooling and visibility involving ERs, EORs and ICUs	SCM, HS2
	consumed at the ERs	higher inventory levels and more frequent replenishment	SCD, HS1
	high demand + high demand dispersion	virtually centralised inventory; information sharing throughout the hospital: POS data, sell-through data, inventory levels, demand forecasts, order status, performance measures, production schedules	Cheng and Whittemore (2008)
flexibility	(very) important (includes critical)	stock in each clinic that uses them; keep a safety stock at every hospital pharmacy or distributed among neighbour hospitals and managed virtually	Danas et al. (2006)
	high unit cost + low demand	make-to-order or assemble (pack) to order; centralised inventory (to lower inventory level); faster transportation; visibility of the entire supply chain	Cheng and Whittemore (2008)
	specific materials provided to innovative services (in the case analysed, cardiovascular surgery)	close communication with the Service professionals (e.g., to forecast demands: the materials used change constantly and there is no historical data)	SCM, HS1

Table 2.11 Time related operational capabilities, and corresponding operational processes and/or resources recommended for typical hospital materials supply chain segments in the previous literature or by the respondents

Operational capability	Type of segment	Operational processes and/or resources	Author(s) or Respondent
quick response/ responsiveness	consumed at ERs, EORs and ICUs	daily replenishment; inventory pooling and visibility among the three wards	SCM, HS2
minimised lead time	high unit cost + low demand	make-to-order or assemble (pack) to order; centralised inventory (to lower inventory level); faster transportation; visibility of the entire supply chain	Cheng and Whittemore (2008)
reliable lead time	medical devices specific to a surgery consumed at the ORs (e.g., orthopaedics' materials)	cross-docking (the materials are not stocked at the hospital) + fast delivery to the OR (after the material is at the hospital)	SCM, HS2
agility	high unit cost + low demand	make-to-order or assemble (pack) to order; centralised inventory (to lower inventory level); faster transportation; visibility of the entire supply chain	Cheng and Whittemore (2008)
minimised material handling time by health professionals	low unit cost	open shelf storage	DeScioli (2005)
	high volume demand + low unit cost (medicine inpatient care)	kanban two bin system	SCM, HS2

Table 2.12 Space related operational capabilities, and corresponding operational processes and/or resources recommended for typical materials hospital supply chain segments in the previous literature or by the respondents

Operational capability	Type of segment	Operational processes and/or resources	Author(s) or Respondent
minimised storage space	critical	frequent review period	DeScioli (2005)
	high unit cost		
high security	critical	closed door storage	DeScioli (2005)
	high unit cost		
tight control	high unit cost	registration of consumption to the patient	SCM, HS2
	high unit cost medicines (ambulatory care)	demand information sharing with the supplier, VMI, RFID	SCD, HS1

2.7 Conclusions

We conclude this chapter by summarising the research work, examining the identified research gaps and linking the chapter findings with the remainder of the dissertation.

We have reviewed the literature related to hospital materials supply chain segmentation. As a result of this work, we concluded that the topic is still under-explored when compared with the same theme on manufacturing contexts.

In fact, there is no empirical evidence supporting the need for segmenting the hospital supply chain, i.e., we have found no published studies providing empirical evidence that segmented hospital supply chains are associated with higher operational performance. However, the available empirical evidence concerning supply chain segmentation in manufacturing contexts revealed that companies may combine more than one typical supply chain strategy (i.e., efficient and responsive, or lean and agile) when in a multi-product situation. For more innovative products or in unstable environments, responsive or agile strategies are preferred, and, for more functional products or in stable environments, efficient or lean strategies are preferred. Thus, although the adequacy of the abundant supply chain diversification recommendations has not been proved in a hospital context, it has been supported by empirical evidence from other industries. This suggests that segmentation is a strategic opportunity worth exploring in a hospital context too. Additionally, both the analysed studies that involved empirical research at real hospitals, and the supply chain managers interviewed, provided arguments explaining why some materials should have a different supply chain management.

We analysed, reconciled and condensed the information on the literature related to the segmentation variables used, the resulting segments, and the recommended operational strategies for those segments, thus contributing to the systematisation and integration of the literature related to the supply chain segmentation topic, on a hospital context. The results of this effort were compared with qualitative information collected from two hospital systems, enabling the identification of points of agreement, and also of points of discrepancy that can be an indication of research or managerial gaps. This analysis gives access to the insights of otherwise disperse research content in an organised and comparative way.

Additionally, we highlighted the links between desired operational capabilities and the processes and/or resources that have been proposed to support those capabilities. This may be useful both for academics and managers, since it provides a portfolio of hospital supply chain strategies that can be further developed, tested, validated, or implemented in real situations.

The fact that we have adopted an operations strategy perspective to hospital supply chain segmentation, thus linking the desired strategic capabilities for each segment to the associated operational processes or resources, can significantly contribute to the more broad supply chain segmentation literature. Although Nakano and Akikawa (2014) have presented an example of a similar exercise, when they matched structure, processes and performance with two generic supply chain strategies, a broad literature synthesis describing these links is still not available.

One of the main research contributions of this chapter is the identification of gaps that can stimulate interesting future research developments.

When comparing and integrating the four research works analysed, it was not always easy to clearly identify the meaning of the *constructs* used by the different researchers, both in terms of the segmentation variables and operational supply chain capabilities. For the sake of comparability and clarity, it would be useful, in the future, to explicitly define the concepts and measurements of these constructs.

In terms of the variables used to segment a hospital supply chain, some potential approaches have not yet been fully explored, for example:

- *criticality* has been considered, both by academics and hospital supply chain managers, as a variable with an important impact on materials supply chain management, but, while some segmentation approaches considering criticality have been proposed, no associated objective is used in a generalised way in hospital supply chains practice;
- the *number of potential suppliers* for a material or the *existence of substitute products* can be relevant from a strategic point of view, but their impact on a hospital supply chain operational strategy has not received much attention yet.

Although we have only analysed two real hospital systems supply chains (this preventing us from identifying the managerial gaps related to the theme under analysis), by crossing the information obtained from the managers interviewed with that obtained from the literature, we can guess that in most hospitals there is no explicit, systematic differentiation of the supply chain processes or resources used to manage items supply based on their criticality (this does not mean that the managers do not take criticality into account more subjectively, e.g., based on their experience).

In terms of the used research methods, in general the hospital materials supply chain segmentation approaches that have been proposed so far need further empirical support or testing. Some of these proposals originated from case studies (i.e., DeScioli 2005, Cheng and Whittemore 2008). But, even these efforts were not fully capable of empirically supporting the advocated segmentation approaches because no full empirical support for the recommended supply chain segments or related validation is provided.

There is still a need for research that analyses the impact of the proposed diversified supply chain strategies on the whole hospital supply chain, since some of the suggested strategies can be beneficial to hospitals but may imply additional costs for the suppliers. For example, for some segments, materials consignment and VMI have been recommended. While it is expected that these schemes decrease the overall supply chain cost, they may increase suppliers' financial costs and it may not be clear if this rise is compensated by a decrease on their operational costs induced, for example, by increased demand visibility and information sharing. Furthermore, several models to determine inventory policies in consignment situations have been developed, but, although consignment is a frequent practice in hospitals, these models are not used to support hospital decisions (Sarker 2014). The impact of recommended strategies on the global supply chain, and on the sphere of the various stakeholders is thus a topic worth developing.

Finally, as far as we are aware, there have not been any studies analysing the relationship between hospital supply chain strategic fit and hospital performance yet. Even in what concerns specific hospital supply chain segments, it would be useful to see studies analysing the segment performance, given the related service or materials characteristics, the recommended supply chain operational capabilities for those characteristics, and the operational processes or resources used.

In chapter 3, we contribute to narrow two of the gaps identified in this chapter since we:

- use empirical data collected from a real general hospital system and multivariate data analysis to segment the items that flow in a hospital system supply chain;
- propose a service (i.e., ward) related proxy for item *criticality* that can be easily used in practical situations, since, unlike previously suggested measures, it does not require an extensive item classification effort from health professionals.

Later, in chapter 4, we use a System Dynamics approach to develop some simulation models and perform experiences in order to better understand the relation between some supply chain processes and some supply chain capabilities, for a typical material from one of the segments determined in chapter 3. This work is related to the first research gap referred two paragraphs above.

The research work described in this chapter is also used in chapter 3 to support the selection of the segmentation variables to use, to validate the segments determined and to link those segments to specific operational strategies.

3 Hospital supply chain segmentation – a classification scheme

3.1 Introduction

The supply chain of a hospital must gather all resources needed to assure the provision of a great variety of services, involving managing the flows and inventories of numerous and diverse materials, especially in the case of a general hospital. As reviewed in the last chapter, it has been frequently argued that the management of a multi-product supply chain management is best assured by adopting diversified supply chain strategies depending on the characteristics of some homogeneous groups (i.e., segments) of products.

In this work, we first partition the myriad of pharmaceutical and medical and clinical items that flow through the supply chain of a hospital system, into a small, manageable number of homogeneous groups (clusters/segments) different from one another, in terms of the capabilities they need/require from the supply chain. We then link the identified groups to recommended strategic supply chain operational capabilities, processes and resources. In this chapter, the research work described in chapter 2 is used to support the selection of the segmentation variables to use, to validate the segments determined and to link them to specific operational strategies. The result of this effort is a new (although grounded in previous research and in hospital supply chain managers views) classification scheme for the items flowing in a hospital supply chain. This analysis assumes an organisational configuration view of the hospital supply chain (topic that has also been addressed in chapter 2).

Meyer et al. defined an *organisational configuration* as “[…] any multidimensional constellation of conceptually distinct characteristics that commonly occur together” (Meyer et al. 1993: 1175). A *configurational* approach takes a systemic and holistic view of organisations, suggesting that they are best understood as clusters of interconnected structures and practices, where patterns and profiles rather than individual independent variables are related to outcomes, this being particularly relevant in strategic management (Fiss 2007).

Our segmentation scheme was partially derived from quantitative (numeric) empirical data and it has, therefore, many of the characteristics of a taxonomy[22] – it would, for example, fit in the definition of Bozarth and McDermott (1998) that define taxonomy as a classification system that categorises phenomena into mutually exclusive and exhaustive sets. However, since it does not have the hierarchical logic described by Rich (1992) and the link between the identified segments and the strategies recommended for them was not established through

[22] We distinguish classification schemes, typologies and taxonomies in chapter 2 (section 2.1).

numerical empirical analysis, we use the broader term *classification scheme* to categorise it (see chapter 2).

The determination of the groups (clusters/segments) was performed using Cluster Analysis, an area of multivariate statistics that involves the grouping of objects (in our work, the items) based on some measure of proximity defined among those objects (Brusco et al. 2012) and that, following the taxonomy of Miller and Roth (1994), has been frequently used to develop empirical taxonomies in Operations Management (e.g., Frohlich and Dixon (2001), Zhao et al. (2006)) and more specifically in Supply Chain Management (e.g., Cagliano et al. (2003), McKone-Sweet and Lee (2009), Flynn et al. (2010)). However, the scope and objectives of these supply chain taxonomies are different from those of our work and, therefore, in terms of results discussion, our analysis is more comparable to the hospital supply chain materials segmentation approaches (mainly typologies) described in chapter 2. To perform our segmentation, we collected and analysed internal transactional data from a general hospital system composed by three neighbour hospitals, with a total of 550 inpatient beds in 2012[23] (Hospital System 1 in Table 2.1).

The identification of the recommended operational supply chain strategies (i.e., capabilities, processes and resources) for the determined segments was based on the synthesis of related literature and on the information obtained from the supply chain managers of two hospital systems interviewed (as described in chapter 2).

Although we focused the analysis on the items supply chain, the steps and results of our study show that the segments obtained are closely related to the types of service provided. To validate our results, we compared the segments determined with the gathered qualitative information about hospital materials supply chain segments described on the literature.

In recent years, due to the financial and economic crisis, expenditure on health in real terms fell in half of the countries of the European Union and significantly slowed in the rest (OECD 2014a)[24]. This has caused reductions of the total budgets of hospital systems that may have a significant negative impact on the quality, availability and safety of the services provided. A clear identification of a small number of groups of items, homogeneous in terms of the capabilities they require from the hospital system supply chain, and the linkage of these groups with specific appropriate operational supply chain strategies (defined by related operational capabilities, processes and resources) facilitates the task of managers when deciding which supply chain strategy to apply and how to implement it, and contributes to increasing the

[23] Data obtained from the 2012 Financial Statement of the hospital system.
[24] In the US, a growth of 2.1% a year was maintained (OECD, 2014b).

efficiency and the effectiveness of the supply chain system, as it favours a better targeting of actions and managerial and financial efforts (e.g., concerning safety stock levels).

Our approach adds to the literature in three ways. First, we derive a segmentation scheme that brings transparency to the multivariate relations between characteristics of the hospital supply chain items that are relevant from an operational supply chain strategy point of view. Second, we link the determined hospital supply chain segments to operational supply chain strategies (defined in terms of specific supply chain capabilities, processes and resources) that have been recommended for them. Third, we propose a service related proxy for item criticality in hospital contexts that has the advantage of not demanding a burdensome *a priori* classification phase to be implemented, which allows us to incorporate criticality in our empirically derived classification scheme.

In the next section, we address the hospital materials criticality theme and explain how it was considered in our analysis. Then, in section 3.3, we describe the empirical information collected and the Cluster Analysis performed. In section 3.4, we identify the supply chain strategies that have been suggested to fit the requirements of the supply chain segments identified. Finally, in section 3.5 we draw some conclusions, emphasising the relevance of the proposed segmentation, and propose lines for further research.

3.2 Hospital materials criticality: definition and measurement

Hospitals treat urgent and severe needs in emergency departments separately from other cases, this showing the strong organisational impact services criticality has (Lillrank et al. 2010).

The importance of taking items criticality into account in the management of hospital supply chains has been frequently stated:

> *In the health sector, hospitals must hold an inventory of essential drugs and lifesaving equipment based on how critical the items are to the needs of the patients and the strength of the competition. Here, criticality of the items may be more important than cost.* (Flores et al. 1992: 71-72)
>
> *Different from other industries, criticality is very clearly defined in the hospital setting and is the most important factor that should be considered*. (Cheng and Whittemore 2008: 48)
>
> *This* [criticality] *is an important characteristic of the medication inventory environment*. (Gebicki et al. 2013: 216)

However, one can also find statements revealing that the concept is not used in a systematic, objective (i.e., quantitative) way to shape inventory policies or supply strategies, or to evaluate supply chain performance (e.g., Cheng and Whittemore 2008, DeScioli 2005). Others report difficulties in the implementation of methods that depend on *a priori* classification performed by medical staff (e.g., Gebicki et al. 2013 reported that in many situations it is not clear whether a treatment can be replaced or whether it is necessarily critical, or completely not important).

In Table 3.1 and Table 3.2, we present previously proposed definitions and measures of *criticality* in a supply chain context in other industries, and in health care, respectively.

In other industries (mainly manufacturing), criticality is frequently pointed out as an adequate criterion to classify spare parts. As noted by Bacchetti et al. (2013) in their recent review investigating the gap between research and practice in spare parts classification, it was one of the two[25] most frequently used criteria in the analysed research studies. However, only two of the ten companies that were object of study used criticality to categorise their spare parts and, in both cases, criticality was assessed through qualitative judgments in a non-formalised way (Bacchetti et al. 2013). The authors do not describe how the companies defined criticality.

In another recent review of multi-criteria classification of spare parts, Roda et al. (2014) use the term criticality not to designate a criterion but as a broader concept referring to the importance of each part, criticality being the end result of a multi-criteria classification effort.

Some of the studies included in the table (Flores et al. 1992) use *criticality* as a possible segmentation criterion to exemplify the proposed classification method, but they do not explain or support the adopted criticality definitions, assessment methods or measurements. There have also been researchers that state that *criticality* may be an important criterion when classifying or segmenting products, but that do not define or explain how to measure it (e.g., Partovi and Anandarajan 2002, Chen et al. 2008). Others use the term *criticality* referring to the rank position of the item resulting from the ranking obtained through the classification method they propose (e.g., Cavalieri et al. 2008).

In general, the item criticality has been associated with the seriousness of the consequences of its lack, both in health care and in other industries (see Table 3.1 and Table 3.2). In health care, it has also been associated to the criticality of the service that will consume the item and with the criticality of the wards at which that consumption will occur (see Table 3.2), with the ERs, ORs, ICUs and/or the Neonatology being considered critical. The definition of *process criticality* by Huiskonen (2001), which links the seriousness of the

[25] The other popular criterion was the part cost.

consequences of an item lack to the time available to replenish it, relates to health care contexts where criticality is also linked to the time window of the services provided (i.e., to emergency situations). As pointed out by Huiskonen (2001), from a logistics control point of view, it is most essential to know how much time there is to react to the demand need, that is, whether the need is immediate or whether there is some time to fulfil it.

Table 3.1 Materials or services criticality definition and assessment outside the health care contexts

Authors	Definition	Assessment or measurement
Duchessi et al. (1988)*	simultaneous consideration of downtime cost, lead time and number of failures per unit time (as described by Roda et al. 2014)	not described by Roda et al. (2014)
Flores et al. (1992)	impact upon integrated operations (quantitative or qualitative), possible scarcity of supply and existence (or not) of substitutes	• subjective
Partovi and Burton (1993)	consequence of not having an item on hand when it is required	• high (complete shutdown), moderate (partial shutdown), and low (no real problem)
Huiskonen (2001)	*process criticality*: consequences caused by the failure of a part on the process in case a replacement is not readily available	• high: the failure has to be corrected and the spares should be supplied immediately; medium: the failure can be tolerated with temporary arrangements for a short period of time, during which the spare can be supplied; low: the failure is not critical for the process, and can be corrected and spares can be supplied after a longer period of time.
	control criticality: possibility to control the part failure situation	• e.g., predictability of failure, availability of spare part suppliers, lead-times, etc.
Braglia et al.(2004)	failure mode effects	• criticality analysis based on logic trees • major categories: criticality to the plant, the supply characteristics, the inventory problems, and usage rate • for each major category, further characteristics are examined • within each major category its characteristics are classified as critical, important or desirable
Porras and Dekker (2008)	impact of unavailability of equipment spare part	• expert judgment • high (expensive downtime or cause danger to the safety of the people and the environment), medium (significant loss of production, but does not endanger the safety of the people or the environment), low (not serious effects on the processes or on the safety of the people and the environment)

*We did not have direct access to the paper.

Table 3.2 Materials or services criticality definition and assessment in health care contexts

Authors	Definition	Assessment
Jack and Powers (2004)	characteristic of acute care services	• services provided at emergency care, intensive care, and neonatology are considered critical
DeScioli (2005)	no definition presented	• non-critical, critical, and highly-critical materials • categorisation may be customised to each ward and hospital
Danas et al. (2006) (based on Braglia et al. 2004)	characteristic of the pharmaceuticals determined from their patient treatment criticality	• expert advice of doctors and pharmacists • pharmaceuticals are classified according to their patient treatment criticality: danger of loss of life (1: critical, 2: important, 3: not important), quality of treatment, and replacement with other treatment • at the end a weighted average describes the level of patient treatment criticality (1: critical, 2: important, 3: not important)
Gupta et al.(2007)		• classification by a panel of ten (a physician, a surgeon, a gynaecologist, a anaesthetist, a pathologist, a paediatrician and four medical officers) • VED classification (V: Vital, E: Essential, D: Desirable)
Cheng and Whittemore (2008)	characteristic of materials to be delivered to critical wards	• extremely critical wards: ERs, ORs or ICUs • may vary amongst hospitals
Gebicki et al. (2013)	consequences of a stock-out	• criticality of a drug is based on the criticality of the treatment for which it is used

Cheng and Whittemore (2008) analysed the hospital materials supply chain and concluded that, in a segmented hospital chain, a ward oriented approach to criticality is more practical than a product oriented approach. This argument is true from an ease of implementation perspective, and it is in line with the qualitative information we collected (see information mentioning critical items and services in Appendix 2.3, p.227, Appendix 2.4, p.230 and Appendix 2.5, p.237). In fact, the interviewed supply chain managers have clearly associated materials criticality more with the characteristics of the services that use/consume them than with some intrinsic characteristics of the materials or any other factor. I.e., materials are considered critical if consumed/used by services provided at Emergency Rooms (ERs), Emergency Operating Rooms (EORs) or Intensive Care Units (ICUs).

Hence, we propose the use of the proportion of the total demand of an item occurring at critical wards/services (i.e., ERs, EORs or ICUs) to assess the criticality of that item. We left the items consumed at other operating rooms out of this definition because the corresponding surgeries are planned in advance, decreasing the urgency pressure on supply chain operations. Hospital supply chain managers and health professionals must still play a role on the refinement of this assessment, and the degree of criticality of an item determined the way we suggest can be easily changed individually if these professionals feel it is does not suit its purposes.

Previous research, both in health care and in other industries, has usually proposed schemes that assess criticality considering three ordinal levels, generally obtained with the participation of experts. In a health care context, it has also been directly associated with the items consumed at critical wards (e.g., Cheng and Whittemore 2008). Our *a priori* measure assumes a continuum of criticality degrees. This measure can be corrected *a posteriori* by hospital supply chain managers with the collaboration of health professionals (e.g., to rise the criticality degree of an item consumed by a critical service performed outside the wards considered critical by definition.)

3.3 Segmentation process

3.3.1 Introduction

We used Cluster Analysis (see, e.g., Hair. et al. 2014) to segment all pharmaceutical and medical and clinical items that flow through the supply chain of the hospital system under analysis. Cluster Analysis groups objects (in our case, the items) in clusters by maximising the similarity of cases within each cluster and the dissimilarity between clusters.

There is no single approach to clustering that can be regarded as appropriate for most situations (Milligan 1996). Consequently, the numerous decisions that have to be taken during the clustering procedure must take into account the purposes of the clustering process, the type of clusters one wishes to construct and the characteristics of the underlying data (Hartigan 1996, Milligan 1996).

We collected data corresponding to all item movements (i.e., entries and exits) of all types in the internal supply chain of the hospital system during a month (in the spring season), in a total of 169.977 movements. Then, we selected the supply movements that corresponded to the delivery of items at a point as close as possible to their final consumption (e.g., exits from automated medication dispensing systems, unit dose dispensing and supplies to two-bin systems located in several wards). We have also obtained a database that stored the items, their suppliers and their unit cost average resulting from the supplier price in recent purchases.

The segmentation process followed the standard steps of Cluster Analysis (Hair. et al. 2014, Ketchen and Shook 1996) illustrated in Figure 3.1 and described in detail in the next subsections. First, we defined the clustering elements, i.e., the cases that were segmented (in this work, the items) and selected and determined the clustering (segmenting) variables. Second, we standardised the variables to avoid that variables with large ranges (i.e., where elements are separated by large distances) are given more weight in defining a cluster solution than those with small ranges (Hair. et al. 2014, Ketchen and Shook 1996). And third, we performed the chosen clustering process, i.e., we applied the selected clustering methods using the adequate similarity (dissimilarity) measures. We have analysed the characteristics of the obtained clusters and their reliability (i.e., accuracy and consistency), and finally, the obtained clusters were compared with results in the literature and with the information obtained from health care supply chain managers (described on chapter 2).

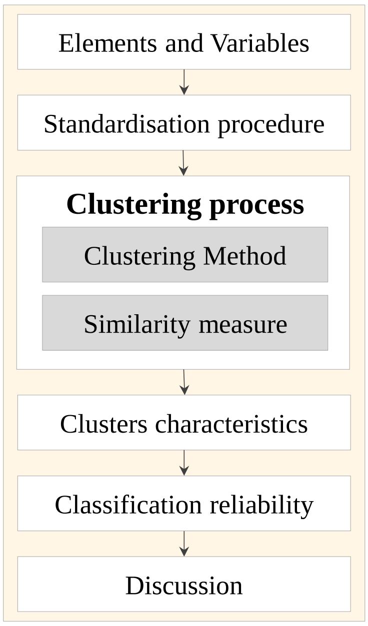

Figure 3.1 Segmentation process

Finally, it is important to note that the expected result of our segmentation exercise is the general characterisation – using a combination of a set of relevant variables – of a small number of groups of materials that can be managed using the same specific operational supply chain strategy, and not an individual classification of all the items flowing in the hospital system. The individual classification of each of the materials would require a refinement of the determined classification performed by the supply chain managers of the hospital system in close collaboration with the health professionals that use each of the materials.

3.3.2 Clustering elements and variables

The clustering elements are the items consumed at the hospital supply chain under analysis.

The appropriateness of the segmentation variables used in a segmentation process depends on the objectives of that process. Indeed, only variables that relate specifically to objectives of the Cluster Analysis and that characterise the objects (i.e., items) being clustered should be included (Hair. et al. 2014). In our case, we want to segment the materials that flow in a hospital supply chain with the aim of obtaining a few groups of materials that have the same operational requirements from the supply chain, and that are therefore best managed under the same diversified operational strategy. The segmentation variables selected must be those with a higher impact on those operational requirements, and it is also important that the solution to satisfy these requirements implies a diversified strategy. For example, if the main solution to improve the management of materials with a limited expiry date is to adopt an adequate information and traceability system, and the same solution responds also to requirements related to other materials (e.g., safety in medicine distribution, security for narcotics or traceability for medical devices), the expiry date should not be chosen as a segmentation variable, even though it is important for the management of the affected items.

Having this objective in mind, and considering results from the literature, information about the phenomena under analysis obtained through qualitative interviews and statistical criteria, we selected a final set of five segmentation variables expected to help discriminate the clustering in the data: demand volume, demand variability, demand frequency, demand dispersion, criticality and unit cost. We have not considered the following variables that have been referred as potentially suitable for hospital materials supply chain segmentation (see section 2.6.2):

- item *variety*, since we have analysed individual stock keeping units (SKUs);
- *physical size/weight*, mainly because the materials master file of the studied hospital system did not have information about the size of the supply materials (this problem has been faced or referred by previous researchers (e.g., DeScioli (2005), Danas et al. (2006), Cheng and Whittemore (2008)), but, given the typical size/weight range of most materials supplied by a hospital supply chain - relatively small and light when compared with those flowing through other supply chains - this was not a major limitation to our work;
- the *shelf life* or *expiry date*, first, because the hospital system master file did not provide the related detailed information, but mainly because it is not an important feature to distinguish the supply chain strategy to guide the management of different materials (as pointed out in the previous chapter, the operational management of

materials with limited shelf life or expiry date can be improved through the adoption of adequate information and traceability systems that will be beneficial to the management of diverse and numerous types of materials flowing in a hospital supply chain);

- *storage conditions* or *handling characteristics* required, because the hospital products master file did not provide related information, and also, because the involved supply chain consequences are not much related to the objectives of our work, since they are relevant for facility and equipment planning, investment and management, or more operational supply chain issues (e.g., assuring the control of the required conditions during transportation and storage); additionally, according to the qualitative information collected, the storage conditions may not be very important to distinguish between pharmaceuticals (see section 2.6.2).
- the *number of potential suppliers* and the *existence of substitute* materials were not used as potential segmentation variable in our analysis, because there was not related quantitative information available to incorporate into our study; these may be relevant variables from a strategic point of view, but they have not been used as segmentation variables by previous researchers, and the qualitative information collected has not been very informative about the corresponding effects on materials supply chain requirements (see section 2.6.2).

The details about how we measured each of the considered variables and the reasons why they were selected are described in Table 3.3. Only variables that are believed to help discriminate the clustering in the data were included in the analysis, since it has been shown that the addition of irrelevant variables can interfere significantly with the capacity to recover a known cluster structure from data (Milligan 1996). Other variables or ways of measuring variables were considered during an initial phase of exploration of the data (e.g., considering *security* or measuring *criticality* using the proportion of the number of deliveries at the ERs, ICUs or EORs, instead of the proportion of the demand volume at these wards), having been disregarded later.

To perform the Cluster Analysis, we computed the first 6 variables listed in Table 3.3 relative to each item using the supply movements corresponding to the delivery of the items at a point as close as possible to their final consumption. The last variable (i.e., the unit cost) was obtained from a database that stored the items, their suppliers and the unit cost average of their recent supplies. When an item was supplied by multiple suppliers, the lowest price was selected.

Table 3.3 Potential segmentation variables to segment the hospital items supply chain

Variable	Measurement	Key reasons for use as segmentation variable
Demand volume	Average daily demand	• High volume items allow for lean and make/buy-to-forecast strategies to take advantage of economies of scale, and lower volume items benefit from flexibility in the entire supply chain (Childerhouse et al. 2002).
Demand frequency	Percentage of days with item demand	• Demand frequency is negatively correlated with Demand variability (see Table 3.5), consequently, it relates to demand lumpiness, disturbing capacity planning and predictability (Childerhouse et al. 2002).
Demand dispersion	Percentage of hospital locations with item demand	• Relates to distribution modes and inventory holding location, e.g., in a hospital, a high demand dispersion increases the number of places where the item is stored (see Danas et al. 2002, Cheng and Whittemore 2008)
Demand variability	Standard deviation of daily demand or Coefficient of variation of daily demand	• Demand variability relates to demand lumpiness, disturbing capacity planning and predictability (Childerhouse et al. 2002).
Criticality	Percentage of total period demand that occurred in the ERs, EORs or ICUs	• Considered by both academics and practitioners as having an important impact on supply chain requirements (see section 3.2). • Influences the positioning of stock, i.e., the decision on whether to use time or a material buffers (i.e., safety stocks) against demand variations (Huiskonen 2001). • Critical items require high availability and responsiveness (see subsection 2.6.4).
Unit cost	Average unit cost (= average supplier unit price)	• High unit cost results in higher acquisition and inventory holding costs, and, at a hospital supply chain, inventory tracking needs (see subsection 2.6.4).

The resulting data set contained information on 2,290 items. From these, 16 items were excluded due to missing values and 1 because it was considered an outlier. The final data set includes 2,273 items – the clustering elements -, with the characteristics described in Table 3.4.

Table 3.4 Characteristics of the final data set

	Max	Higher 10%	Higher 25%	Median	Lower 25%	Min
Average daily demand (units)	3326	35	7	1		0,03
Demand frequency (% of days with demand)	100%	94%	58%	16%	6%	3%
Demand dispersion (% of places of delivery)	100%	30%	11%	4%		4%
Criticality (% of demand at critical wards)	100%	50%	9%	0%		0%
Unit cost (euros)	26250	347,4	33	4		0,01
Demand variability (coefficient of variation)	5,77		4,81	2,64	1,41	0,33

By observing the table, we can confirm the enormous diversity of the items flowing in the hospital supply chain in terms of the analysed characteristics. For example, the daily demand average ranged from 3326 to 0.03 units, the daily demand average being 75% of the items lower than 7 units. The observed diversity is also very impressive, for example, in terms of items unit cost (that ranged from 26250 to 0.01) or the demand variability (the coefficient of variation[26] of the daily demand ranged from a very high 5.77 to a relatively low 0.3).

In a health care setting, it was expected that the data related to demand could exhibit non-normal behaviour and non-linear association between the variables, as we observed. In Table 3.5, we present the Pearson and Spearman correlation coefficients measuring the association among seven potential clustering variables.

Table 3.5 Correlation between possible clustering variables (Pearson an *Spearman* coefficients)

				Demand variability			
Variable	Demand volume	Demand frequency	Demand dispersion	Standard deviation of daily demand	Coefficient of variation of daily demand	Criticality	Unit cost
Demand volume	1	0.293	0.408	0.716	-0.210	0.127	-0.032
		0.793	*0.633*	*0.972*	*-0.754*	*0.410*	*-0.602*
Demand frequency	0.293	1	0.728	0.198	-0.848	0.191	-0.131
	0.793		*0.737*	*0.649*	*-0.975*	*0.485*	*-0.485*
Demand dispersion	0.408	0.728	1	0.271	-0.538	0.296	-0.087
	0.633	*0.737*		*0.557*	*-0.677*	*0.691*	*-0.492*
Standard deviation of daily demand	0.716	0.198	0.271	1	-0.127	0.068	-0.037
	0.972	*0.649*	*0.557*		*-0.590*	*0.358*	*-0.588*
Coefficient of variation of daily demand	-0.210	-0.848	-0.538	-0.127	1	-0.182	0.146
	-0.754	*-0.975*	*-0.677*	*-0.590*		*-0.451*	*0.433*
Criticality	0.127	0.191	0.296	0.068	-0.182	1	-0.080
	0.410	*0.485*	*0.691*	*0.358*	*-0.451*		*-0.401*
Unit cost	-0.032	-0.131	-0.087	-0.037	0.146	-0.080	1
	-0.602	*-0.485*	*-0.492*	*-0.588*	*0.433*	*-0.401*	

In general, the traditional statistical assumptions regarding variable selection do not apply within the clustering framework and, therefore, most clustering methods do not have assumptions of normally distributed or uncorrelated data (Milligan 1996). We have, nevertheless, decided not to consider the *demand variability* (either measured using the standard deviation or the coefficient of variation of the daily demand), in the set of potential clustering

[26] Coefficient of variation = Standard deviation/ Average

variables, because of the very high correlation of these variables with others considered (i.e., demand volume and demand frequency, respectively). As explained, for example, by Ketchen and Shook (1996), the high correlation among clustering variables can be problematic because it may overweight one or more underlying constructs. Although not assessed by the daily demand standard deviation or its coefficient of variation, *demand variability* continued to be considered in our analysis, although measured using another indicator, since it roughly corresponds to the inverse of demand frequency (i.e., a final cluster with high demand frequency will have low demand variability and vice-versa).

Finally, it is important to note that, although from a global supply chain point of view the most important segmentation variables have been included in our approach, on a day-to-day basis at the operational level, pharmacists and material managers have, and should keep, an important role managing the logistical and supply specificities of individual items and services.

The variables were standardised using $Z = (X - Min(X))/ (Max(X)-Min(X))$, because this procedure showed a good performance in terms the of the capacity of the subsequent clustering algorithms to recover known cluster structure from data under various circumstances (namely, in the presence of outliers) in the simulations performed by Milligan and Cooper (1988), when compared with using unstandardized variables or alternative standardisation procedures.

3.3.3 Clustering process

Since the number of clusters that would emerge in our sample was not known *a priori*, we performed a two-stage analysis: a hierarchical method was used to determine the number of clusters, and then a non-hierarchical method was used to allocate the sample items to a particular cluster, as recommended by experts (e.g., Milligan 1980, Ketchen and Shook 1996, Hair. et al. 2014), and frequently applied for the determination of configurations (in operations management, e.g., Frohlich and Dixon 2001, Cagliano et al. 2003, Zhao et al. 2006, Flynn et al. 2010, Macchion et al. 2015). As stated by Brusco et al. (2012), although some emergent clustering methods for empirical Operations Management (OM) research are available, these "venerable methods should continue to be employed effectively in the OM literature". In association with the clustering method, a similarity measure that represents the degree of correspondence, or resemblance, among the cases (i.e., the items) across all the characteristics (i.e., the variables) is used in the analysis (Hair. et al. 2014).

The hierarchical clustering method used was Ward's (1963) minimum variance agglomerative hierarchical clustering method (i.e., cluster membership is assessed by calculating the total sum of squared deviations from the mean of the cluster (Burns and Burns

2008)), because, when compared with alternative methods, it has maintained high absolute and relative capacity to recover known cluster structure from data with various characteristics or containing anomalies, such as the presence of outliers or irrelevant variables (Milligan 1996), having the advantage of being available at commercial statistical packages such as SPSS. Accordingly, the similarity (i.e., since the chosen measure is a distance, dissimilarity) measure used was the squared Euclidean distance because this is the measure recommended for the Ward's method (see e.g., Hair. et al. 2014).

To decide the number of clusters to form, we analysed the SPSS agglomeration schedule (see Table 3.6) and observed the hierarchical tree diagram (dendrogram) (see Figure 3.2). A large increase in the agglomeration coefficient implies that dissimilar clusters have been merged; thus, the number of clusters prior to the merger is most appropriate (Ketchen and Shook 1996). As a result, we decided to partition the items into three clusters.

Table 3.6 Agglomeration schedule analysis

No. of clusters	Agglomeration coefficient* (this step)	Change	% Change
1	497.548	245.432	97%
2	252.116	106.401	73%
3	145.715	43.972	43%
4	101.743	17.434	21%
5	84.308	11.315	16%
6	72.993	10.702	17%
7	62.291	9.893	-

* Distance between the two clusters joint at each step.

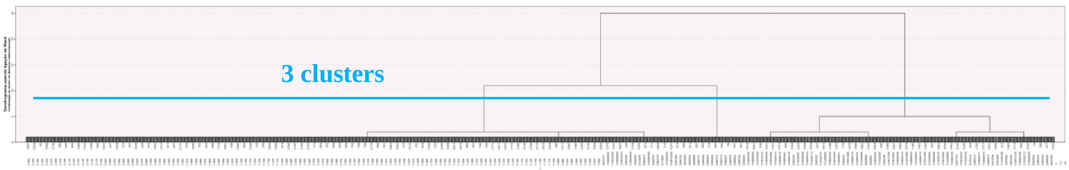

Figure 3.2 Cluster analysis hierarchical tree diagram (dendrogram)

The hierarchical methods have the disadvantage of only making one pass through the data set, not searching for improvement of poor cluster assignments (Ketchen and Shook 1996, Hair. et al. 2014). Consequently, to define the final three clusters, we used a non-hierarchical method, K-means[27], that has the advantage of, by iteratively switching the cluster membership of the cases (items), optimising the within-cluster homogeneity and between-cluster heterogeneity

[27] We have also rerun the hierarchical cluster analysis with the determined number of clusters, having obtained very similar results (the cluster centroids were very close and only approximately 5% of the items were classified in different clusters).

(Ketchen and Shook 1996). In this case, the similarity (i.e., dissimilarity) measure used was the simple Euclidean distance.

3.3.4 Clusters characteristics

The Cluster Analysis, performed using SPSS, resulted in three clusters. A comparison of the centroids (i.e., the means) of the three clusters is presented in Table 3.7. We assigned labels to the three identified segments, in order to highlight their empirically distinct characteristics:

- X: *expensive, specific use* items,
- V: high *volume, frequent and generalised use* items, and
- C: *critical* items.

Table 3.7 Description of the determined clusters

Variables			All observa-tions average	Cluster averages (centroids)		
Name	**Measurement**	**Units**		**X** ***expensive, specific use***	**V** ***high volume, frequent and generalised use***	***C critical***
Demand volume	Average daily demand	item units	29.1	4.1^{C}	100.7	5.1^{X}
Demand frequency	Percentage of days with item demand	%	34%	15%	85%	24%
Demand dispersion	Percentage of hospital locations with item demand	%	11%	5%	28%	9%
Criticality	Percentage of total period demand that occurred in the ERs or ICUs	%	12%	1%	17%	85%
Unit cost	Unit average cost (= average supplier unit price; €)	€	159.5	238.4	5.7^{C}	7.8^{V}
Demand variability	Coefficient of variation	proportion	3	3.77	1.03	3.08
Number of items in the cluster			2273	1500	586	187
% of total items in the cluster			100%	66%	26%	8%

Tamhane T2 test: C: cluster average is not significantly different from that of cluster C, X: cluster average is not significantly different from that of cluster X, V: cluster average is not significantly different from that of cluster X; all other variable averages are different among clusters at levels of significance lower than 0.00001.

We provide more details about the three clusters in Table 3.8, Table 3.9, and Table 3.10. From the 1,500 items classified in cluster X: *expensive, specific use* items, 56.5% are medical and clinical materials and 43.5% are pharmaceuticals, which corresponds to 73% of the medical and clinical materials and 58% of the pharmaceuticals. From the 586 items classified in cluster V: high *volume, frequent and generalised use* items, 24% are medical and clinical materials and 76% are pharmaceuticals, which corresponds to 12% of the medical and clinical materials and 40% of the pharmaceuticals. Finally, from the 187 items classified in the cluster C: *critical* items, 89% are medical and clinical materials and 11% are pharmaceuticals, which corresponds to 14% of the medical and clinical materials and 2% of the pharmaceuticals.

Table 3.8 Characteristics of cluster X: *expensive, specific use* items

	Max	Higher 10%	Higher 25%	Median	Lower 25%	Lower 10%	Min
Average daily demand (units)	581	5	2	0.4			0.03
Demand frequency (% of days with demand)	55%	39%	23%	10%	3%		3%
Demand dispersion (% of places of delivery)	22%	7%	4%				4%
Criticality (% of demand at critical wards)	40%	0%					0%
Unit cost (euros)	26250	583	102	13	2		0.01
Demand variability (coefficient of variation)	5.57		5.57	3.87	2.35	1.72	0.98

We can see from the characteristics of cluster X that 90% of the items classified on this cluster had a demand average of 5 or less units a day, were consumed in 7% or less of the locations of the hospital system or had a degree of criticality of 0%[28]; half of the items classified on this cluster were consumed in less than 10% of the days or had a unit cost higher than 13 euros. The items on cluster X have relatively low daily demand, low demand frequency, and thus, a high demand variability[29], low demand dispersion, very low criticality, and high unit cost when compared with the items classified in clusters V and C.

Table 3.9 Characteristics of cluster V: *high volume, frequent and generalised use* items

	Max	Higher 10%	Higher 25%	Median	Lower 25%	Lower 10%	Min
Average daily demand (units)	3326	200	61	18	6	3	0.70
Demand frequency (% of days with demand)	100%	100%	100%	90%	71%	61%	45%
Demand dispersion (% of places of delivery)	100%	59%	44%	22%	10%	4%	4%
Criticality (% of demand at critical wards)	96%	48%	27%	9%	0%		0%
Unit cost (euros)	298	9	2	1			0.01
Demand variability (coefficient of variation)	3.70	1.56	1.25	0.96	0.70	0.53	0.33

[28] Note that the items that compose each partition of 90% of the items classified in the cluster in relation to each variable are not necessarily the same (e.g., a specific item belonging to the cluster can have a demand below 5, but have a criticality above 0%).

[29] Although the coefficient of variation of the daily demand was not used to determine the clusters, we used it to characterise the clusters (so that the inverse relation with demand frequency can be observed).

From the characteristics of cluster V, we can see that 90% of the items classified on this cluster were consumed in more than 61% of the days or had a degree of criticality lower than 48%; 75% of the items classified on this cluster had a unit cost lower than 2 euros or were consumed/used in at least 10% of the locations of the hospital system; and half of the items classified on this cluster had a demand average higher than 18 units a day or a demand variability lower than 0.96. When compared with the items classified on clusters X and C, the items on cluster V have relatively high daily demand, very high demand frequency, and thus, low demand variability, high demand dispersion and low unit cost. In terms of criticality, they stand between the items in cluster X, that have very low criticality levels, and those on cluster C, that have very high criticality levels.

Table 3.10 Characteristics of cluster C: *critical* items

	Max	Higher 10%	Higher 25%	Median	Lower 25%	Lower 10%	Min
Average daily demand (units)	168	8	3	1	0.19		0.03
Demand frequency (% of days with demand)	90%	52%	35%	16%	6%	3%	3%
Demand dispersion (% of places of delivery)	37%	19%	11%	7%	4%		4%
Criticality (% of demand at critical wards)	100%		100%	97%	71%	50%	43%
Unit cost (euros)	206	14	6	2			0.01
Demand variability (coefficient of variation)	5.57	5.57	3.96	2.73	1.96	1.37	0.59

From the characteristics of cluster C, it can be observed that 90% of the items classified on this cluster had a degree of criticality of at least 50% or were consumed in only 52% or less of the days; 75% of the items classified on this cluster had a demand average of 6 or less units a day, were consumed in 11% locations of the hospital system or less or had a unit cost of 6 euros or less; finally, half of the items classified on this cluster were consumed only in 16% or less of the days. The most impressive characteristic of the items on cluster C is their high degree of criticality. In terms of demand volume, the average of the items on cluster C cannot be considered significantly different from that of the items on cluster X and, in terms of unit cost, the average of cluster C cannot be considered significantly different from that of cluster V. In terms of demand frequency, and thus, demand variability, and demand dispersion, the items of cluster C stand, in average, between clusters X and V.

As a final remark, it must be noted that it is acceptable that some of the individual variable observations in the tails of the clusters have values that are not in accordance with the general cluster description – first, the items that originated those extreme values can be in accordance with the cluster description in all other variables; second, the objective of our work is not to classify individual items but to generally identify and characterise supply chain segments. If the objective was to classify all the individual items, the final classification had to be screened and assessed by supply chain and professionals of the analysed hospital system.

A few typical examples of the items included on each cluster are:

- X: *expensive, specific use* items: materials for cardiac (e.g., implantable defibrillators, stents and pacemakers), orthopaedic (e.g., prostheses and mechanical devices for spine surgery) or other surgeries (e.g., devices for minimally invasive oncological treatments or bariatric surgery), i.e., materials frequently named as *physicians preference items (PPIs)* (see e.g., Montgomery and Schneller 2007), biological medicines, and medicines for oncological or HIV treatment;
- V: *high volume, frequent and generalised use* items: ordinary use clinical material (e.g., compresses, syringes and gloves) and medicines (e.g., paracetamol, ibuprofen, amoxicillin + clavulanic acid);
- C: *critical* items: clinical materials used to perform emergency interventions (e.g., materials to preform tracheostomies), treat physical injuries (e.g., bandages) or treat patients in critical situations (e.g., oxygen), and medicines used in emergency situations (e.g., for poisoning treatment).

The examples above show that each of the three item clusters can be associated to a different type of service provided by a hospital. In fact, the existence of close relationships between types of services and types of products is logical. Besides the already addressed fact that services' criticality has an impact on the criticality associated to the materials they consume, we can think of many other examples: the demand volume of a service will have an impact on the demand volume of the materials it consumes; if the materials consumed by a service are expensive, that will have an impact on the service cost; if a type of service is frequent, the consumption of related materials will also be frequent, etc.

3.3.5 Cluster classification reliability (accuracy and consistency)

The classification accuracy of the clustering process was evaluated using a simultaneous estimation Discriminant Analysis (DA)[30] (see, e.g., Hair. et al. 2014), resulting in 98.4% of the cases (i.e., items) being correctly classified using the discriminant functions that were determined from the classification of the cases according to *a priori* assignment to a cluster (as a consequence of the clustering process described on previous sections). The detailed classification results are presented in Table 3.11. The results obtained are good when compared to a chance classification taking the size of each cluster into consideration (see Table 3.12).

Table 3.11 Discriminant Analysis classification results

			Forecasted group association (using Discriminant Analysis)			
		Cluster	X	V	C	**Total**
Original cluster assignment (Clustering results)	**# of cases**	X	1491	9	0	1500
		V	7	570	9	586
		C	9	2	176	187
	%	X	99.4	0.6	0.0	100.0
		V	1.2	97.3	1.5	100.0
		C	4.8	1.1	94.1	100.0

Table 3.12 *A priori* probability of chance classification for each group (cluster)

Cluster	***a priori* probability**	**# of cases in the analysis**
X	0.660	1500
V	0.258	586
C	0.082	187
Total	1.000	2273

Since the number of clusters determined exceeds two, we performed post-hoc multiple mean comparison tests using Tamhane's T2 tests because Levene tests showed that we could not assume homogeneity of the variances for all of our segmentation variables. According to the Tamhane's T2 tests, all the within cluster variable averages (including that of the coefficient of variation) are significantly different, at levels of significance lower than 0.00001, except the demand volume average of clusters X: *expensive, specific use* items and C: *critical* items, and the unit cost average of clusters V: *high volume, frequent and generalised use* items and C: *critical* items.

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[30] There has been some evidence that CA is relatively robust to violations of multivariate normality of the independent variables and unknown (but equal) dispersion and covariance structures (matrices) for the groups as defined by the dependent variable, the effect of unequal covariance matrices can be minimised by increasing sample size, and the impact of multicolinearity is higher if stepwise DA is used. (Hair et al., 2014). We do not use stepwise DA and our sample has a satisfactory size.

Figure 3.3 shows a graphical representation of the cluster cases (i.e., items) against the canonical discriminant functions. This representation highlights the fact that the items belonging to the determined clusters are clearly different. This representation can be easier interpreted when confronted with the correlations between discriminant variables and standardised canonical discriminant functions presented in Table 3.13. The discriminant variables with higher absolute correlation with the standardised canonical discriminant functions, i.e., structure correlations higher than 0.4, are demand frequency, criticality and demand dispersion, so these are the most substantive variables to discriminate between the three clusters. These results are consistent with those of the Tamhane's T2 tests according to which the demand volume and unit cost averages of two of the three clusters cannot be assumed to be significantly different.

By observing the diagram, we can see that the centroid of cluster V is relatively distant from the centroids of clusters X and C relatively to Function 1, and the centroid of cluster C is relatively distant from the centroids of clusters X and V relatively to Function 2. Since Function 1 is highly positively correlated with demand frequency and demand dispersion, these variables are the most important to discriminate between cluster V and the other two clusters. Similarly, criticality is the most important variable to distinguish cluster C from the other clusters.

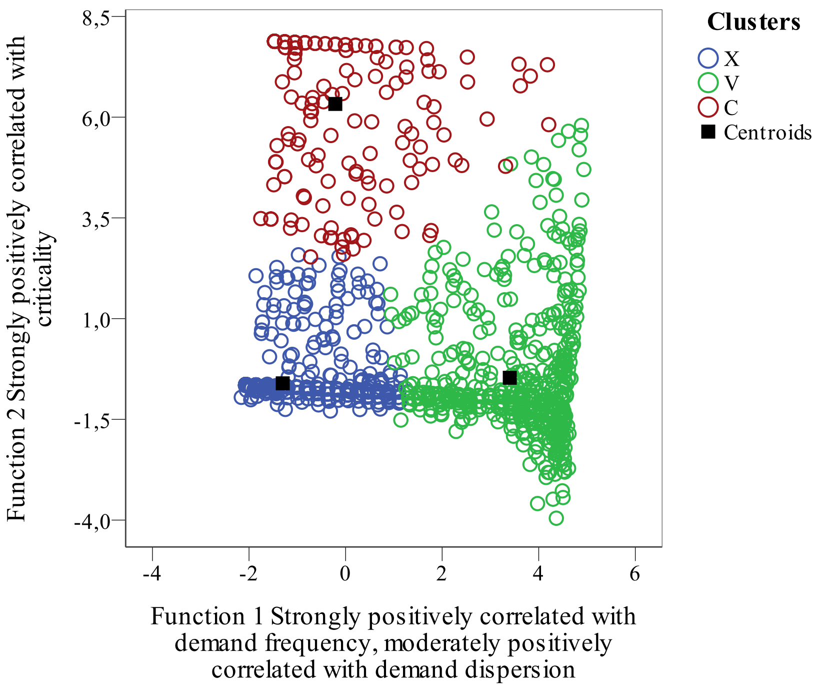

Figure 3.3 Graphical representation of cluster cases against canonical discriminant functions

Table 3.13 Correlations between discriminant variables and standardised canonical discriminant functions

Variables	Measurement	Function 1	Function 2
Demand frequency	Percentage of days with item demand	0.995	-0.070
Demand dispersion	Percentage of hospital locations with item demand	0.443	-0.013
Demand volume	Average daily demand	0.133	-0.020
Unit cost	Unit average cost (= average supplier unit price)	-0.055	-0.029
Criticality	Percentage of total period demand that occurred in the ERs or ICUs	0.232	0.894

To assess the consistency of the clusters, we have also randomly split our sample in two groups, using a Bernoulli process with p=0.5 to assign items to the first sample, having obtained sub-samples of size 1,142 and 1,131, respectively. Then, we repeated the clustering process independently for the two samples (Hambrick 1983, Ketchen and Shook 1996). A comparison of the centroids of the obtained clusters is presented in Table 3.14. The results were very similar between the two sub-samples and also very similar to those obtained with the full sample.

Table 3.14 Centroids of the clusters obtained with the full sample (S) and with the sub-samples (s_1 and s_2)

	Cluster X			Cluster V			Cluster C		
Variables	S	s_1	s_2	S	s_1	s_2	S	s_1	s_2
Demand volume	4.1	5.2	3.0	100.7	116.1	84.8	5.1	3.8	6.3
Demand frequency	14.7%	15.0%	14.3%	84.7%	87.3%	81.8%	23.7%	23.0%	24.3%
Demand dispersion	4.9%	5.0%	4.8%	28.3%	31.7%	24.9%	9.3%	9.7%	8.8%
Criticality	1.4%	1.6%	1.2%	17.2%	19.1%	15.3%	85.2%	83.3%	87.0%
Unit cost	238.4	162.7	316.1	5.7	3.5	7.0	7.8	8.1	7.4
% of items	66.0%	66.2%	65,7%	25.8%	25.7%	25.9%	8.2%	8.1%	8,4%

Additionally, we have split the sample into two different samples: one composed by the 1,116 pharmaceuticals and the other composed by the 1,157 medical and clinical materials, and, once more, repeated the clustering process independently for the two samples. A comparison of the centroids of the obtained clusters is presented in Table 3.15. In the table, we do also compare the proportion of the pharmaceuticals (medical and clinical materials) that was classified in each cluster with that same proportion when the clustering process was performed with the full sample. We can see that the obtained proportions were very similar, and that, if we had made our analysis only with the pharmaceuticals or the medical and clinical materials, we would obtain three clusters with the same characteristics as the ones obtained with the full sample. These results highlight the resemblances between the pharmaceuticals and the medical and clinical materials in a hospital supply chain.

Table 3.15 Centroids of the clusters obtained with the full sample (S) and with the sub-samples of pharmaceuticals (ph) and medical and clinical materials (m)

	Cluster X			Cluster V			Cluster C		
Variables	**S**	**ph**	**m**	**S**	**ph**	**m**	**S**	**ph**	**m**
Demand volume	4.1^{C}	3,4	$5,1^{C}$	100.7	51,7	261,5	5.1^{X}	1,4	$3,7^{X}$
Demand frequency	14.7%	$21,2\%^{C}$	10,4%	84.7%	85,0%	87,6%	23.7%	$25,3\%^{X}$	21,7%
Demand dispersion	4.9%	5,2%	4,6%	28.3%	24,9%	41,7%	9.3%	10,4%	8,5%
Criticality	1.4%	0,8%	0,9%	17.2%	9,9%	45,8%	85.2%	42,9%	88,4%
Unit cost	238.4	59,4	372,5	5.7^{C}	$6,1^{C}$	$2,9^{C}$	7.8^{V}	$6,0^{V}$	$8,4^{V}$
% of items	66%	57%	74%	26%	39%	12%	8%	5%	14%
% in the clusters with the full sample	-	58%	73%	-	40%	12%	-	2%	14%

Tamhane T2 test: C: cluster average is not significantly different from that of cluster C, X: cluster average is not significantly different from that of cluster X, V: cluster average is not significantly different from that of cluster X; all other variable averages are different among clusters at levels of significance lower than 0.0005.

For the pharmaceuticals, the results of the Tamhane T2 test were similar to those obtained for the whole sample: all the within cluster variable averages (including those of the coefficient of variation) are significantly different, at levels of significance lower than 0.0005, except the demand frequency average (and the average of the coefficient of variation) of clusters X: *expensive, specific use* items and C: *critical* items, and the unit cost average of clusters V: *high volume, frequent and generalised use* items and C: *critical* items. The only difference relatively to the results of the whole sample is relative to the differences between clusters V and C in terms of demand volume and frequency (and thus, demand variability).

For the clinical and medical materials, the results of the Tamhane T2 test were identical to those obtained for the whole sample: all the within cluster variable averages (including that of the coefficient of variation) are significantly different, at levels of significance lower than 0.00001, except the demand volume average of clusters X: *expensive, specific use* items and C: *critical* items, and the unit cost average of clusters V: *high volume, frequent and generalised use* items and C: *critical* items.

3.3.6 Classification scheme discussion

Comparison of emergent clusters with a theory-based typology can provide evidence regarding the typology's [and the clusters] descriptive validity (Ketchen and Shook 1996), since direct comparisons of alternative means of defining configurations will contribute to the development of valid and precise frameworks for describing organisations (Ketchen et al. 1993).

The main difficulty that we have faced when comparing the determined classification scheme with those proposed in the literature was the fact that none of the previous studies assuming a segmenting perspective of the materials flowing in a hospital supply chain used a multivariate method[31]. As a consequence, frequently we do not have a full view of the characteristics of the items in each segment, and sometimes the suggested categories are not mutually exclusive – for example, one item may, at the same time, belong to the *high demand and high dispersion*, the *high demand and high frequency* and the *high demand and low cost* segments proposed by Cheng and Whittemore (2008). We can, however, confirm that the authors have already empirically observed the link between *high demand* and the other three mentioned variables, in a hospital geographically distant from the one we analysed.

We can also establish a clear link between cluster C: *critical items* and the fact that critical and/or urgent items have been considered on autonomous segments by researchers that have segmented the hospital supply chain (i.e., DeScioli 2005, Cheng and Whittemore 2008). It is also relevant that the authors have proposed this segment as a consequence of empirical research in real hospital settings.

The segmentation of the items supply chain has also been strongly determined by the unit cost, having a high unit cost been associated with a low demand volume and vice-versa (e.g., Cheng and Whittemore 2008). Furthermore, several studies have focused specifically on the specificities of medical materials with the characteristics of cluster *X: expensive, specific use* items, the Physician Preference Items (PPIs), (see e.g., Montgomery and Schneller 2007, Wilson et al. 2008, Ketcham and Furukawa 2008). All these studies involved empirical research. Montgomery and Schneller (2007) describe some specificities of managing the supply of these items relatively to other items flowing in a hospital supply chain.

We have also confirmed that many of the hospital materials supply chain segments recommended by previous researchers combine two of the characteristics of the determined

[31] The classification method proposed by Danas et al.(2006) is multi-attribute, but the authors do not present an application of the method to a real situation, and, consequently, it is difficult to understand what type of segments would result from its application.

clusters (see Table 3.16, Table 3.17, Table 3.18 in the next section relatively to cluster X, cluster V and cluster C, respectively).

Although our classification scheme was grounded on previous research and on qualitative information obtained from two hospital systems, the obtained results are in accordance with our expectations and existent research, and it showed internal reliability (i.e., accuracy and consistency) in the various post-hoc analysis we performed, it would be interesting to see it being further validated, for example, through replication in other hospitals.

Although many of the associations between some of the characteristics of determined clusters have already been mentioned in the literature, and hospital supply chain managers may be aware of them, the lack of structured and explicit knowledge about the multivariate relations between the various variables considered relevant to segment the items in a hospital supply chain may originate segmentations schemes that are complicated (e.g., Danas et al. (2006), since it is difficult to understand how the tree-based classification will be applied in practise relatively to some variables and what kind of segments will result from it) and/or potentially non-mutually exclusive (e.g., Cheng and Whittemore 2008) and/or non-comprehensive (e.g., DeScioli (2005), since, for example, segments for small items with high unit cost or vice-versa are not addressed). Besides contributing to the understanding of those relations and organising the items that flow through the hospital supply chain in a manageable way, the performed work highlights supply chain management related similarities between pharmaceuticals and medical and clinical materials.

3.4 Operational supply chain strategies recommended for the determined hospital supply chain segments

After determining the hospital materials supply chain segments, we aimed at linking them to specific operational strategies. In order to do so, we identified the operational capabilities, and the corresponding operational processes and resources, recommended on the literature and by the supply chain managers interviewed for materials' segments with some of the characteristics the determined segment. The result of this cross-reference effort is presented in Table 3.16, for *expensive, specific use* items, in Table 3.17, for *high volume, frequent and generalised use* items, and in Table 3.18, for *critical* items. Some conclusions can be drawn from the analysis of the information in the tables, as expounded bellow and summarised in Table 3.19.

Table 3.16 Operational capabilities proposed in the literature and by interview respondents for typical hospital supply segments with the same characteristics as cluster X: *expensive, specific use* items

Type of segment	Capabilities	Processes and/or resources	Authors or Respondents
high unit cost + low demand	minimised lead time flexibility agility	• make-to-order or assemble (pack) to order • centralised inventory (to lower inventory level) • faster transportation • visibility of the entire supply chain	Cheng and Whittemore (2008)
high unit cost + high variety (e.g., stents)	cost containment/ optimised resource utilisation	• consignment, demand information sharing with the supplier and VMI combined with two alternative suppliers • registration of consumption to the patient	SCM, HS2
high unit cost (e.g. medicines provided to patients by ambulatory care)	cost containment/ optimised resource utilisation	• demand information sharing with the supplier; VMI • RFID	SCD, HS1
	tight control/ high security	• demand information sharing with the supplier; VMI • RFID • registration of consumption to the patient • closed door storage	DeScioli (2005) SCM, HS2; SCD, HS1
	minimised inventory value	• frequent review period	DeScioli (2005)
	minimised storage space	• frequent review period	DeScioli (2005)
specific materials provided to innovative services (e.g., cardiovascular surgery)	flexibility	• close communication with the Service professionals (e.g., to forecast demands: the materials used change constantly and there is no historical data)	SCD, HS1
medical devices specific to a surgery consumed at the ORs (e.g., orthopaedics' materials)	reliable lead time	• cross-docking (the materials are not stocked at the hospital) • fast delivery to the OR (after the material is at the hospital)	SCM, HS2

Operational strategies for *expensive, specific use* items (Table 3.16)

For materials with characteristics common with those of cluster X: *expensive, specific use* items (i.e., high unit cost, low demand dispersion, low demand volume, low demand frequency, high relative demand variability, and low criticality), the recommended operational capabilities have been *cost containment* or *optimised resource utilisation*, namely through minimised inventory value and storage space, *tight control* and *security*, *flexibility* and *agility*, and *reliable lead time*.

For achieving cost containment, the sharing of information with the suppliers and VMI schemes, including materials consignment, and more frequent inventory review periods were recommended. For assuring tight control and security, the processes that have been proposed are the registration of consumptions to the patient, and the use of closed door storage (e.g., automated dispensing cabinets) and of RFID. Relatively to flexibility and agility, it has been suggested that it is attained through inventory centralisation.

Inventory centralisation in the internal hospital supply chain would not be effective for the materials in the determined segment, because they are mainly consumed in a limited number of wards (frequently just one). On the other hand, when the services that consume these materials or the materials themselves are innovative (as in the case of the cardiovascular surgery service in one of the analysed hospital systems, or of the high unit cost medicines provided to patients at ambulatory care), fast/effective delivery of unusual items to the wards may be required, and changes in the hospitals' formulary[32] are accelerated. In these situations, flexibility obtained through close communication with the related health services professionals is important, since the absence of historical data makes demand forecasts difficult without their collaboration, and any non-anticipated prescription change can result in the accumulation of significant obsolete inventory. In the case of the materials specific for planned surgeries, for attaining a reliable lead time, i.e., assuring that the material is where it is needed at the moment of the surgery, one of the analysed hospital systems uses cross-docking (the materials are not stocked at the hospital) and fast internal distribution to the OR after the material is at the hospital.

[32] The list of the medicines and medical devices that can be prescribed at the hospital.

Table 3.17 Operational capabilities proposed by previous literature and interview respondents for typical hospital supply segments with the same characteristics as cluster V: *high volume, frequent and generalised* use

Type of segment	Capabilities	Processes and/or resources	Authors or Respondents
high demand volume + high demand dispersion	low cost/ cost efficiency; minimised inventory value; high availability/ service level	• virtually centralised inventory • information sharing throughout the hospital: consumption, inventory levels, demand forecasts, order status, production schedules, etc.	Cheng and Whittemore (2008)
high demand volume + high demand frequency	reduced supply chain costs	• horizontal cooperation: shared distribution networks and warehouses among neighbour hospitals	Cheng and Whittemore (2008)
low unit cost + high demand volume	low cost/ cost efficiency	• lean supply chain • if demand is expectedly stable, periodic replenishment with decentralised inventory location	Cheng and Whittemore (2008)
less important	low cost/ cost efficiency	• stock only in each clinic that uses them; the clinic is responsible for stock management	Danas et al. (2006)
not important	low cost/ cost efficiency	• JIT supply in each clinic that requires them; no safety stock	Danas et al. (2006)
high volume demand + low unit cost (medicine inpatient care)	minimised material handling time by health professionals	• kanban two bin system	SCM, HS2
low unit cost	minimised material handling time by health professionals	• open shelf storage	DeScioli (2005)

Operational strategies for *high volume, frequent and generalised use* items (Table 3.17)

For materials with characteristics common with those of cluster V: *high volume, frequent and generalised use* items (i.e., high demand volume, high demand frequency, high demand dispersion. low relative demand variability, low unit cost), the recommended operational capabilities have been *low cost* or *cost efficiency*, namely through minimised inventory level or reduced supply chain costs, *high availability* or *service level* and *minimised material handling time by health professionals*. The types of materials included in this segment were those that received less attention from the interview respondents relatively to the supply chain practices used to manage them.

The operational processes that have been recommended for attaining low cost or cost efficiency, namely through minimised inventory value or reduced supply chain costs, have been: virtually centralised inventory information sharing throughout the hospital (e.g., concerning consumption, inventory levels, demand forecasts, order status, and production schedules); horizontal cooperation, namely shared distribution networks and warehouses among neighbour hospitals; a lean supply chain; and, if demand is expectedly stable, periodic replenishment with decentralised inventory location. The virtual centralisation of inventory information and its sharing through the hospital has also been considered a mean of assuring a high service level for these materials. Finally, a kanban two bin replenishing system, and the use of open shelf storage were recommended to minimise the time dedicated by health professionals to material handling tasks.

Table 3.18 Operational capabilities proposed by previous literature and interview respondents for typical hospital supply segments with the same characteristics as segment C: *critical* items

Type of segment	Capabilities	Processes and/or resources	Authors or Respondents
critical	high availability/ service level	• higher inventory levels • more frequent (daily) replenishment • storage of specific materials only in the services • inventory virtual pooling and visibility involving ERs, EORs and ICUs	DeScioli (2005), Danas et al. (2006), Gupta et al. (2007), Cheng and Whittemore (2008) SCM, HS2; SCD, HS1
	responsiveness	• daily replenishment • inventory virtual pooling and visibility involving ERs, EORs and ICUs	SCM, HS2
	flexibility	• placement of safety stocks in centralised locations downstream the supply chain (e.g., physical or virtual centralisation among several neighbour hospitals)	Danas et al. (2006)
	minimised material handling time by health professionals	• kanban two bin system (avoiding inventory records updating)	SCM, HS2
	minimised storage space	• frequent reviews	DeScioli (2005)

Operational strategies for *critical* items (Table 3.18)

For materials with characteristics common with those of cluster C: *critical* items (i.e., high criticality, low demand volume, high relative demand variability, low unit cost), the recommended operational capabilities have been *high availability* or *high service level*, *responsiveness*, *flexibility*, *minimised material handling time by health professionals* and *minimised storage space*.

Higher inventory levels, more frequent (daily) replenishment, storage of specific[33] materials only in the critical services (i.e., ERs, EORs and ICUs), and inventory virtual pooling and visibility involving these services have been proposed to accomplish high materials availability. For achieving responsiveness, daily replenishment, inventory virtual pooling, and visibility involving ERs, EORs and ICUs were proposed. Placement of safety stocks in centralised locations downstream the supply chain (e.g., physical or virtual centralisation among several neighbour hospitals) has been proposed to obtain flexibility. To minimise the time dedicated to material handling tasks by health professionals by avoiding that they have to update inventory records while providing critical care, a kanban two bin system was recommended. In the case of the inventories located at the critical services, the minimisation of

[33] That is, items that are only consumed in the services that are being considered.

storage space may be important, and to progress to that goal the use of small review periods (i.e., frequent inventory reviews) was suggested.

Finally, it is also important to emphasise that neither the four research works analysed in the previous chapter nor the interviewed supply chain managers referred any operational capability related to quality or reliability as a supply chain requirement of a specific, identifiable supply chain segment. However, the supply chain managers interviewed made some related comments transversal to all the three segments. For example, the director of the pharmacy of one of the analysed hospital systems said that *safety* – namely, assuring that medicines are administered to patients exactly how prescribed – was the main focus of his job (PHD, HS2). Bhakoo and Choi (2013) have identified safety as an endogenous pressure to implement inter-organisational systems (IOS) in the materials supply chain in all the five hospitals they analysed.

The logistics director of the other analysed hospital system noted that sometimes the capabilities required by the different hospital stakeholders may differ: while the purchasing department may value the unit cost, for the logistics department the fact that a material has a bar code or that the supplier is willing to take it back, if it is not consumed, are also important, and the physicians value what is important for the patients, but also what is important for them, for example, the materials they are used to or that have technical assistance by the supplier (SCD, HS1). De Vries (2011) has analysed these issues, even though not considering differences by supply chain segment, and refers “high quality medicines” as one of the supply chain interests of hospital medical specialists.

Since our analysis was supported by the perspectives of supply chain managers, in general, the focus they expressed in terms of supply chain capabilities is centred on efficiency and issues related to materials flows and stocks. It would be interesting if, in the future, the supply chain capabilities considered important by different stakeholders, including health professionals, for the determined materials segments could be investigated.

Table 3.19 Summary of the operational strategies that have been suggested for the identified hospital supply chain segments

Supply chain segment	Characteristics	Needed operational capabilities	Recommended operational strategies
X: ***expensive, specific use***	• high unit cost • low demand dispersion • low demand volume • low demand frequency • high relative demand variability • low criticality	• cost containment • high security • flexibility (fast delivery of unusual items and/or incorporation of innovative items in the formularies) • safety • quality*	• agile/ responsive supply chain (through enhanced cooperation with the various SC stakeholders) • centralised inventory holding (when the item is consumed only at one ward, the inventory holding point should be located at that ward)
V: ***high volume, frequent and generalised use***	• high demand volume • high demand frequency • high demand dispersion • low relative demand variability • low unit cost	• low cost/ cost efficiency • high availability • minimised material handling time by health professionals • safety • quality*	• lean supply chain • information sharing throughout the hospital • virtual inventory centralisation • horizontal cooperation • decentralise inventory (if demand is stable) • kanban two bin system • open shelf storage
C: ***critical***	• high criticality • low demand volume • high relative demand variability • low unit cost	• high availability • responsiveness • flexibility • minimised material handling time by health professionals • safety • quality*	• higher inventory levels • frequent replenishment • storage of specific materials only in the services • inventory virtual pooling and visibility involving ERs, EORs and ICUs • placement of safety stocks in centralised locations downstream the supply chain • kanban two bin system

* While we assume that *quality* is a required hospital supply chain capability for the three segments, the specific dimensions of quality for each of the segments need to be further investigated.

3.5 Conclusions

In this chapter, we have proposed a service related proxy for item *criticality* in a hospital supply chain context. The method developed for this purpose has three main advantages: 1) it is in accordance with the link usually established between the criticality of a material and the criticality of the service that will consume it; 2) it is easy to implement since it does not require any *a priori* material classification by health professionals; and 3) the criticality levels determined using the proposed measure can be easily adjusted to reflect managers or health professionals views on individual materials criticality, when necessary.

We have then considered a group of variables expected to influence the operational capabilities required by the materials and, using Cluster Analysis, segmented the materials that flow in a hospital system supply chain. This segmentation resulted in the identification of three supply chain segments: X – *expensive, specific use* items; V - *high volume, frequent and generalised use* items; and C - *critical items.*

Finally, we resorted to previous literature to identify operational strategies proposed for hospital materials supply chain segments with characteristics similar to those of the determined segments, and we have complemented this effort with the suggestions obtained from the hospital supply chain managers interviewed.

Our segmentation has been empirically developed using multivariate data analysis, and it has the following advantages over previous taxonomies or typologies for hospital supply chain materials:

a) the determined segments are mutually exclusive and comprehensive, and they consider all items flowing in a hospital supply chain;
b) the relations between several item associated variables relevant for operational supply chain strategy are highlighted;
c) it has been compared with previously proposed hospital supply chain item segmentations, and it incorporates knowledge both from the literature and from the hospital supply chain managers.

We have not linked our classification scheme to any supply chain outcome measure as it is usual in configurational research, but, as stated by Ketchen et al. (1993), parsimonious, theory-based configurations should be developed before making attempts to relate configurations to outcome variables such as performance.

The developed classification scheme may be useful to managers because it presents a way of reducing the large diversity of materials flowing in the hospital supply chain into a practical small number of segments, and systematises some operational supply chain strategies applicable to each segment. Furthermore, it proposes a simple and easy to use measure of item criticality in hospital contexts that, after being adjusted by hospital supply chain managers possibly with the help of health professionals, may be a useful quantitative measure for managerial purposes. We do not intend to offer a closed supply chain segmentation solution, but our work can be a useful starting point to think about how to develop a hospital supply chain segmentation strategy.

Supply chain management of pharmaceuticals and medical and clinical devices have been frequently separated in the hospitals, where traditionally much of the logistic process is assured at the Pharmacy, while medical and clinical materials are dealt with by Materials Management Departments. This separation can also be noticed in the literature (the works by DeScioli (2005) and Cheng and Whittemore (2008) were exceptions). Maybe some of the difficulties faced when trying to transpose management practices that have been successful in the supply chain management of pharmaceuticals to that of medical devices (described by, e.g., Montgomery and Schneller (2007), Burns and Lee (2008) or Sorenson et al. (2011)) arise because the correspondence between the two types of materials is not correctly made, that is, when searching supply chain management similarities or synergies, the right comparison is, for example, between *expensive, specific* medical devices and *expensive, specific* pharmaceuticals. The developed segmentation scheme highlights some similarities between pharmaceuticals and medical and clinical devices, and this feature may contribute to enhance management practices and research, aiming at handling these two types of materials in a common way, or through similar processes.

Additionally, our work can be a first step in the application of empirical taxonomies in the health care supply chain context. We believe it would be quite interesting to replicate and assess the developed segmentation in other hospitals. Furthermore, further research aiming at determining the most appropriate supply chain strategy for each segment and comparing the performance of different operational strategies for different materials segments might also be very useful.

4 A System Dynamics based simulation of alternative supply chain strategies for hospital high volume, frequent and generalised use items

4.1 Introduction

As determined in the previous chapter, *high volume, frequent and generalised use* items have relatively high demand volume, high demand frequency, high demand dispersion (in terms of the locations where demand occurs), low relative demand variability and low unit cost. These materials are used daily and throughout the entire hospital, including at critical wards like the ERs, the EORs and the ICUs.

The internal hospital supply chain for this type of materials is similar to the supply chain of a distributor that supplies a group of retail shops, or all other systems where there is a central warehouse serving a set of satellite storage locations, in an *arborescent* or *divergent* network design (also called a *distribution inventory system*), since these materials are distributed to the wards from a Distribution Centre (DC), and the wards where the materials are consumed, and near which they are stored before that, frequently function with a relative high autonomy from the hospital central management.

In a hospital context there are, however, some particularities relatively to a pure arborescent supply chain[34]. In a hospital setting, a high service level at the wards is desirable, since stock-out situations interfere with health professional work causing distractions and time delays even when the item being demanded is not critical or can be substituted. These issues are particularly relevant at critical services. In practical situations, when there are not enough available item units at the DC to fulfil the requests of all the hospital wards, the critical wards may have priority in the distribution of the available units. Additionally, frequently there are direct emergency deliveries from the DC or from other wards in case of a stock-out at a ward, as described by a supply chain manager working at one of the analysed hospital systems (SCM, HS2):

> *[…] diapers, it must be seen that they are used and stored everywhere in a hospital. Therefore, the wards should have a culture that favours the exchange of inventory among the wards, instead of recurring to the central distribution centre. What is classic is not to look to the side, and to immediately look down[35], to the central distribution departments. And what is true is that there is inventory nearby, right at their side.*

[34] In a pure arborescent system, each stock has only one immediate predecessor.
[35] The central warehouse is located in the basement of the hospital.

Under these circumstances, the DC has a *dual-role* (Cattani et al. 2011) since it serves the wards and it may also serve some final demand directly.

As described on the previous chapter (see section 3.4), the operational capabilities that have been recommended for materials with these characteristics have been *low cost* or *cost efficiency*, namely through minimised inventory or supply chain costs, *high availability* or *service level* and *minimised material handling time by health professionals*, that, according to previous research, are attainable through a *lean supply chain*, *information sharing throughout the hospital*, *virtual inventory centralisation*, *horizontal cooperation* or *decentralised inventory* (if demand is stable) (Cheng and Whittemore 2008), a *kanban two bin system* (SCM, HS2), or *open shelf storage* (DeScioli 2005). The alternative supply chain operational processes analysed in this chapter are decentralised inventory control with no information sharing versus centralised inventory control and some information, and horizontal cooperation between wards through lateral transshipments (specifically, from the other wards to the ER)[36].

In order to analyse the impact of these supply chain operational processes, as well as the impact of decision rules aiming at improving the service level in (critical) wards, we develop and apply in this chapter a set of System Dynamics (SD) models, parameterised with data from our case studies. When compared to previous supply chain SD models, our models have the advantage of being hospital supply chain specific; when compared to previous optimisation approaches, they have the advantage of being easier to understand and taking into account the analysis and interactions of features that usually are addressed separately.

Consequently, we developed models with some features aimed at improving the service level at the wards and specifically at critical wards. Thus, the analysed decision rules include the possibility of emergency deliveries from the DC in case of a stock-out at a ward, giving (or not) priority to the emergency room (ER) in the allocation of inventory when the inventory available at the DC is insufficient to meet all requests and/or the existence of lateral transshipments – i.e., stock movements between locations of the same echelon (Paterson et al. 2011) - from the other wards to the ER. Furthermore, we analyse the effects of some usual behavioural based hospital management practices, namely the "just-in-case" approach to inventory control (see e.g., Ritchie et al. 2000, Burns et al. 2002: 13, Tucker et al. 2013).

Our analysis seeks to yield simple rules for inventory management. We assume a context, inspired in the hospital supply chain current situation in many countries, where hospital supply chains are fragmented (i.e., integration is relatively low), managed based on traditional practices and there are no sophisticated ICT systems to optimise the hospital supply chain globally or such systems are not used in practice. Nevertheless, we assume that the inventory records are

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[36] In the next chapter, we address the topic of horizontal cooperation between neighbour hospital systems.

updated regularly and relatively accurate, mainly at the DC level, and that item consumptions may be registered near to the patient (at least at the ward level). In such a context, the existence of simple inventory management rules that can be used by managers on a daily basis and have been derived from the knowledge of the consequences of alternative processes on systems' performance is useful. As acknowledged by Axsäter (2006: 281), […] *it may be difficult to replace an existing simple control system with a relatively advanced multi-echelon technique* […] and […] *the required computational effort will also grow considerably*. Furthermore, […] *in most realistic stock management situations the complexity of the feedbacks among the variables precludes the determination of the optimal strategy.* (Sterman 1989: 324)

The use of System Dynamics allows us to cope with a number of difficult challenges in the structure and behaviour of these systems. When the focal phenomena involve multiple and interacting processes, time delays, or other non-linear effects, such as feedback loops and thresholds, simulation is likely to reveal non-intuitive elaborations of simple theory that are difficult to uncover using other methods (Davis et al. 2007). Since supply chains *involve multiple chains of stocks and flows, with the resulting time delays*, and *the decision rules governing the flows create important feedbacks among supply chain partners, System Dynamics is well suited for supply chain modelling and policy design* (Sterman 2004: 664). Tako and Robinson (2012) state in their recent review of research applying Discrete Event Simulation and System Dynamics in the logistics and supply chain context that it has been generally accepted that System Dynamics is suited for high level strategic modelling because, as originally enunciated by Rabelo et al. (2005), it: a) takes a holistic approach of systems, integrating many subsystems; b) focuses on policies and system structure instead of focusing on individual decisions and entities; c) uses feedback loops to represent the effects of policy decisions; d) represents a dynamic view of the cause-effect relationships among the system elements; and e) requires minimal data to build and run a model.

The developed set of models aims at serving as a "management simulator" to test possible alternative management processes, and at unveiling some management heuristics (technological rules) (van Aken 2004) that can be useful for hospital decision makers. Since the developed models are simple to understand, they can be used to involve managers in the simulation so that they understand better the full impact of the interactions of the various models components and the effects of the multiple involved system feedback loops.

The main advantage of our approach is that the analysis is applied to the hospital context in a combined, transparent and simple way - that is, the impact of a change in a part of the model (e.g., in a decision rule or a parameter level) on the whole system or on its parts can be analysed effortlessly. Moreover, we raise some management insights, sometimes contradicting usual hospital supply chain practices that can be easily understood by hospital managers.

This chapter is organised as follows. In the next section, we present a review of relevant literature, focusing mainly on the various features of the developed simulation models. Then, we describe the develop models in order to assure that they can be replicated (following the recommendations of Rahmandad and Sterman 2012). Afterwards, we describe the results of the simulations performed with the models of serial supply chains with one DC and one ward (section 4.5) and quasi-arborescent models with one DC and three wards (section 4.6), and summarise and discuss the most relevant of these results (section 4.7). Finally, we draw some final conclusions, describe several managerial implications of the obtained results and suggest some paths for future research.

4.2 Literature review

The management of multi-echelon inventory has been object of research since the ground-breaking paper by Clark and Scarf (1960). The related literature from 1996 to 2005 has been reviewed by Gümüs and Güneri (2007). This review effort was proceeded by Cattani et al. (2011) who concluded that traditional multi-echelon inventory research has considered standard arborescent structures consisting of multi-tier systems - for example, a single central warehouse (the DC) that supplies a set of second-tier warehouses that serve directly a set of uniquely defined regional customers, having neglected distribution supply chains with other structures. The authors have also concluded that a significant part of the related literature can be characterised as highly theoretical and too abstract to be of use in a real-world setting (Cattani et al. 2011). In health care, this gap between the availability of sophisticated but complex models in the literature and the simple inventory management rules used and desired by the professionals at exemplary (i.e., best in class) services was recently described by Stanger et al. (2012) in the context of blood inventory management in the UK. Dellaert and van de Poel (1996) had already emphasised that the existence of simple inventory rules is more important in a hospital setting than in a typical company.

In an arborescent supply chain, the DC supports the second-tier warehouses (i.e., the retailers or, in our models, the wards), therefore higher inventory levels at the warehouse will mean shorter and less variable lead-times for the second-tier retailers, enabling them to reduce their stocks (Axsäter 2006). Nevertheless, although the best distribution of the total system stock depends on the structure of the system, the demand variations, the lead-times and the involved costs, in most common situations the optimal solution results in a much lower inventory level at the DC than what most practitioners would expect (Axsäter 2006). Following the scheme of Clark and Scarf (1960), Eppen and Schrage (1981) considered a fixed-length order cycle for all warehouses, including the DC, and normally distributed demand. By assuming that the DC can make negative inventory allocations to second-tier warehouses, so that the total stock at these warehouses can be optimally distributed, i.e., *balanced*, in any period (even if there is not enough inventory at the DC to do so), the authors found that the best solution would be to push all available inventory from the DC to the second-tier warehouses during each order cycle. The same balancing approximation has been used by numerous subsequent researchers with the consequence that, if the inventory holding cost is the same at all the warehouses, there is no reason to keep inventory at the DC. Using the same model characteristics as Eppen and Schrage (1981), but a different allocation procedure, Jackson (1988) has also concluded that the best solution would be not to hold inventory at the DC. Graves (1996) studied an arborescent system with fixed replenishment intervals and Poisson demand arrival, using order-up-to and virtual allocation logic and concluded that both central and second-tier warehouses should hold safety stock, but most of it should be placed at the second-tier warehouses. Under these conditions, the probability that there are stock-outs at the DC may be high, but this will not necessarily have an impact on the service level to the final customer.

The balancing assumption is not appropriate if the demands and/or the required service levels at the second-tier warehouses are very different (Axsäter 2006). This is the case in a hospital: in terms of service level, there are wards where the requirements of a high service level are particularly important; in terms of the items demand, there are also important differences between the wards (as observed in the analysed item: see the differences between the collected samples at three wards in Figure 4.4). If the DC has dual-role (i.e., it does also satisfy some final demand directly), even if this is done as a backup, it necessarily needs to hold some inventory. Moreover, since the variability of the demand at the ward level of the items flowing in the hospital supply chain is frequently high (e.g., for the analysed item, the coefficient of variation of the daily demand at the considered wards ranged from 0.93 to 1.16), the DC may have an important risk pooling function.

In the following paragraphs, we address research related with the specific features of the developed models, namely, those related to the characteristics of a hospital supply chain (listed on the previous section).

<u>Inventory allocation</u>

In arborescent supply chains, inventory allocation rules are necessary to distribute the available inventory among the second-tier warehouses in case of insufficient inventory at the DC. While simple rules, such as regional priorities, requests or most needed, may be applied to deal with this problem (Cattani et al. 2011), several researchers have addressed the topic in search of fair allocation (rationing) rules: for example, the Fair Share (FS) rule (Clark and Scarf

1960, Eppen and Schrage 1981), the Consistent Appropriate Share (CAS) rule (de Kok 1990), the Balanced Stock (BS) rule (van der Heijden et al. 1997), or the Linear Rationing (LR) class[37] of allocation rules (van der Heijden et al. 1997, Lagodimos and Koukoumialos 2008). These works analyse supply systems under various assumptions, but their underlying general principle is the balancing of the stock-out probabilities at the second-tier warehouses. We have not modelled any rule trying to achieve this result, because it is difficult to operationalise a simple rule to be applied at a hospital rapidly and on a daily basis, when the demands of the wards are different.

Some researchers have also considered or analysed rules that involve giving priority to orders from some group of clients. Our study has some relation to those that define the groups of clients according to their sensitivity to time. The importance of time at some wards, such as an emergency room, is also the reason why we consider giving different priorities to the wards in inventory allocation. Most related research (e.g., Cattani and Souza 2002, Wang et al. 2014) has linked the time sensitivity with different prices or margins (i.e., there is some willingness of the clients that want shorter lead times to pay for that possibility). Since, the underlying assumptions of the models are very different from ours (e.g., Poisson demands are considered, there is a trade-off between price and lead-time and/or production decisions are included in the analysis), and because most of the studies prior to Wang et al. (2014) determined a threshold representing the maximum number of orders to be reserved for each customer class, which we consider a procedure too static and stakeholder sensitive to be implemented on a hospital supply chain, we did not incorporate significant insights from this stream of research on our research.

In our models, when we do not give priority to the emergency room, we use an allocation rule similar to the *proportional allocation rule* defined in Geng et al. (2010)[38].

Emergency deliveries and lateral transshipments

In real hospital settings, emergency deliveries from the DC to the wards or lateral transshipments between wards or even neighbour hospitals are not only possible but frequent. For example, Guerrero et al. (2013) describe a real hospital supply chain where emergency deliveries from the DC with negligible lead-time and lateral transshipments complementary to the emergency deliveries and undesirable (because they disturb the supply chain network due to unregistered movements of materials) are described. In the hospital supply chains analysed, both situations were also referred, although some difficulties in the wards willingness to use

[37] The FS and CAS rationing rules belong to the LR class (Lagodimos and Koukoumialos, 2008).
[38] The differences are the facts that we consider backorders in our calculations and that we do not distribute units remaining at the DC due to integer rounding.

lateral transshipments were noted. Nevertheless, the lateral transshipments were viewed as a practice worth exploring.

Paterson et al. (2011) have recently reviewed the extent literature related to lateral transshipments and concluded that, regardless of the diversity of possible schemes, lateral transshipments are an important tool to be used in a supply chain as they help to reduce costs or increase service levels.

Several types of lateral transshipments have been addressed in previous literature (a few examples in each category have been reviewed by Paterson et al. 2011):

- reactive, i.e., happening at any time in response to a stock-out (normally, it is considered that the customer is willing to wait for the arrival of the item), or proactive, i.e., occurring at fixed points in time and consisting of planned redistributions of stock over the various warehouses,
- bilateral or unilateral,
- involving complete or partial inventory pooling, when, respectively, all or only part of the stock available at the dispatching location can be transshipped.

In this work, we consider reactive, unilateral transshipments involving complete pooling. Lateral transshipments are still not an established practice in the analysed hospital systems; therefore it would be difficult that proactive lateral transshipments would be well accepted and implemented. Unilateral transshipments are reasonable when the stock-out costs at the various retailers are significantly different (Axsäter 2003, Olsson 2010), which is the case at a hospital since a higher degree of seriousness is associated to stock-outs at critical services. We consider complete inventory pooling, because the item that is being analysed is not critical and can be substituted (although this involves a time and cost loss), the lead time from the DC is relatively small, and a higher importance is associated to a stock-out event at the ER in the present day than to a possible stock-out at an ordinary ward in the following days.

Some researchers (e.g., Liao et al. 2014, Alvarez et al. 2014) analyse the emergency deliveries from the DC and lateral transshipments as alternative and/or complementary policies. In this type of analysis, the relation between the lead times of the lateral transshipments and of an emergency from the DC is considered and shipment costs of the deliveries between second-tier warehouses and from the DC to these locations play an important role in the analysis. Liao et al. (2014) consider that the lateral transshipments have shorter lead times that the emergency deliveries from the DC, and that there are a regular order cost, an emergency order cost and a transshipment cost that is lower than the emergency cost; under these assumptions, the emergency deliveries will only be interesting if there is aggregation of requests. Alvarez et al. propose that lateral transshipments and emergency deliveries are used only for premium customers; if there is available stock, lateral transshipments will be given preference since they are considered faster and cheaper; the unmet orders of non-premium customers will result in backorders.

To choose the warehouse from which the lateral transshipment is dispatched, the most used rule has been to select the closest warehouse with stock on hand (i.e., dispatching the required quantities from the warehouse nearest to that needing the transshipment), based on argument that the transportation costs between the origin and the destination depend on the distance travelled (Yang et al. 2014). However, as stated by the authors, this rule has the disadvantage of failing to incorporate the fact that the transshipment will reduce the source ability to meet its own future demand.

In our analysis, we assume that the DC and the wards are located in the same building, so there are no reasons to admit that there will be differences in the lead times or costs of the deliveries from these locations. The impact of the choice on the supply chain system will be related with the demands that are served from the location that provides the necessary units: an emergency delivery from the DC will lower its inventory level and may affect the fulfilment of pending orders of the various wards; a delivery from another ward will lower the inventory level at that ward, and may affect the subsequent fulfilment of demand at that ward. To choose the ward from which the transshipment is provided, we use an indicator of the probability that the chosen ward will be able to fulfil the demand it faces (the adopted procedure is described in detail in subsection 4.3.6).

Inventory control and visibility (centralised versus decentralised)

When we identify one of the modelled systems as *centralised*, we refer to centralised inventory control of the supply chain and not to a centralisation (pooling) of inventory locations.

In the supply chain of a hospital system, the central (the DC) and the second tier warehouses (at the wards) have the same owner, therefore the coordination of the inventory control should be easier than when the supply chain is composed by independent companies. The possibility of centralising inventory control in a supply chain is closely linked to the type of information that is shared in that supply chain. The impact of various information sharing strategies on the supply chain is addressed below, where experimental research aimed at studying the importance of behavioural issues for supply chain management is discussed.

Geng et al. (2010) analysed six operating alternatives – five considering decentralised inventory control and one considering centralised control – for an arborescent system, and tested them considering two different allocation rules and Poisson or Normal demands. They concluded that centralised control is the one that performs the best for all the considered scenarios, under the assumptions of the analysis, namely in terms of system's costs. The authors warn that high information sharing may not perform well when retailers are competing with each other, since the rationing game among selfish retailers yields significant information distortion, by which more leftover goods at retailers and higher shortage at the distributor occur. Duan and Liao (2013) determined optimal replenishment policies of capacitated supply chains operating under two decentralised versus centralised control strategies and various alternative demands, and concluded that, given the assumptions of the developed models, overall it is beneficial to adopt centralised control strategies.

Several researchers have shown through the conduction of experiments that the decisions taken in a supply chain / inventory control contexts are influenced by behavioural factors (see e.g., Sterman 1989, Schweitzer and Cachon 2000, Croson and Donohue 2005, 2006, Cantor and Macdonald 2009, Zhao and Zhao 2015).

Using a controlled version of the beer game (Sterman 1989), Croson and Donohue (2005) concluded that sharing downstream inventory information (i.e., information available at downstream locations) is more effective at reducing bullwhip behaviour than sharing similar upstream information, and that sharing only upstream information offers no significant performance improvement. Croson and Donohue (2006) support that sharing inventory information can mitigate the bullwhip effect by helping upstream chain members anticipate and prepare for fluctuations on inventory needs downstream.

In the context of the beer game based experiment performed, Cantor and Macdonald (2009) obtained the unexpected result that the hypothesis that individuals with access to system-wide supply chain information would contribute to lower total supply chain cost than individuals with limited information was not supported, having the opposite been observed. The authors concluded that individuals may have an absorptive capacity for information (at least in the short run). Zhao and Zhao (2015), based on a five-echelon experiment, concluded that full information sharing cannot guarantee performance improvement (in terms of bullwhip effect and operating cost) and observed the tendency that, without information sharing, experiment participants paid more attention to reducing on-hand inventory, while with information sharing, they paid more attention to reducing stock-out.

Given the conclusions of the referred studies, when we model supply chains with centralised inventory control and information visibility, we assume that the information visibility in the supply chain is asymmetric, i.e., at the DC, there is total visibility and therefore the ward demands and inventory levels are visible; at the wards, only the information needed to run the system is visible (e.g., if the system admits lateral transshipments, the inventory levels and past demands at the other wards have to be visible, but the ward does not have visibility over the inventory level at the DC).

In our models, we consider over-ordering effects at the wards (a detailed description of how these effects were modelled is available in subsection 4.3.3, p.104), aimed at imitating the frequently observed "just-in-case" approach to inventory management by health care professionals (see e.g., Ritchie et al. 2000, Burns et al. 2002: 13, Tucker et al. 2013). This behaviour is similar to the *stock-out aversion* behaviour defined by Schweitzer and Cachon (2000) in the context of a newsvendor problem. There are also some similarities with the *phantom orders* analysed by Gonçalves (2003), but in the case of the orders issued by the wards, since they do not pay the materials to the central warehouse, the orders are not cancelled or returned. Instead, there is stock accumulation.

The application of System Dynamics modelling to Supply Chain Management had its origins in the seminal work of Forrester (1961), who has pointed out many of the current research issues in the field, including demand amplification, inventory swings, the effect of advertising policies on production variations, decentralised control, or the impact of the use of information technology on the management process (Angerhofer and Angelides 2000). Tako and Robinson (2012) reviewed modelling approaches using Discrete Event Simulation and System Dynamics in the logistics and supply chain context between 1996 and 2006, having analysed 110 published papers using System Dynamics, and identified the demand amplification effect, also known as the *Forrester effect* and nowadays frequently termed as the *bullwhip effect* (Lee et al. 1997b, 1997a), as the most frequently addressed topic using System Dynamics.

In health care contexts, System Dynamics has been frequently used to analyse political decisions (Dangerfield 1999, Brailsford 2008, Mingers and White 2010). However, in health care supply chain management at a micro level, the applications have been rare – the work by Samuel et al. (2010), who analyse the bullwhip effect in health care service-oriented supply chains, seems to be an exception. This model is, however, very different from ours in terms of focus and structure as it considers a serial supply chain with three steps (i.e., registration and categorisation, consultation, and testing and treatment) and it appears not to have any health specific characteristics.

Given the specific characteristics of the health care supply chain (see section 1.1.2) and the fact that existent sophisticated inventory control models are not widely used at health care organisations, it would be important that the insights from the System Dynamics field could be used to analyse health care supply chains, so that supply chain managers could have more indications to guide their actions.

In summary, the up-to-date models originated by the multi-echelon inventory management stream of literature are informative in terms of driving a better understanding of the related phenomena, but have three disadvantages: a) they often analyse different supply chain processes or policy rules separately; b) they are too complicated to be applied in a common hospital supply chain, and c) they often generate results that are very dependent on the specific assumptions made in terms of parameters of the model, which hinders the transposition of derived insights to practical situations.

In this research, we intend to understand how alternative supply chain operational processes (namely, decentralised inventory control with no information sharing versus centralised inventory control and some information sharing[39] and horizontal cooperation between wards through lateral transshipments) and policy rules (namely, alternative inventory allocation and unilateral transshipments from the other wards to the ER) impact the outcomes of a hospital supply chain in terms of inventory (that affects cost) and service levels. As far as we are aware, this issue has not been addressed before in an integrated way that takes into account the complexity of a hospital supply chain, using System Dynamics or other modelling approaches.

4.3 Developed models

4.3.1 Introduction

All the models developed assume a hospital supply chain with a loose internal replenishing capacity able to assure daily replenishing of all wards one day after their request. We considered that the costs associated with this replenishing capacity are fixed, i.e., there is no variable cost associated to the number of orders or deliveries within the hospital internal supply chain, since this capacity is shared by all items replenished in the hospital internal chain, that is, a replenishing team can visit all the wards daily and, in each of these visits, it may (or not) deliver a certain item. Additionally, we assume that the number of workers dedicated to replenishing tasks is fixed[40]. For similar reasons, Guerrero et al. (2013) have also not considered a variable ordering cost when modelling the joint inventory control of a one-warehouse, n-wards distribution system for a specific item family (infusion solutions) in the context of real hospital system in France. All the developed models assume a fixed one-day review period in the interal hospital supply chain.

[39] I.e., ward demand and downstream or same echelon inventory visibility.

[40] In the short run, with fixed salaries and inflexible workforce.

In all the models, when there are stock-outs at the DC, there are back-orders; if there are stock-outs at the wards, we consider that the demand is lost[41] (e.g., an alternative material is used, but there is a negative impact on the service in terms of cost and/or time).

The first model family described is based on a very simple (serial) hospital supply chain, with one distribution centre (DC) and one ward. The underlying supply chain has also at least one supplier, but it is considered external to the analysed system, i.e., it replenishes the DC after the supplier delivery time has passed, but its inventory level has not been modelled. This model is used only to describe the logic behind the developed models since its dimension allows an easier description of the links between variables, and to make some comparisons that give insights about the impact of some model components on the overall system behaviour. It is also useful to assess the validity of the various developed models, since its simulations results can be compared with previous knowledge about supply chain system dynamics.

A variation of the model, incorporating direct emergency deliveries from the DC to satisfy demand in excess of the inventory available at the ward has also been developed. This type of procedure is frequently observed in real hospitals (see an example in Guerrero et al. 2013). From a model construction perspective, this is a small variation, but it implies that the DC becomes a *dual-role* warehouse (Cattani et al. 2011), since it serves the ward warehouses and simultaneously acts as a backup warehouse serving final demand directly. However, the warehouse described and analysed by the authors is different from ours: it supplies the final demand of one regional area directly while our warehouse may supply demand at all wards, but only if the inventory on hand at the wards is not enough to meet all demand faced there.

Afterwards, we describe similar models of arborescent supply chains, formed by a DC, various wards and at least one supplier external to the analysed system. In terms of the demand of the wards, two different situations were considered: all the wards having identical, stationary daily demand (i.e., generated using the same random distribution) and wards with different, stationary daily demand (i.e., generated using distributions that reproduce demand data obtained from a real hospital system).

For both topologies, two alternative supply chain strategic processes were modelled and simulated: a traditional supply chain, with decentralised inventory control and no information visibility (i.e., at a ward, only that ward demand and inventory are visible; and, at the DC, only the orders from the various wards and the DC inventory are visible), and an alternative approach with centralised inventory control and some information visibility in the supply chain,

[41] This corresponds to what happens relatively to the item used as an example in our simulations (see section 4.4). In the case of other items, we could have order back-orders or a mixed situation combining back-orders and lost demand.

specifically, information concerning demand and inventory levels at the ward(s) is(are) visible at the DC, and, for models of arborescent supply chains, inventory levels at the wards are visible at the other wards.

We characterise the modelled supply chains as *traditional* when each supply chain intervenient makes its decisions locally, independently of the global state of the system, and the decision makers at the ward (typically, health professionals) adopt a "just-in-case" inventory ordering approach, that is, they increase the quantity ordered when the ward inventory falls considerably below the desired inventory level. We do also consider that they may decrease their orders if they observe that inventory is much above that level. Moreover, when modelling traditional supply chains, we consider that these decision makers (i.e., health professionals at the wards) evaluate demand level and variability considering only what happened during a few previous days (i.e., have memory limitations). Chen et al. (2000) have shown that when forecasts are made using exponential smoothing methods, the bullwhip effect increases when the smoothing constants increase. Likewise, the bullwhip effect is magnified when the length of the memory period considered decreases.

In terms of inventory allocation (rationing) rules, two alternatives have been simulated:

- dividing the available units by the wards with pending requests proportionally to the weight of their pending orders on total pending orders;
- giving priority to the fulfilment of the demand of the ER and applying the proportionally rule described before to the remaining quantity available at the DC.

In our models, the inventory is only distributed by the wards reactively, that is, after an order from the ward is issued (in the case of the models of centralised supply chains, where the ward does not have any margin to influence the quantity ordered to the DC, this can happen after the ward daily demand is known). In our models, the allocations rules are used for distributing the (insufficient) inventory on hand at the DC by the wards, in the fulfilment of wards' orders, or in the fulfilment of final unmet demand at the wards (without entering in the ward stock), when emergency deliveries from the DC are needed.

For the centralised serial supply chain and arborescent topologies, we have only considered models with the possibility of emergency deliveries from the DC in case the inventory level at the ward is insufficient to fulfil all demand derived from patient care needs, since in a hospital system the occurrence of stock-outs (and lost demand) should be avoided. Because this characteristic distinguishes the modelled supply chain from a pure arborescent one, we designate it as quasi-arborescent.

Finally, a model considering reactive (i.e., only triggered in case of a stock-out), unilateral transshipments from the ordinary wards to the ER has also been developed. Unilateral transshipments are reasonable when the stock-out costs at the various retailers are significantly different (Axsäter 2003, Olsson 2010). In the case of a hospital supply chain, frequently the stock-outs at the ward level will result in lost demand that, whenever possible, will be transferred to a substitute item. This is especially so at the ER, where the time of response is very important and the effects of a stock-out may be more serious than in other wards. Therefore, in our model, the ER receives but it does not dispatch lateral transshipments. In case of insufficiency of the ER inventory, first, the ER will resort to lateral transshipments from the other wards, and, only if the other wards do not have enough inventory on hand, will urgent direct deliveries from the DC be used to fulfil ER demand. Guerrero et al. (2013) describe the use of lateral transshipments, complementarily to emergency deliveries from the DC, in a real hospital setting. The authors refer that, in the case analysed (the distribution of infusion solutions), the hospital wishes to eliminate transshipments. In our model, in line with some indications obtained in conversations with supply chain managers wishing to increase lateral transshipments, the emergency deliveries from the DC are considered only when the lateral transshipment is not enough to fulfil all demand at the ER.

The ward chosen to serve the ER is the one with the lowest probability of stock-out at the moment of the decision. This assumes some degree of inventory centralisation, since it requires that the demand historical data and the inventory on hand of the various wards are visible. Alternatively, if in a practical situation this was not possible, other rules like the "closest neighbour" could be used. However, this alternative rule would damage the service level at the neighbour ward, unless some protection measure was taken. In our model, the transshipment originates only from one ward, since it would be unpractical from a logistical point of view to collect units from various wards.

Our model assumes complete pooling – i.e., all the inventory available at the selected ward can be used to fulfil demand at the ER – because the various wards can be replenished daily from the DC and the considered replenishing times after an order is placed are short (in accordance with what has been described by hospital supply chain professionals interviewed), therefore eventual inventory shortages at the replenishing ward caused by a transshipment to the ER can be rapidly compensated.

The models have been developed following System Dynamics principles, and were formulated and simulated using Vensim Professional 6.3.

4.3.2 Notation

In the tables and graphs presenting simulation results, the models are identified using the following classification: management process/ SC topology (and inventory allocation rules and possibility, or not, of lateral transshipments)/ Possibility of emergency deliveries/ Ordering effects at the ward/ Ordering effects at the DC:

- Management process:
  - T: Traditional;
  - C: Centralised, with inventory visibility.
- SC topology (and inventory allocation logic and possibility, or not, of lateral transshipments):
  - S: Simple, linear, with one DC and one ward;
  - AI: quasi-Arborescent with Identical wards;
  - AI+ER: quasi-Arborescent with identical wards, including an Emergency Room (i.e., if the inventory at the DC is insufficient to meet the requests of all the wards, the ER has priority over the other wards);
  - AD: quasi-Arborescent with Different wards;
  - AD+L: quasi-Arborescent with Different wards and Lateral transshipments to the emergency room;
  - AD+ER: quasi-Arborescent with Different wards, including an Emergency Room;
  - AD+ER+L: quasi-Arborescent with Different wards, including an Emergency Room, and Lateral transshipments to the emergency room.
- Possibility (or not) of emergency deliveries:
  - N: No emergency deliveries from the DC to the point of consumption if the inventory level at the ward is insufficient to fulfil all demand;
  - P: Possibility of emergency deliveries from the DC to the point of consumption if the inventory level at the ward is insufficient to fulfil all demand.
- Existence of over and/or under-ordering effects at the wards:
  - N: No over or under-ordering;
  - O: Over-ordering;
  - U: Under-ordering.
- Existence of under-ordering effects at the DC:
  - N: No over or under-ordering;
  - U: Under-ordering.

4.3.3 Traditional, serial supply chains with one DC, one ward and at least one external supplier

A simplified causal diagram of the model of a supply chain with one DC, one ward and at least one external supplier, managed through decentralised inventory control and without information sharing, i.e., a very simple, serial traditional supply chain, is presented in Figure 4.1. On the top of the scheme, we represented the stock and flow structure of the model and below the decision rules used by the decision makers to manage the orders of units to upstream entities on the supply chain. The daily demand is an exogenous variable. Some auxiliary parts of the model are hidden in the view presented, to facilitate readability (the sketches of these parts of the model are presented in Appendix 4.1).

DC inventory and *Ward inventory* are state (stock) variables. The model also considers order backlog state variables and the corresponding flows, related to the DC, to assure that orders that cannot be fulfilled in the period of their occurrence due to inventory insufficiencies are not forgotten by the model and are taken into account in the following periods. This variable and the related feedback loops have been omitted in the diagram presented, because it is not central to the system behaviour we want to emphasise, and its inclusion could compromise the readability of the scheme. The influence of order backlog variables on a supply chain system dynamics has already been described (see e.g., model Z502 in H. Bossel 2007: 12-16). All the model feedback loops involving *Ward inventory* and *DC inventory* are described on detail in Appendix 4.2. The model formulation is described and explained in Table 4.1 and Table 4.2**.**

As real supply chain systems and any System Dynamics based supply chain model, our models include various negative feedback loops, i.e., sets of system monitoring and corresponding decision rules, through which orders to upstream supply chain members are adjusted to control local inventory levels (see Sterman 2004). This type of structure is the cause for supply chain systems oscillations (e.g., Sterman 2004, Hartmut Bossel 2007). In the model of a simple serial supply chain (see Figure 4.1), two sets of such decision rules affect the system behaviour: those applied locally at ward, on the right-hand side of the scheme, and those applied locally at the DC, in the left-hand side of the scheme. When systems with more wards are modelled (see the next subsections), the models include a set of such rules for each ward.

The presented description considers a Normal daily demand, generated from a distribution compatible with the behaviour of sampled data for a specific material. Other possible daily demand distributions or other parameter options have been modelled and simulated, as described in section 4.4.

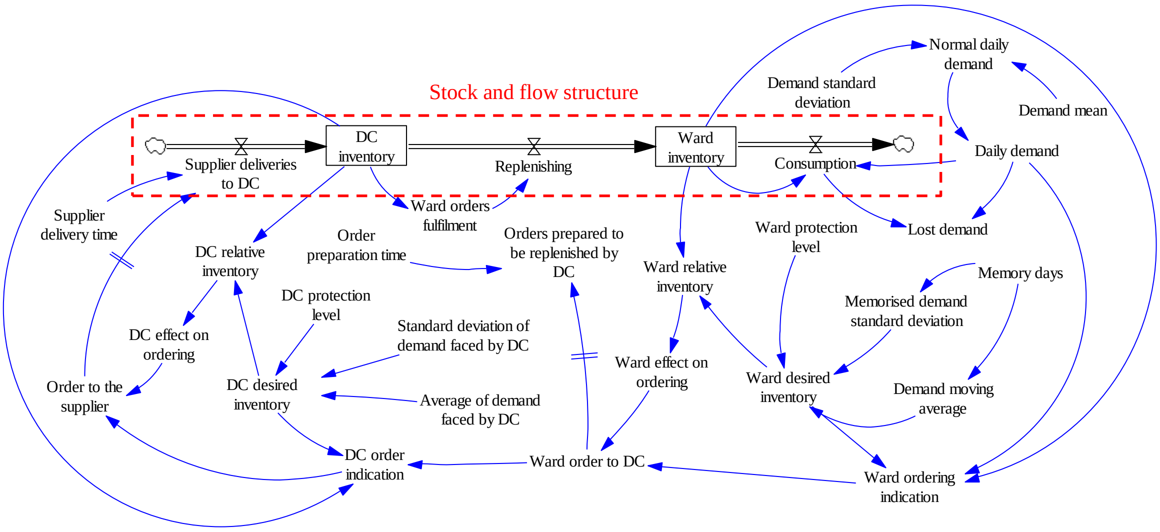


Figure 4.1 Simplified causal diagram of the model for a traditional supply chain with one DC and one ward

The independent variables and parameters (i.e., constant and lookup functions) are:

- the *Daily demand* of the item object of analysis faced at the ward (randomly generated using a distribution compatible with the characteristics identified in a real demand sample);
- the *Ward protection level*, a constant that is based on classical inventory control theory and incorporates the aversion to the risk of inventory stock-out of the relevant decision makers into the model; this constant is multiplied by a measure of demand variability – specifically, the standard deviation of daily demand during the period of memory formation – to determine the ward desired safety sock (which, summed to the average of memorised demand, forms the *Ward desired inventory*);
- the *DC protection level* is a constant similar to the Ward protection level, except that it was considered that at the DC managers are able to remember all past observed demand (namely, by using computers to store information), since it has been observed that inventory control is more professional at the DC level;
- *Memory days* is a constant that represents decision makers ability to retain past demand information; in our model, we considered that the health professionals that are responsible for inventory ordering at the ward base their decisions on the demand level and variability they observed in the last days, therefore the demand average and standard deviation are calculated considering a limited number of days, the *Memory Days*. The bullwhip effect increases when the *Memory days* decrease (which derives from the work of Chen et al. 2000).

- *Ward (DC) effects on ordering* are lookup functions that take into account the decision makers' reactions to *Ward (DC) relative inventory* (i.e., the ratio between actual inventory and *Ward (DC) desired inventory*). For example, we can model over-ordering effects when *Ward relative inventory* (i.e., the relation between the ward inventory level, *Ward inventory*, and the *Ward desired inventory*) drops significantly below one, which would be consistent with the frequently described "just-in-case" logic towards materials management by health care professionals (see e.g., Ritchie et al. 2000, Burns et al. 2002: 13, Tucker et al. 2013), or we can model an under-ordering effect at the ward and/or at the DC if *Ward 1/ DC relative inventory* is significantly higher than one.

The ordering effects we modelled are related to the *stock adjustment time* (*SAT*) frequently used in System Dynamics (see Sterman 2004: 671-673). In our model, the quantity ordered is a quantity aimed at fulfilling the demand of the day and restore the desired inventory level, e.g., at the ward, it is *Daily demand+Ward desired inventory-Ward inventory* multiplied by an ordering effect (*e*), or, using a notation similar to that used by Sterman, $e \times [D + (S^{*}-S)] = e \times D + e \times (S^{*}-S)]$. If S^{*}/S is near 1, $e = 1$; if S^{*}/S is significantly below 1, there is an over-ordering effect, i.e., $e > 1$; if S^{*}/S is significantly below 1, there is an under-ordering effect, i.e., $e < 1$. Thus, the ordering effect *e* in our model is corresponding to 1/*SAT*. Consequently,

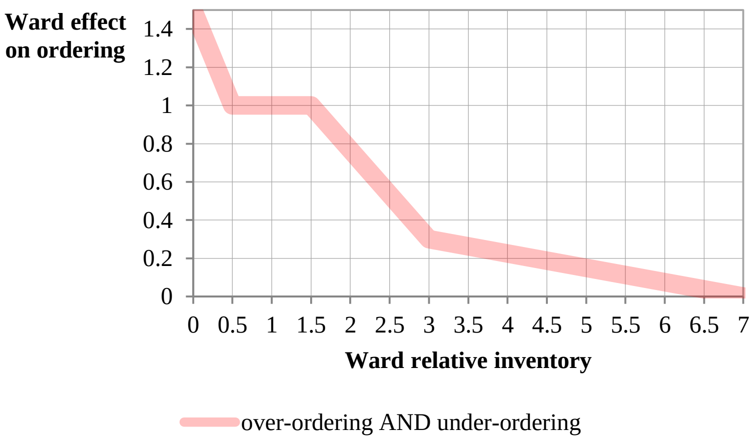
- an $e = 1$ corresponds to a $SAT = 1$ time unit;
- an $e > 1$, corresponds to a $SAT < 1$ time unit (i.e., adjusting the stock to the ideal in less than a period; in the case of our model, a day); and
- an $e < 1$, corresponds to a $SAT > 1$ time unit (i.e., adjusting the stock to the ideal in more than a period).

A longer SAT (and thus, a smaller ordering effect, *e*) reduces the amplification ratio (i.e., at the ward, the relation between the orders placed to the DC and the daily demand), but it does also extend the time required to close the gap between the desired inventory and the inventory on hand, and vice-versa (Sterman 2004).

In our model, *D*, the expected loss rate in a anchoring and adjustment heuristic (Sterman 1989, 2004: 670), is also augmented or reduced by the ordering effect, *e*.

Table 4.1 Constants and lookup functions of the model of a traditional supply chain with one DC and one ward

	Constants and lookup functions	**Units**
Demand mean	= 105 (compatible with the characteristics of sampled data, see Appendix 4.9)	Units/Day [0, ?]
Demand standard deviation	= 98 (compatible with the characteristics of sampled data, see Appendix 4.9)	Units/Day [0, ?]
Ward protection level	= 2 (if the ward daily demand has a normal distribution, it means that an inventory level equal to the daily demand average plus the desired safety stock would have a 0.9775 probability of being enough to fulfil the daily demand; a protection level of 3 would rise this probability to 0.99865)	Dimensionless [0, 5]
DC protection level	= 2 (similar to *Ward protection level*)	Dimensionless [0, 5]
Memory days	= 5 (health professionals make decisions considering their perceptions of demand level and variability in the last 5 days)	Days [1, 30, 1]
Order preparation time	= 1 (an order issued by the ward one day, is fulfilled by the DC on the next day)	Days [0, 15, 1]
Supplier delivery time	= 2 (informed by hospital supply chain managers)	Days [0, 15, 1]
Ward effect on ordering	= WITH LOOKUP (Ward relative inventory, ([(0,0)-(25,2)], (0,1.5),(0.5,1),(1.5,1),(3,0.3),(7,0),(M,0))	Dimensionless [0, ?]



We consider an over-ordering effect (hoarding) when the *Ward relative inventory* (i.e., the *Ward inventory* divided by the *Ward desired inventory*) is lower than 0.5 and an under-ordering (smoothing) effects when the *Ward relative inventory* is higher than 1.5[42].

[42] Other ordering-effect options have been considered and simulated (see details on subsection 4.3.1).

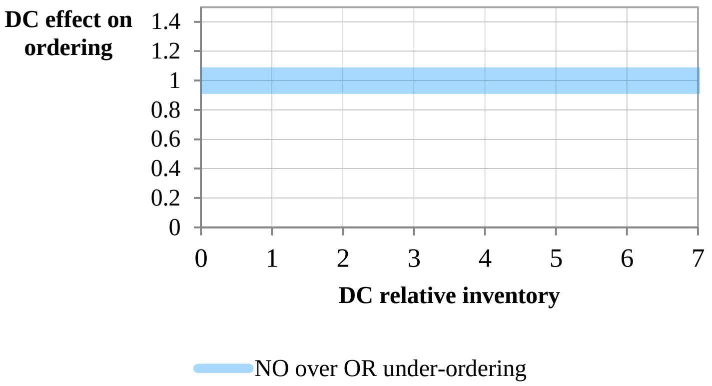
	Constants and lookup functions	Units
DC effect on ordering	= WITH LOOKUP (DC relative inventory, ([(0,0)-(6,3)],(0,1),(M,1)))  No over or under-ordering at the DC were considered[42].	Dimensionless [0, ?]
FINAL TIME	= 365 (the final time for the simulation)	Days [0, ?]
INITIAL TIME	= 0 (the initial time for the simulation)	Days [0, ?]
TIME STEP	= 1 (the time step of the simulation)	Days [0, ?]

Table 4.2 Stocks and auxiliary variables of the model of a traditional supply chain with one DC and one ward

	Stocks and auxiliary variables	Units
Daily demand[43]	= IF THEN ELSE(Normal daily demand>=0, Normal daily demand, 0) Number of units demanded per day at the ward. Only positive values generated using the Normal distribution for daily demand, randomised based on real sampled data (see Appendix 4.9), are considered; if the generated normal value is negative, the daily demand is considered to be 0.	Units/Day [0, ?]
Normal daily demand[43]	= INTEGER(RANDOM NORMAL(-M, M, Demand mean, Demand standard deviation, 0)) M is a number big enough not to truncate the determined normal values; *Demand mean* and *Demand standard deviation* are constants based on the characteristics of the real demand sample obtained (see Appendix 4.9); a seed of 0 was used.	Units/Day [-M, M]

[43] In the presented formulation, the example of a normal daily demand is used. Other daily demand distributions were modelled and simulated, as explained on section 4.4. The corresponding model modifications are presented in Appendix 4.3.

Stocks and auxiliary variables		Units
DC inventory	= INTEG (Supplier deliveries to DC-Replenishing, INTEGER(Demand mean)*Corrected time) Accumulates the *Supplier deliveries to DC* and declines with the *Replenishing* of the ward; the initial DC inventory is the integer of the *Demand mean* multiplied by *Corrected time* (which at the beginning of the simulation is 1).	Units [0, ?]
Ward inventory	= INTEG (Replenishing-Consumption, INTEGER(Demand mean)*Corrected time) Accumulates the *Replenishing* from the supplier and declines with the *Consumption* at the ward; the initial *Ward inventory* is the integer of the *Demand mean* multiplied by *Corrected Time* (which at the beginning of the simulation is 1).	Units [0, ?]
Consumption	= MIN(Daily demand, Ward inventory) Equal to *Daily demand*, if the available inventory at the ward is enough to fulfil that demand; otherwise, it is equal to the available inventory at the ward.	Units/Day [0, ?]
Lost demand	= IF THEN ELSE(Daily demand>Consumption, Daily demand-Consumption, 0) A variable to register the positive differences between *Daily demand* and *Consumption*, i.e., situations when demand exceeds the item quantity that can be consumed, due to inventory insufficiency.	Units/Day [0, ?]
Ward desired inventory	= ACTIVE INITIAL (Demand moving average+ Ward protection level*Memorised demand standard deviation, INTEGER(Demand mean)*Corrected time) The desired inventory level at the ward (defined in the health professionals' minds) is enough to cover the demand moving average and the desired safety stock (i.e., the *Ward protection level* multiplied by the *Demand standard deviation*); at the beginning of the simulation it is equal to the Demand mean. The demand average and standard deviation are calculated based only on the demand during the previous *Memory Days.*	Units [0, ?]
Demand moving average	= Demand accumulation during memory days/Memory days An indicator of daily demand level; memory limitation (to *Memory Days*) is considered.	Units/Day [0, ?]
Memorised demand standard deviation	= SQRT((Squared demand accumulation during memory/ Memory days)-POWER(Demand moving average, 2) An indicator of daily demand variability; memory limitation (to Memory Days) is considered.	Units/Day [0, ?]
Ward ordering indication	= ACTIVE INITIAL (IF THEN ELSE((Daily demand+Ward desired inventory-Ward inventory)>0, (Daily demand+Ward desired inventory-Ward inventory), 0), INTEGER (Demand mean)) Positive difference between the quantity needed to fulfil the daily demand and to form the ward desired inventory stock, and the current inventory level; at the beginning of the simulation it is equal to the integer of Demand mean.	Units/Day [0, ?]
Ward relative inventory	= IF THEN ELSE(Ward desired inventory>0, Ward inventory/ Ward desired inventory, Ward inventory/1) Relation between *Ward inventory* and *Ward desired inventory*.	Dimensionless [0, ?]

	Stocks and auxiliary variables	Units
Ward order to DC	= ACTIVE INITIAL (INTEGER(Ward ordering indication*Ward effect on ordering), INTEGER(Demand mean)) The quantity ordered by the ward to the DC is determined by multiplying the *Ward ordering indication* (i.e., the quantity to be ordered determined taking only demand information into account) by the *Ward effect on ordering* (that incorporates the effect caused by the relation between existent and desired inventory); at the beginning of the simulation, a quantity equal to the integer of *Demand mean* is ordered.	Units/Day [0, ?]
Orders prepared to be replenished by DC	= DELAY FIXED (Ward order to DC, Order preparation time, INTEGER(Demand mean)) Delays the *Ward order to DC* by the *Order preparation time*.	Units/Day [0, ?]
Ward orders placed	= Orders prepared to be replenished by DC	Units/Day [0, ?]
Ward orders backlog	= INTEG (Ward orders placed-Ward orders fulfilment, INTEGER(Demand mean)*Corrected Time) Accumulates the *Ward orders placed* and declines with the *Ward orders fulfilment*; the initial *Ward orders backlog* is the *Demand mean* multiplied by *Corrected Time* (1, at the beginning of the simulation).	Units [0, ?]
Ward orders fulfilment	= MIN(Ward orders backlog, DC inventory) If there is enough inventory at the DC, all *Ward orders backlog* will be fulfilled.	Units/day [0, ?]
Replenishing	= Ward orders fulfilment	Units/Day [0, ?]
DC desired inventory	= ACTIVE INITIAL (Average of demand faced by DC+ DC protection level*Standard deviation of demand faced by DC, INTEGER(Demand mean)*Corrected time) Similar to *Ward desired inventory* (see above), with the only difference that we do not consider memory limitations to determine the DC demand level (i.e., *Average of demand faced by DC*) and variability (i.e., *Standard deviation of demand faced by DC*); at the beginning of the simulation, it is equal to the *Demand mean* multiplied by *Corrected time* (i.e., 1).	Units [0, ?]
Average of demand faced by DC	= Accumulated demand faced by the DC/Corrected time An indicator of the level of the demand faced by the DC; no memory limitations are considered.	Units/Day [0, ?]
Standard deviation of demand faced by DC	= IF THEN ELSE(((Accumulated squared demand faced by the DCs/ Corrected time)-(Average of demand faced by DC* Average of demand faced by DC))>=0, SQRT((Accumulated squared demand faced by the DCs/ Corrected time)-(Average of demand faced by DC* Average of demand faced by DC)),Demand standard deviation) An indicator of the variability of the demand faced by the DC; no memory limitations are considered.	Units/Day [0, ?]

	Stocks and auxiliary variables	Units
DC ordering indication	ACTIVE INITIAL (IF THEN ELSE((DC desired inventory+ Ward order to DC-DC inventory)>0, (DC desired inventory+ Ward order to DC-DC inventory), 0), INTEGER(Demand mean)) Similar to *Ward ordering indication* (see above).	Units/day [0, ?]
DC relative inventory	IF THEN ELSE(DC desired inventory>0, DC inventory/ DC desired inventory, DC inventory /1) Similar to *Ward relative inventory* (see above).	Dimensionless [0, ?]
Order to the supplier	= ACTIVE INITIAL (INTEGER(DC order indication* DC effect on ordering), INTEGER(Demand mean)) The quantity ordered by the DC to the supplier is determined by multiplying the *DC order indication* by the *DC effect on ordering*.	Units/day [0, ?]
Supplier deliveries to DC	= DELAY FIXED (Order to the supplier, Supplier delivery time , INTEGER(Demand mean)) Delays the *Order to the supplier* by the *Supplier delivery time*.	Units/day [0, ?]
Delayed demand	= DELAY FIXED (Daily demand, Memory days, INTEGER(Demand mean)) This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	Units/Day [0, ?]
Demand accumulation during memory days	= Demand accumulation during memory days= INTEG (Daily demand-Delayed demand, Demand mean* Memory days) This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	Units [0, ?]
Squared delayed demand	= Delayed demand*Delayed demand This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	(units/Day)* (units/Day) [0, ?]
Squared demand	= Daily demand*Daily demand This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	(units/Day)* (units/Day) [0, ?]
Squared demand accumulation during memory	= INTEG (Squared demand-Squared delayed demand, (Demand mean*Demand mean)*Memory days) This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	(Units*Units) /Day [0, ?]
Accumulated demand faced by the DC	= INTEG (Ward order to DC, Demand mean*Time) This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	Units [0, ?]
Accumulated squared demand faced by the DC	= INTEG (Ward order to DC*Ward order to DC, (Demand mean*Demand mean)*Time) This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	(Units*Units) /Day [0, ?]
Corrected time	= IF THEN ELSE(Time>0, Time, 1) This is an auxiliary variable, used to determine other, more conceptual, variable(s) in the model.	Days [1, ?]

A variation of the model with direct emergency deliveries from the DC to fulfil demand at a ward (i.e., at the point of consumption), in case of on hand inventory insufficiency at the ward, was also developed to emulate a usual practice in hospital settings. The variable additions and changes corresponding to the creation of this version of the model(s) are described in Appendix 4.4.

4.3.4 Traditional quasi-arborescent supply chains with one DC and N wards

The model considering N wards, identical relatively to their daily demand distribution is conceptually similar to the model of traditional, serial supply chains with one DC and one ward with emergency deliveries (described at section 4.3.3). The fundamental difference rises from the fact that the considered supply chain has various wards. The constants and lookup functions used in the model are also similar, and identical for the all the wards, with the only exception that different seeds are used to generate the daily demands of the wards. The conceptual logic behind many of the variables, and their mathematical formulation, is identical to that described for the base model with emergency deliveries (see Appendix 4.4), with the main difference that a subscript for the ward is used. The full mathematical formulation of the model is presented in Appendix 4.5, where the variables related to the distribution of the inventory on hand at the DC (i.e., those that distribute the DC inventory by the various wards proportionally to their ward backlog quantities or missing units, when the DC inventory is insufficient to fulfil the ward backlog of all the wards or the missing units at all wards) are explained in detail.

In Appendix 4.6, we present the model formulation changes, namely, those related to DC inventory allocation, so that one of the wards modelled is considered an ER having priority over the other wards in case the inventory available at the DC is not enough to fulfil all the orders placed by the various wards.

4.3.5 Supply chains with centralised inventory control and inventory visibility

For all the supply chain topologies described previously, models assuming centralised inventory control at the DC level and inventory visibility in the entire supply chain have also been developed. For simplicity reasons, the underlying systems are sometimes designated as *centralised* systems. The logic behind all the models is the same, so we base the description of these models on a simple serial supply chain with one DC and one ward.

This model family distinguishes from that described previously (see section 4.3.3) because:

- the ward orders to the DC are only based on the daily demand, since the quantity ordered to the DC equals the daily demand faced and there are no ordering effects at the ward; this corresponds to the following order-up-to policy: at the end of the day, a new order equal to demand is placed to bring the inventory level (on hand and on order) back to the order-up-to level (the inventory level at the ward at the beginning of the simulation);
- the DC orders to the supplier depend on final demand level and variability, because they are calculated using the average and standard deviation of the demand faced at the ward, and the whole hospital inventory is used to compare the current inventory with the desired inventory.

In this model family, the freedom of decision about orders timing and size at the ward level is inexistent.

These models consider emergency deliveries from the DC to fulfil demand at the ward when the inventory available at the ward is not sufficient to fulfil all demand. A simplified causal diagram of the model considering a normal daily demand (i.e., daily demand generated through process 1, as described in section 4.4) is presented in Figure 4.2. The most noticeable difference relatively to the model of a traditional supply chain (see Figure 4.1) is that the inventory control process at the ward is much simpler.

In Appendix 4.7, we present the formulation changes of these models relatively to the model described in subsection 4.3.3.

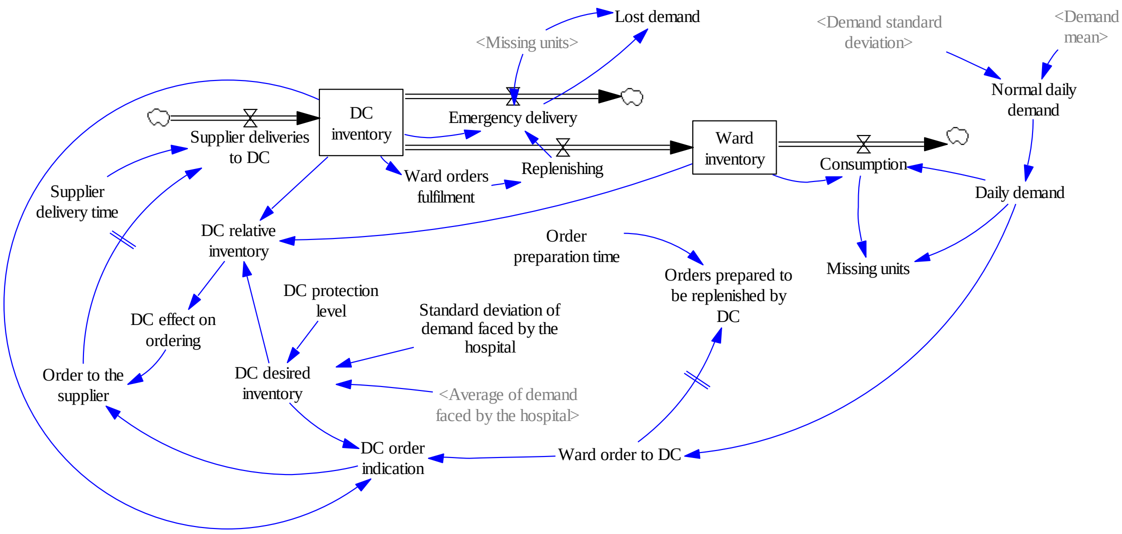


Figure 4.2 Simplified causal diagram of the model for a centralised control supply chain with inventory visibility, with one DC and one ward

4.3.6 Quasi-arborescent supply chains with lateral transshipments

We have modelled only reactive lateral transshipments – i.e., there are lateral transshipments if a ward – in the case, the emergency room (ER) - does not have enough inventory to fulfil all faced demand on a given day.

Generally, lateral transshipments have been described in the literature as a mean to reduce inventory levels and costs at the echelon where they are used (e.g., at the retailer level), without harming the service level (see Paterson et al. 2011). In our model, the lateral transshipments are mainly viewed as a mean to improve the service level. Therefore, we have not implemented any scheme to reduce the orders from the ER to the DC, as a mean to reduce the inventory at the ER, as a consequence of receiving lateral transshipments. Nevertheless, to prevent the inventory at the ER to grow unnecessarily, when determining the quantities to be ordered to the DC, the quantities received from other wards are subtracted to the daily demand faced by the ER.

In our model, the ward chosen to serve the ER is the one with the lowest probability of stock-out at the moment of the decision (i.e., the ward with the highest probability of fulfilling the daily demand). Since the daily demands of the wards analysed have characteristics compatible with a Normal distribution (see Appendix 4.9), the *standardised available inventory at ward n*, i.e., $\frac{\textit{Inventory on hand at ward } n - \textit{Average of ward } n \textit{ (daily) demand}}{\textit{Standard deviation of ward } n \textit{ (daily) demand}}$, where *Inventory on hand at ward n* = *Ward inventory[n]* – *Consumption[n]*, where the average and the standard deviation of the ward daily demand are calculated using the historical daily demand (since the beginning of the simulation), is used as an indicator of probability that ward *n* is able to fulfil all faced daily demand.

When the inventory at the ER is not sufficient to fulfil the demand, lateral transshipments are used to try to meet this demand before resorting to emergency deliveries from the DC.

In Appendix 4.8, we present the necessary variable additions and changes to add the lateral transshipments feature to the traditional quasi-arborescent models.

4.4 Data

The simulation experiments were performed using the illustrative example of a typical *high demand, frequent and generalised use* item: a given type of sterilised compress. If there is lack of the desired compress in a ward, nurses have to cut bigger compresses to obtain the desired size, and, since the compresses are sterilised, leftovers are wasted. Stock-out situations are therefore undesired.

Our analysis used information concerning the inventory exits of the selected item at three wards (one of which is an emergency room). Since the size of the items' demand samples obtained is relatively small, we analysed the available data in order to find statistical distributions that could be compatible with the behaviour it exhibited - Anderson-Darling, Kolmogorov-Smirnov and Chi-square goodness of fit tests for continuous distributions were performed using Easyfit Professional 5.5 by Mathwave Technologies[44] to determine random distributions compatible with the samples obtained (the analysis performed is described in detail in Appendix 4.9). Several of the possible distributions were then used to generate alternative sets of random data mimicking the behaviour observed in the sample. The simulation models developed were run using some of these different, but plausible, demands. The performed simulations model one year of operation of the considered hospital supply chains.

Based on the demand analysis performed, the following four alternative processes based on ward 1 sample were used to generate demands for the experiments concerning models of simple, serial supply chains or quasi-arborescent supply chains with identical wards:

- Process 1: *Daily demand* generated from a Normal distribution with mean 105 units and standard deviation 98 units;
- Process 2: *Daily demand* = *Demand size* × *Day with occurrence of demand* (1=yes; 0=no), where *Demand size* is generated from a Normal distribution with mean 147

[44] http://www.mathwave.com

units and standard deviation 85 units, and *Day with occurrence of demand* from a Bernoulli distribution with success proportion of 0.71;

- Process 3: *Daily demand* = *Inventory exit size* × *Number of inventory exits per day*, where *Inventory exit size* is generated from a Normal distribution with mean 120 units and standard deviation 82, and *Number of inventory exits per day* is generated from a Poisson distribution with mean 1 exit;
- Process 4: *Daily demand* = *Inventory exit size* × *Number of inventory exits per day*, where *Inventory exit size* is generated from a Normal distribution with mean 120 units/exit and standard deviation 82 units/exit, and *Number of inventory exits per day* is generated from a Binomial distribution with N = 4 and proportion 0.23.

We designate the daily demand generated by Process *n* by the term *generated demand n*, or simply *demand n*, with *n* = 1, …, 4.

The chart presented in Figure 4.3 compares the daily demands thus generated for simple serial supply chains simulations with the sample that has been obtained. Some location and dispersion measures describing the various series are presented in Table 4.3. We can see that all the generated series have similarities to the sample, mainly below the median or third quartile. The series *generated daily demand 4* and, even more, *generated daily demand 3* exhibit some demand peaks, and the analysis of their impact on the system is interesting for the purposes of our work. In Appendix 4.18 similar descriptions are made for demands generated to simulate quasi-arborescent supply chains with identical wards.

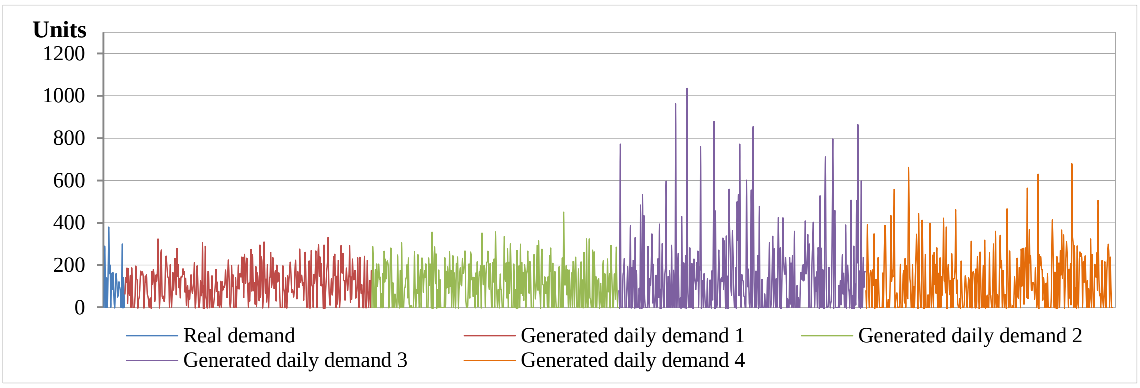


Figure 4.3 Comparison between ward 1 daily demand sample and the four alternative generated daily demands

Table 4.3 Measures of location and dispersion describing ward 1 daily demand sample and related alternative generated daily demands

	Minimum	**1st quartile**	**Median**	**3rd quartile**	**Maximum**	**Average**	**Standard deviation**
Sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8
Generated demand 1	0.0	45.0	110.0	168.0	329.0	112.2	81.5
Generated demand 2	0.0	0.0	103.0	193.0	447.0	110.3	99.2
Generated demand 3	0.0	0.0	87.0	204.0	1036.0	141.8	186.8
Generated demand 4	0.0	0.0	94.0	203.0	672.0	123.4	131.4

The following generation processes, based on the characteristics of the real demand samples (see Appendix 4.9), were used for modelling supply chains with wards that differ in terms of their demand characteristics:

- Ward 1: *Daily demand* generated from a Normal distribution with mean 105 units and standard deviation 98 units (i.e., generated by Process 1);
- Ward 2: *Daily demand* generated from a Normal distribution with mean 190 units and standard deviation 226 units;
- Ward 3/ ER: *Daily demand* generated from an Exponential distribution with mean 1/0.0013 = 769.23 units (i.e., λ=0.0013).

Figure 4.4 and Table 4.4 present comparisons of the generated daily demands with the real demand samples.

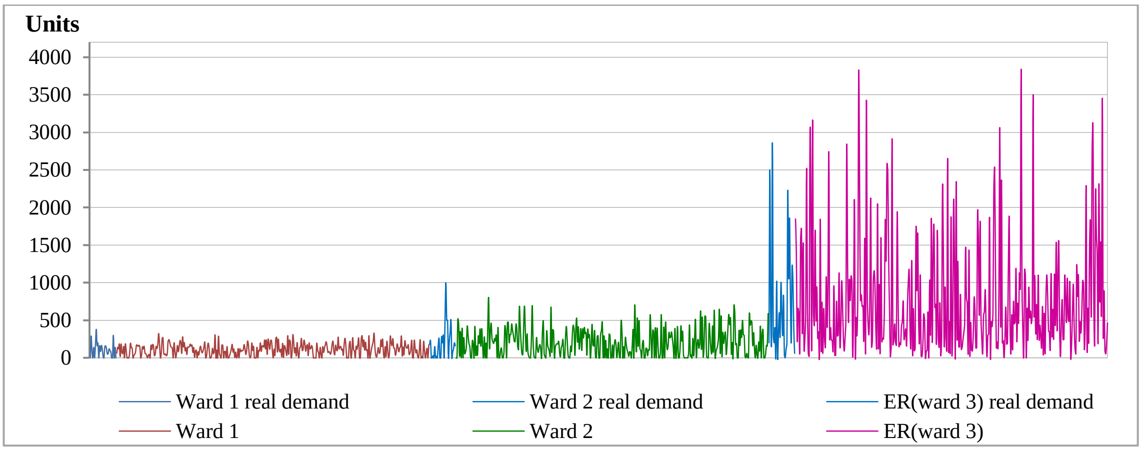


Figure 4.4 Comparison between ward 1, ward 2 and ER (ward 3) daily demand samples and related generated daily demands

Table 4.4 Measures of location and dispersion describing ward 1, ward 2 and ER (ward 3) daily demand samples and related generated daily demands

	Minimum	**1st quartile**	**Median**	**3rd quartile**	**Maximum**	**Average**	**Standard deviation**	**CV***
Ward 1 sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8	0.93
Ward 1 generated demand	0.0	45.0	110.0	168.0	329.0	112.2	81.5	0.73
Ward 2 sample	0.0	0.0	150.0	270.5	1000.0	191.0	222.0	1.16
Ward 2 generated demand	0.0	22.0	170.0	343.5	800.0	203.8	184.1	0.90
ER(ward 3) sample	0.0	200.0	400.0	1010.0	2860.0	692.9	741.8	1.07
ER(ward 3) generated demand	1.0	212.3	523.5	1053.8	3840.0	764.2	762.8	1.00

*Coefficient of variation (CV) = Standard deviation/Average

The fact that, in accordance with what happens in the analysed hospital system, the ER is the ward with the higher demand level may have consequences in the simulated systems behaviour (as it would have on a real situation). For example, when modelling a system with priority given to the ER in inventory allocation or lateral transshipments from the other wards to the ER, it is likely that a demand peak at the ER will cause important inventory reductions or even stock-outs in the other ward(s).

4.5 Results for serial supply chains with one DC and one ward

4.5.1 Introduction

In Figure 4.5, we summarise the model alternatives considered for simulating serial supply chains with one DC and one ward. Apart from the alternatives represented, we have also considered four alternative daily demands, generated using the processes explained in section 4.4. The simulated alternatives compare the impact of ordering effects at the ward and at the DC, as explained in detail in the next subsections. We have simulated the models of supply chains with both decentralised and centralised inventory control. The impact of the possibility of emergency deliveries from the DC to the ward when the inventory on hand at the ward is insufficient to meet all demand has also been analysed. When centralised inventory control and some inventory visibility were considered, only models with this possibility were simulated because of the impressive positive impact on service level obtained with this rule on previous simulations (see subsection 4.5.4).

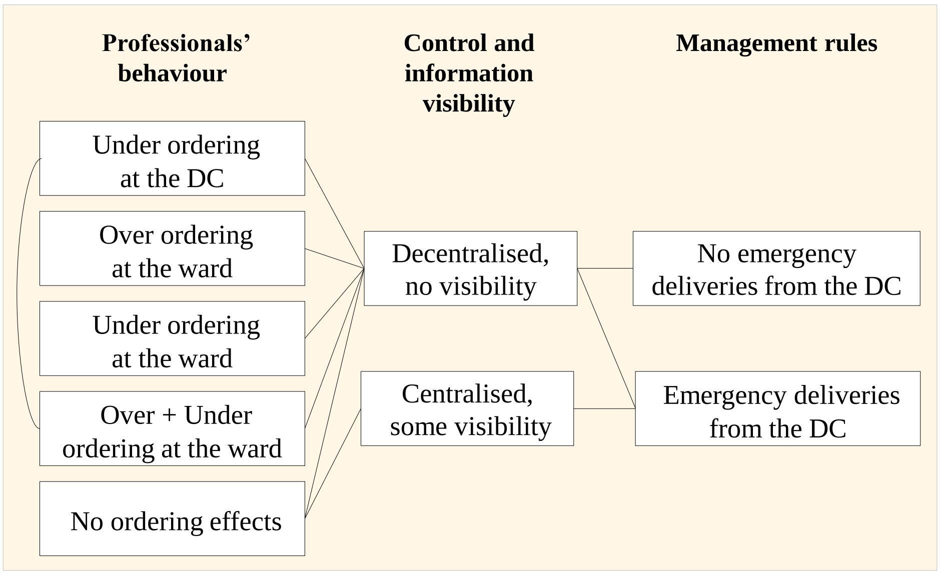


Figure 4.5 Characteristics of simulated the models of a serial supply chains with one DC and one ward

4.5.2 Traditional supply chain with over and/or under-ordering effects at the ward

To analyse the impact of over and under-ordering effects at the ward on the behaviour of simple serial supply chains with one DC and one ward, we compared the results of the following alternative situations, all of them with no ordering effects at the DC:

- Both over and under-ordering effects at the ward (model as described in section 4.3.3);
- Over-ordering (but no under-ordering) effect at the ward;
- Under-ordering (but no over-ordering) effect at the ward;
- No over or under-ordering effects at the ward.

The simulated alternative over and under-ordering effects at the ward are represented in Figure 4.6.

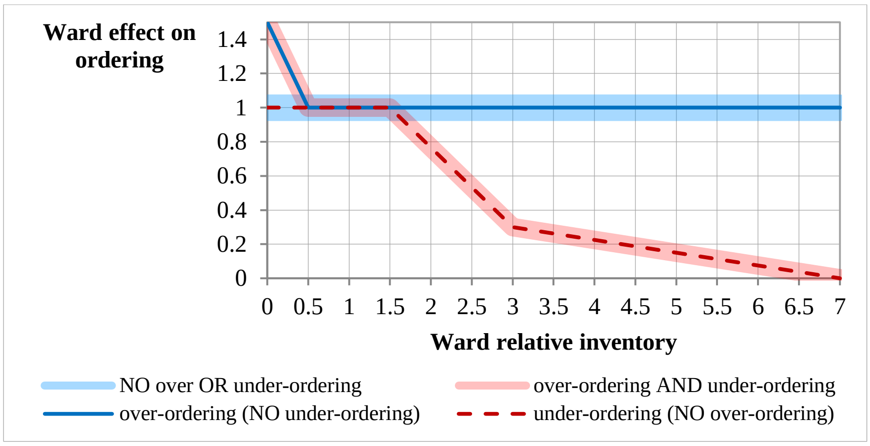


Figure 4.6 Traditional supply chain (SC), one DC, one ward: alternative over and under-ordering effects at the ward

In Table 4.5, we present some descriptive measures comparing the demands faced at the various supply chain echelons resulting from the simulation of the four alternative ward ordering effect with the four generated demands. In Figure 4.7 and Figure 4.8 we present graphical representations of the series corresponding to the demands faced by the various echelons when, respectively, over and under-ordering effects or no ordering effects are considered for generated demand 1 (similar graphs considering only over or under-ordering effects at the ward and for demands 2 to 4 are presented in Appendix 4.10). We can observe that demand variability is amplified at the ward (i.e., the variability[45] of the demand faced by the DC is much higher than the variability of the demand faced by the ward), and this effect is bigger when over-ordering effects at the ward are simulated (jointly, or not, with under-ordering effects at the ward). It can also be observed that the variability of the orders to the supplier is usually lower than the variability of the ward orders to the DC. Moreover, when the models considering over-ordering effects are simulated, the demand levels[46] at the DC and at the supplier are higher and the number of orders placed to the DC or the supplier is lower (i.e., orders are less frequent) – this is very evident in Figure 4.9[47], that compares the orders of the ward to the DC when the system has over-ordering effects at the ward with the system with no ordering effects for generated demand 3 (the most variable generated demand, for which this effect is more easily visible).

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[45] Evaluated using the coefficient of variation.
[46] Evaluated using the daily demand average.
[47] Caution must be taken in the comparison of the graph with the previous two, since their scales are different.

Table 4.5 Traditional SC, one DC, one ward: daily demand faced at the various supply chain echelons for alternative over and under-ordering effects at the ward

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Demand 1	T/ S /N /O+U /N	103.7	144.8	1.40	101.3	162.8	1.61	112.2	81.5	0.73
	T/ S /N /O /N	103.3	157.3	1.52	100.9	159.3	1.58			
	T/ S / N /U /N	99.5	124.8	1.25	98.8	132.2	1.34			
	T/ S /N /N /N	99.4	131.8	1.33	99.1	134.5	1.36			
Demand 2	T/ S /N /O+U /N	102.9	160.7	1.56	101.8	172.5	1.69	110.3	99.2	0.90
	T/ S /N /O /N	102.0	169.1	1.66	100.4	175.5	1.75			
	T/ S / N /U /N	101.5	151.5	1.49	99.2	145.6	1.47			
	T/ S /N /N /N	100.6	148.7	1.48	98.4	146.0	1.48			
Demand 3	T/ S /N /O+U /N	136.7	307.8	2.25	131.2	356.9	2.72	141.8	186.8	1.32
	T/ S /N /O /N	136.4	317.7	2.33	130.3	351.0	2.69			
	T/ S / N /U /N	133.7	246.4	1.84	130.4	270.9	2.08			
	T/ S /N /N /N	131.7	254.1	1.93	129.8	270.4	2.08			
Demand 4	T/ S /N /O+U /N	116.4	228.5	1.96	114.0	230.4	2.02	123.4	131.4	1.06
	T/ S /N /O /N	117.9	246.3	2.09	115.5	231.7	2.01			
	T/ S / N /U /N	111.2	187.2	1.68	110.8	194.3	1.75			
	T/ S /N /N /N	111.3	191.5	1.72	111.0	193.7	1.75			

*Coefficient of variation (CV) = Standard deviation/Average

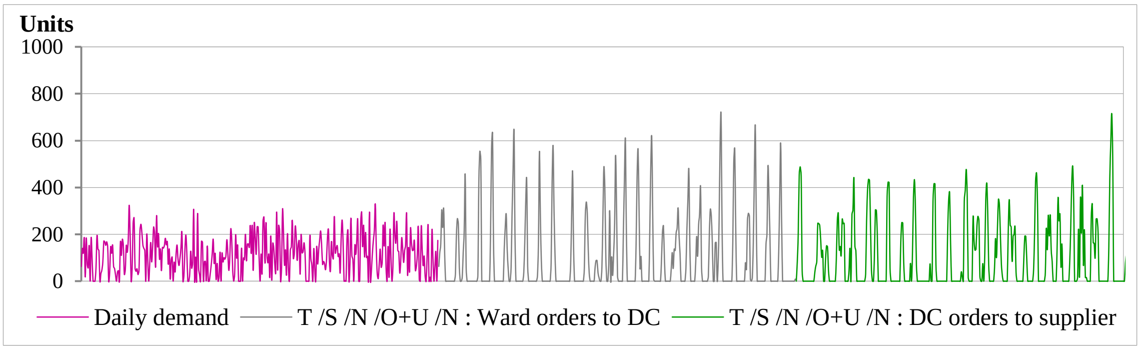

Figure 4.7 Traditional SC, one DC, one ward: demand faced by the ward (*demand 1*), by the DC and by the supplier – over and under-ordering effects at the ward

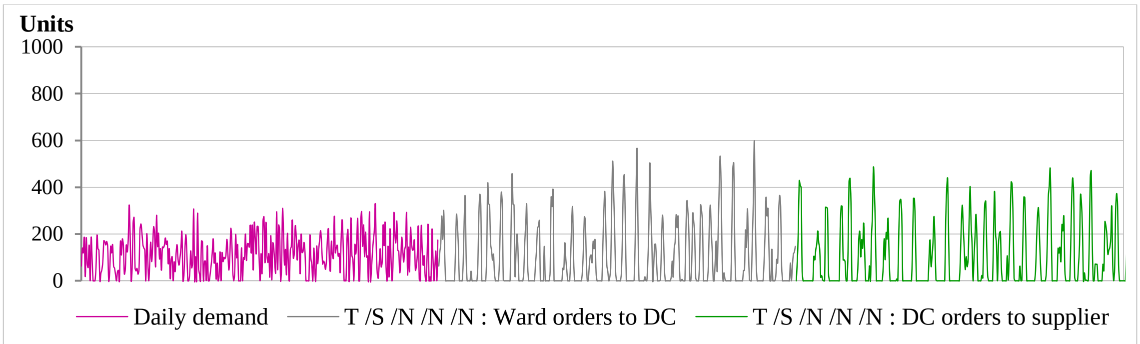

Figure 4.8 Traditional SC, one DC, one ward: demand faced by the ward (*demand 1*), by the DC and by the supplier - no ordering effects at the ward or at the DC

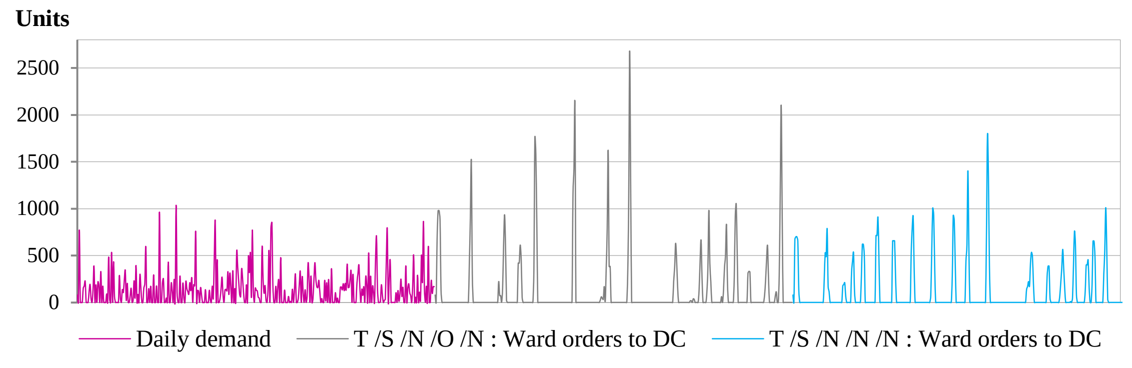

Figure 4.9 Traditional SC, one DC, one ward: demand faced by the ward (*demand 3*) and by the DC – over-ordering at the ward (no ordering effects at the DC) versus no ordering effects

In Table 4.6, we present some descriptive measures comparing the simulation results of the same sixteen alternatives in terms of total inventory in the system and inventory level at the ward and at the DC. The corresponding total inventory in the system is represented graphically in Figure 4.10 for generated demand 1 (similar graphs for generated demands 2 to 4 are presented in Appendix 4.11).

Table 4.6 Traditional SC, one DC, one ward: inventory level(s) and lost demand for alternative over and/or under-ordering effects at the ward

		Inventory level							**Lost demand**		
		At the ward		At the DC		At the whole hospital					
	Model	Average	CV*	Average	CV*	Average	CV*	Difference to lowest	Average (units per day)	% days w/ lost demand	% of lost demand
Demand 1	T /S /N /O+U /N	441.2	0.65	565.3	0.58	1006.6	0.34	27.1%	10.4	14.0%	9.3%
	T /S /N /O /N	453.9	0.68	585.7	0.56	1039.6	0.36	31.2%	10.8	11.8%	9.6%
	T /S /N /U /N	362.2	0.64	429.9	0.54	792.1	0.33	0.0%	13.7	14.8%	12.2%
	T /S /N /N /N	362.3	0.65	453.9	0.59	816.3	0.33	3.0%	13.3	15.9%	11.9%
Demand 2	T /S /N /O+U /N	527.3	0.69	664.1	0.55	1191.4	0.38	17.2%	9.7	9.3%	8.8%
	T /S /N /O /N	533.2	0.66	714.9	0.57	1248.1	0.36	22.8%	9.6	10.4%	8.7%
	T /S /N /U /N	462.3	0.64	554.2	0.59	1016.6	0.37	0.0%	11.1	11.0%	10.1%
	T /S /N /N /N	480.3	0.61	539.6	0.58	1019.9	0.37	0.3%	11.9	11.8%	10.8%
Demand 3	T /S /N /O+U /N	1740.0	0.69	1472.7	0.47	3212.8	0.40	40.3%	16.2	6.0%	11.5%
	T /S /N /O /N	1593.7	0.75	1559.2	0.52	3152.9	0.48	37.6%	18.6	6.3%	13.1%
	T /S /N /U /N	1220.9	0.68	1069.7	0.53	2290.6	0.41	0.0%	15.0	6.8%	10.6%
	T /S /N /N /N	1216.6	0.69	1125.6	0.58	2342.2	0.47	2.3%	15.6	7.1%	11.0%
Demand 4	T /S /N /O+U /N	890.4	0.75	869.2	0.54	1759.6	0.45	17.5%	13.3	7.9%	10.7%
	T /S /N /O /N	923.9	0.75	814.0	0.53	1737.9	0.48	16.1%	11.8	8.2%	9.5%
	T /S /N /U /N	719.6	0.71	777.9	0.55	1497.5	0.40	0.0%	14.9	8.8%	12.1%
	T /S /N /N /N	734.6	0.72	786.4	0.53	1521.0	0.42	1.6%	14.6	9.3%	11.8%

*Coefficient of variation (CV) = Standard deviation/Average

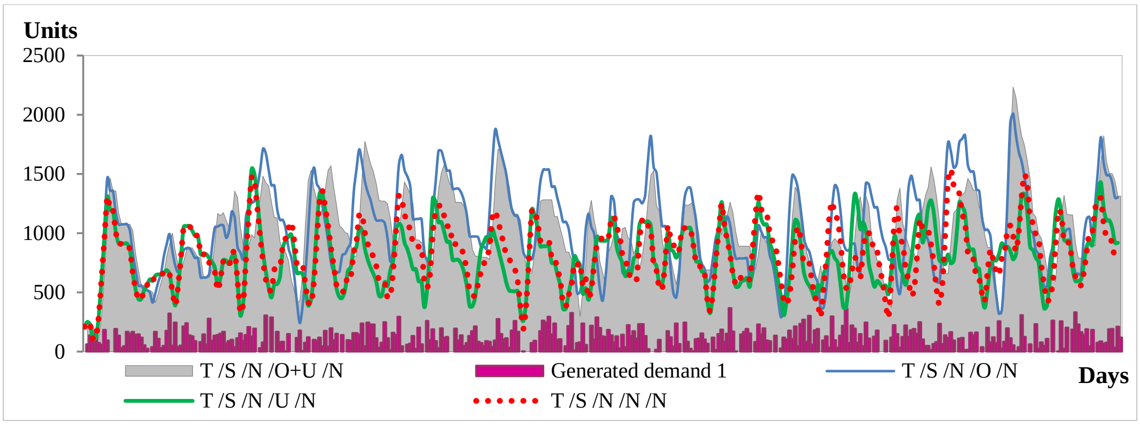

Figure 4.10 Traditional SC, one DC, one ward, *demand 1*: effect of over and/or under-ordering effects at the ward (no ordering effects at the DC) on total inventory level

When more variable daily demands were simulated, higher inventory levels were accumulated in the system, for example:

- demand 3 (the one with the highest variability) resulted in a range of inventory on hand on the whole hospital[48] between 22.5 days (12.3 days in the ward, 11.2 in the DC), when over and under-ordering effects at the ward were simulated, and 16.2 days (8.6 days in the ward, 8.2 in the DC), when only under-ordering effects at the ward were simulated;
- demand 1 (the less variable) resulted in a range of inventory on hand on the whole hospital[48] between 9.3 days (4.1 days in the ward, 5.8 in the DC), when over-ordering effects at the ward are simulate, and 7.1 days (3.2 days in the ward, 4.4 in the DC), when under-ordering effects at the ward are simulated.

The impact of the various alternative effects on the inventory in the system is consistent for the four generated demands. The two models that simulate an over ordering effect when the available inventory is lower than half the desired inventory result in higher average inventory levels, both at the ward and at the DC, and consequently, in the whole system. As a trade-off, in most cases, a better service level (i.e., lower and/or less frequent lost demand) is attained. It is though interesting to observe that, when the generated demands with higher variability (i.e., generated demands 4 and 3) were used to perform the simulations, the over-ordering effect resulted in significantly higher average inventory levels without the corresponding benefit in terms of increased service level. In fact, the system with under-ordering effect at the ward, achieved lower inventory levels with good results in terms of service level at the ward.

To gain more understanding about the impact of the over-ordering effect when the demand variability is higher, we performed some more simulations with the distribution used to

[48] Number of days of inventory on hand in the whole hospital = Total inventory in the hospital/ Final demand (at the ward)

determine generated demand 1, but increasing its standard deviation from 98 units to 200 and 300 units. The resulting daily demands are represented in the graph of Figure 4.11, and some location and dispersion measures describing the various resulting series are presented in Table 4.7.

In Table 4.8, we present some measures comparing the demands faced at the various echelons of the supply chain when the variability of the daily demand increases. The measures calculated from the results in terms of total inventory level are presented in Table 4.9. The results obtained point in the same direction as our previous results: when the variability of the daily demand is higher, the over-ordering effect rises the inventory levels without a corresponding improvement in the service level.

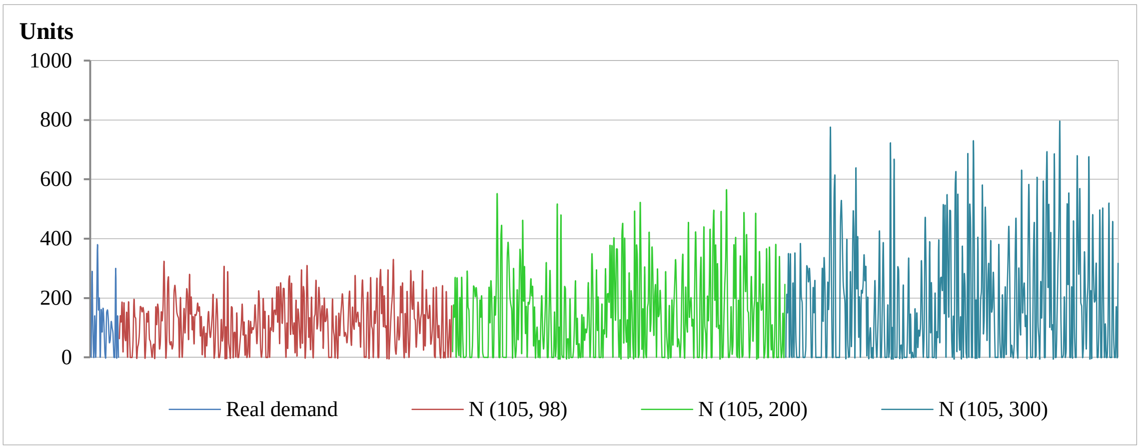

Figure 4.11 Comparison of generated daily demands with different variability

Table 4.7 Measures of location and dispersion describing ward 1 daily demand sample and related alternative generated daily demands using Normal distributions with several standard deviations

	Minimum	1st quartile	Median	3rd quartile	Maximum	Average	Standard deviation
Sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8
N(105, 98)	0.0	45.0	110.0	168.0	329.0	112.2	81.5
N(105, 200)	0.0	0.0	116.0	234.8	563.0	142.0	140.9
N(105, 300)	0.0	0.0	121.0	299.8	793.0	177.2	195.6

Observation: The daily demand averages of the generated demands are higher than the demand mean used to generate the data, and increase with the distribution variability, because the number of generated negative demands increases, situation in which a zero daily demand was considered. For the same reason, the standard deviations of the generated daily demands are lower than the standard deviation considered in the generating processes.

Table 4.8 Traditional SC, one DC, one ward, different daily demand variabilities: daily demand faced at the various supply chain echelons for alternative over and/or under-ordering effects at the ward

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
N(105, 98)	T/ S/ N /O+U /N	103.7	144.8	1.40	101.3	162.8	1.61	112.2	81.5	0.73
	T/ S/ N /O /N	103.3	157.3	1.52	100.9	159.3	1.58			
	T/ S/ N /U /N	99.5	124.8	1.25	98.8	132.2	1.34			
	T/ S/ N /N /N	99.4	131.8	1.33	99.1	134.5	1.36			
N(105, 200)	T/ S/ N /O+U /N	132.4	216.8	1.64	129.6	235.4	1.82	142.0	140.9	0.99
	T/ S/ N /O /N	128.7	215.2	1.67	124.6	248.1	1.99			
	T/ S/ N /U /N	132.3	198.0	1.50	129.6	204.1	1.57			
	T/ S/ N /N /N	130.8	203.8	1.56	129.3	203.5	1.57			
N(105, 300)	T/ S/ N /O+U /N	161.4	281.2	1.74	157.4	317.7	2.02	177.2	195.6	1.10
	T/ S/ N /O /N	167.6	272.9	1.63	163.0	321.0	1.97			
	T/ S/ N /U /N	164.5	275.0	1.67	162.2	255.8	1.58			
	T/ S/ N /N /N	165.7	255.0	1.54	163.7	255.1	1.56			

*Coefficient of variation (CV) = Standard deviation/Average

Table 4.9 Traditional SC, one DC, one ward, different daily demand variabilities: inventory level(s) and lost demand for alternative over and/or under-ordering effects at the ward

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital					
	Model	Average	CV*	Average	CV*	Average	CV*	Difference to lowest	Average (units per day)	% days w/ lost demand	% of lost demand
N(105, 98)	T/ S/ N /O+U /N	441.2	0.65	565.3	0.58	1006.6	0.34	27.1%	10.4	14.0%	9.3%
	T/ S/ N /O /N	453.9	0.68	585.7	0.56	1039.6	0.36	31.2%	10.8	11.8%	9.6%
	T/ S/ N /U /N	362.2	0.64	429.9	0.54	792.1	0.33	0.0%	13.7	14.8%	12.2%
	T/ S/ N /N /N	362.3	0.65	453.9	0.59	816.3	0.33	3.0%	13.3	15.9%	11.9%
N(105, 200)	T/ S/ N /O+U /N	761.4	0.71	841.9	0.50	1603.3	0.39	23.0%	13.7	9.3%	9.7%
	T/ S/ N /O /N	812.3	0.68	911.0	0.49	1723.3	0.37	32.2%	17.5	11.5%	12.3%
	T/ S/ N /U /N	641.9	0.67	661.4	0.54	1303.3	0.38	0.0%	13.8	11.5%	9.7%
	T/ S/ N /N /N	632.0	0.67	675.0	0.55	1307.0	0.39	0.3%	13.5	10.7%	9.5%
N(105, 300)	T/ S/ N /O+U /N	1056.3	0.71	1120.4	0.46	2176.7	0.37	28.5%	19.5	9.6%	11.0%
	T/ S/ N /O /N	1086.6	0.66	1231.1	0.50	2317.7	0.35	36.8%	15.1	8.8%	8.5%
	T/ S/ N /U /N	896.5	0.72	841.8	0.51	1738.3	0.43	2.6%	16.7	9.0%	9.4%
	T/ S/ N /N /N	887.2	0.71	807.1	0.49	1694.3	0.42	0.0%	15.2	9.0%	8.6%

*Coefficient of variation (CV) = Standard deviation/Average

4.5.3 Traditional supply chain with under-ordering effects at the DC

Assuming that, at the DC, tasks related to inventory are performed in a more professional (and thus, less reactive) manner, we have only considered the possibility of under-ordering effects at the DC. Thus, we compare the results of the model for the following alternative situations:

- Both over and under-ordering effects at the ward, no ordering effects at the DC (model described in section 4.3.3);
- Both over and under-ordering effects at the ward, under-ordering effects at the DC;
- No over or under-ordering effects at the ward, under-ordering effect at the DC;
- No over or under-ordering effects at the ward or at the DC.

The considered alternative over and under-ordering effects at the ward were represented in Figure 4.6 in the previous section; the alternative ordering effects simulated for the DC are represented in Figure 4.12.

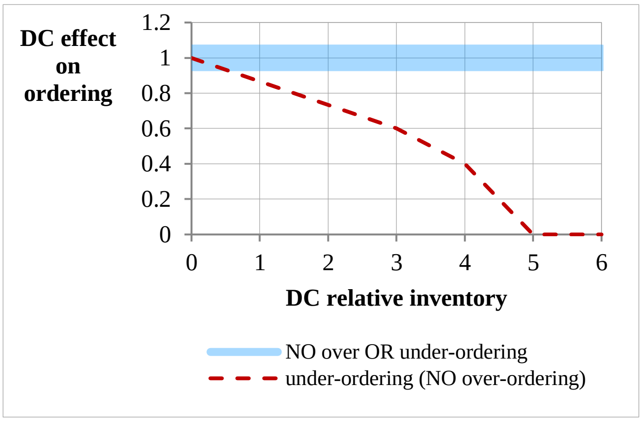

Figure 4.12 Traditional SC, one DC, one ward: simulated alternative ordering effects at the DC

In Table 4.10 and Table 4.11, we present some descriptive measures comparing the results of the simulations with or without under-ordering effects at the DC for the four alternative generated demands in terms of demand amplification in the supply chain and inventory levels, respectively. Additionally, in Figure 4.13 and Figure 4.14, we present graphical representations of the demand faced at the various supply chain echelons for generated demand 1 when under-ordering effects at the DC are simulated (similar graphs for generated demands 2 to 4 are presented in Appendix 4.12).

Table 4.10 Traditional SC, one DC, one ward: comparison of the daily demand faced at the various supply chain echelons for no or under-ordering effects at the DC

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Demand 1	T /S /N /O+U /N	103.7	144.8	1.40	101.3	162.8	1.61	112.2	81.5	0.73
	T /S /N /O+U /U	103.7	154.0	1.49	101.3	164.6	1.62			
	T /S /N / N /U	100.1	134.0	1.34	99.7	131.3	1.32			
	T /S /N /N /N	99.4	131.8	1.33	99.1	134.5	1.36			
Demand 2	T /S /N /O+U /N	102.9	160.7	1.56	101.8	172.5	1.69	110.3	99.2	0.90
	T /S /N /O+U /U	100.8	165.3	1.64	102.1	181.0	1.77			
	T /S /N / N /U	101.8	145.7	1.43	99.5	146.1	1.47			
	T /S /N /N /N	100.6	148.7	1.48	98.4	146.0	1.48			
Demand 3	T /S /N /O+U /N	136.7	307.8	2.25	131.2	356.9	2.72	141.8	186.8	1.32
	T /S /N /O+U /U	138.9	291.6	2.10	133.8	344.0	2.57			
	T /S /N / N /U	131.8	250.3	1.90	129.8	271.1	2.09			
	T /S /N /N /N	131.7	254.1	1.93	129.8	270.4	2.08			
Demand 4	T /S /N /O+U /N	116.4	228.5	1.96	114.0	230.4	2.02	123.4	131.4	1.06
	T /S /N /O+U /U	113.4	233.7	2.06	112.5	232.3	2.06			
	T /S /N / N /U	111.3	192.8	1.73	111.3	193.7	1.74			
	T /S /N /N /N	111.3	191.5	1.72	111.0	193.7	1.75			

*Coefficient of variation (CV) = Standard deviation/Average

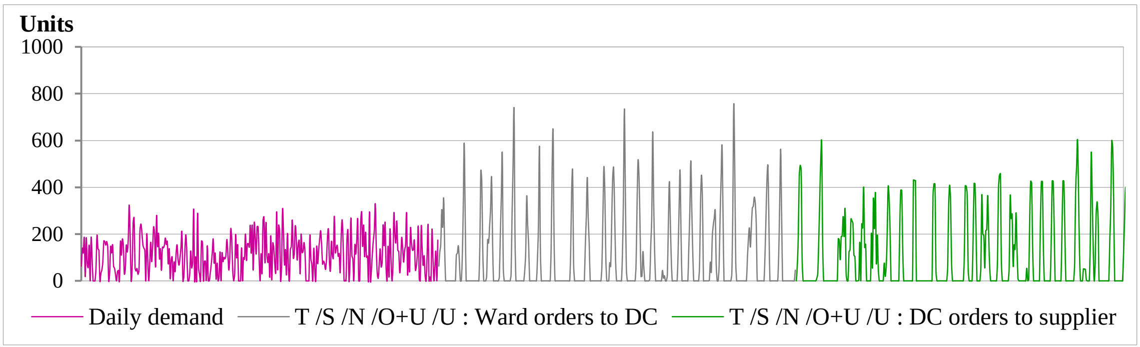

Figure 4.13 Traditional SC, one DC, one ward, *demand 1*: demand faced at the various supply chain echelons - over and under-ordering effects at the ward and under-ordering effect at the DC

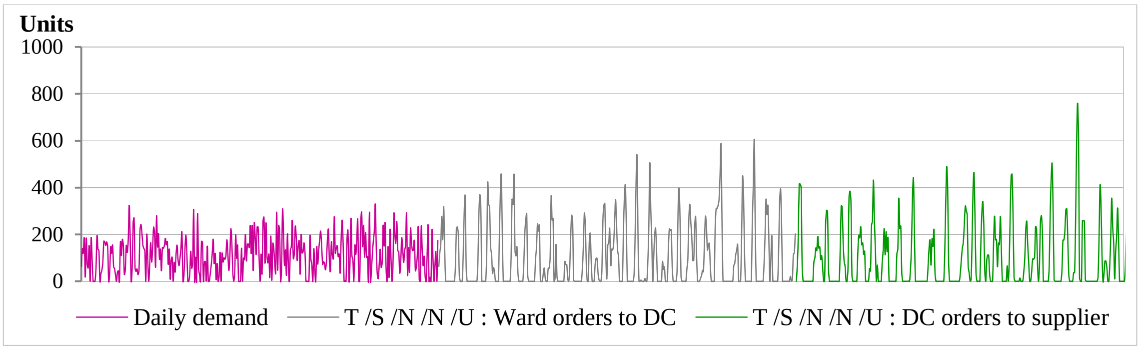

Figure 4.14 Traditional SC, one DC, one ward, *demand 1*: demand faced at the various supply chain echelons - no ordering effects at the ward and under-ordering effect at the DC

Although, when the final daily demands have less variability (i.e., demands 1, 2 and 4), the under-ordering effect seems to decrease the variability of the orders placed by the ward and by the DC, and, when the final demand variability is higher (i.e., demand 3), it seems to increase it, the results are not very conclusive and the observed impacts are not very expressive.

Table 4.11 Traditional SC, one DC, one ward: inventory level(s) and lost demand for no or under-ordering effect at the DC

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital					
	Model	Average	CV*	Average	CV*	Average	CV*	Difference to lowest	Average (units per day)	% days w/ lost demand	% of lost demand
Demand 1	T /S /N /O+U /N	441.2	0.65	565.3	0.58	1006.6	0.34	24.7%	10.4	14.0%	9.3%
	T /S /N /O+U /U	464.9	0.64	577.4	0.62	1042.3	0.34	29.1%	10.4	13.4%	9.2%
	T /S /N /N /U	379.5	0.73	428.0	0.55	807.5	0.39	0.0%	12.8	16.2%	11.4%
	T /S /N /N /N	362.3	0.65	453.9	0.59	816.3	0.33	1.1%	13.3	15.9%	11.9%
Demand 2	T /S /N /O+U /N	527.3	0.69	664.1	0.55	1191.4	0.38	21.3%	9.7	9.3%	8.8%
	T /S /N /O+U /U	507.4	0.63	653.8	0.52	1161.3	0.34	18.2%	10.7	11.0%	9.7%
	T /S /N / N /U	469.4	0.63	513.0	0.57	982.4	0.37	0.0%	10.9	11.0%	9.8%
	T /S /N /N /N	480.3	0.61	539.6	0.58	1019.9	0.37	3.8%	11.9	11.8%	10.8%
Demand 3	T /S /N /O+U /N	1740.0	0.69	1472.7	0.47	3212.8	0.40	41.9%	16.2	6.0%	11.5%
	T /S /N /O+U /U	1548.7	0.72	1420.1	0.49	2968.8	0.42	31.1%	14.1	6.0%	9.9%
	T /S /N / N /U	1209.4	0.68	1055.5	0.57	2264.9	0.47	0.0%	15.6	7.1%	11.0%
	T /S /N /N /N	1216.6	0.69	1125.6	0.58	2342.2	0.47	3.4%	15.6	7.1%	11.0%
Demand 4	T /S /N /O+U /N	890.4	0.75	869.2	0.54	1759.6	0.45	19.9%	13.3	7.9%	10.7%
	T /S /N /O+U /U	887.9	0.77	926.5	0.53	1814.4	0.47	23.6%	12.2	8.2%	9.9%
	T /S /N / N /U	726.3	0.75	741.7	0.52	1468.1	0.43	0.0%	14.2	8.8%	11.5%
	T /S /N /N /N	734.6	0.72	786.4	0.53	1521.0	0.42	3.6%	14.6	9.3%	11.8%

*Coefficient of variation (CV) = Standard deviation/Average

The level of total inventory in the system for the simulated alternative combinations of no or under-ordering effects at the DC with generated demand 1 are presented in Figure 4.15 (similar graphs for generated demands 2 to 4 are presented in Appendix 4.13).

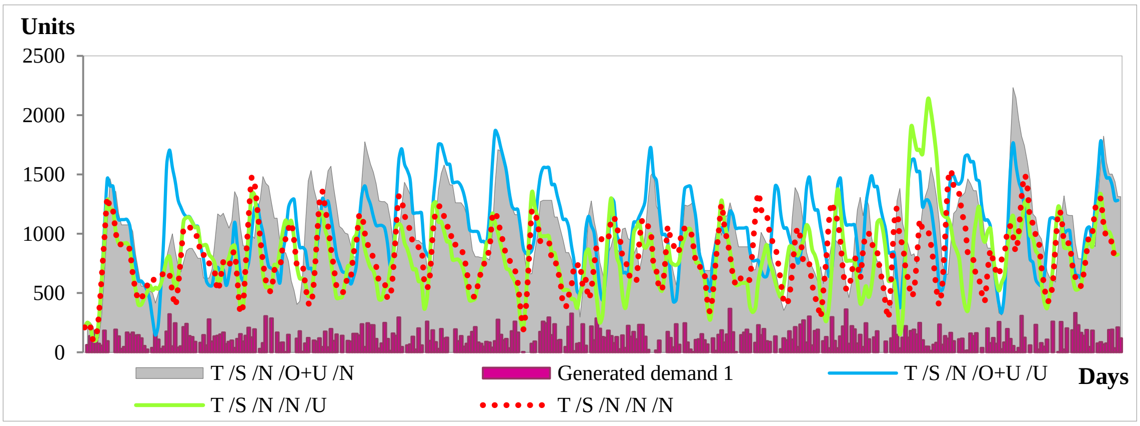

Figure 4.15 Traditional SC, one DC, one ward, *demand 1*: effect of under-ordering effects at the DC on total inventory level

We can observe that the model that resulted in the lower total inventory level was the one with no ordering effects at the ward and under-ordering effects at the DC. However, the difference relatively to the model with no ordering effects at the ward or at the DC was not impressive. In terms of service level, the system with under-ordering effects at the DC (and no ordering effects at the wards) was slightly better than the one with no ordering effects.

When there are over and under-ordering effects at the ward, the effect of the existence of under-ordering effects at the DC has been mixed (in some cases, it resulted in a rise in the total inventory level, in others, in a lower total inventory level). For demand 3 (the generated demand with the highest variability), the existence of an under-ordering effect at the DC seems to have a positive impact counter-balancing the negative impacts of ward effects, both in terms of increasing the inventory levels and of the occurrence of lost demand. To gain more understanding of the effect of the under-ordering effect at the DC when the daily demand variability is relatively high, we performed simulations with the distribution used to determine generated demand 1, but increasing its standard deviation from 98 units to 200 and 300 units (more details about the resulting daily demands can be seen in subsection 4.5.1). The obtained results (see Table 4.12 and Table 4.13) are somehow consistent with the previous results:

- in terms of demand, the obtained results are not conclusive: when the final daily demand variability is higher, the level of the ward orders to the DC is lower in the systems with under-ordering effects at the DC;
- in terms of the inventory levels,
  - when no ordering effects at the ward are simulated, the under-ordering effects at the DC sometimes result in a lower total inventory level, but the obtained difference is not very significant, and, when demand variability is higher, the impact on lost sales is negative,
  - when ordering effects at the ward are simulated, the same positive counter-effect on total inventory level was observed when the final daily demand variability increased; when the demand variability was higher, there was also a positive impact on service level at the ward.

Summarising, the only conclusion we can take from the various simulations is that, when demand variability is high, the under-ordering effects at the DC seem to partially compensate the negative effects of having ordering effects at the wards on the system’s inventory.

Table 4.12 Traditional SC, one DC, one ward: daily demand faced at the various supply chain echelons for alternative over and/or under-ordering effects at the DC and different daily demand variability

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
N(105, 98)	T /S /N /O+U /N	103.7	144.8	1.40	101.3	162.8	1.61	112.2	81.5	0.73
	T /S /N /O+U /U	103.7	154.0	1.49	101.3	164.6	1.62			
	T /S /N / N /U	100.1	134.0	1.34	99.7	131.3	1.32			
	T /S /N /N /N	99.4	131.8	1.33	99.1	134.5	1.36			
N(105, 200)	T /S /N /O+U /N	132.4	216.8	1.64	129.6	235.4	1.82	142.0	140.9	0.99
	T /S /N /O+U /U	131.3	210.3	1.60	127.4	240.6	1.89			
	T /S /N / N /U	130.1	182.8	1.40	128.5	200.5	1.56			
	T /S /N /N /N	130.8	203.8	1.56	129.3	203.5	1.57			
N(105, 300)	T /S /N /O+U /N	161.4	281.2	1.74	157.4	317.7	2.02	177.2	195.6	1.10
	T /S /N /O+U /U	163.9	256.7	1.57	158.5	325.7	2.05			
	T /S /N / N /U	163.4	263.0	1.61	159.2	268.0	1.68			
	T /S /N /N /N	165.7	255.0	1.54	163.7	255.1	1.56			

*Coefficient of variation (CV) = Standard deviation/Average

Table 4.13 Traditional SC, one DC, one ward: comparison of inventory level(s) and lost demand for alternative over and/or under-ordering effects at the DC and different daily demand variability

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital					
	Model	Average	CV*	Average	CV*	Average	CV*	Difference to lowest	Average (units per day)	% days w/ lost demand	% of lost demand
N(105, 98)	T /S /N /O+U /N	441.2	0.65	565.3	0.58	1006.6	0.34	27.1%	10.4	14.0%	9.3%
	T /S /N /O+U /U	464.9	0.64	577.4	0.62	1042.3	0.34	29.1%	10.4	13.4%	9.2%
	T /S /N / N /U	379.5	0.73	428.0	0.55	807.5	0.39	0.0%	12.8	16.2%	11.4%
	T /S /N /N /N	362.3	0.65	453.9	0.59	816.3	0.33	3.0%	13.3	15.9%	11.9%
N(105, 200)	T /S /N /O+U /N	761.4	0.71	841.9	0.50	1603.3	0.39	26.0%	13.7	9.3%	9.7%
	T /S /N /O+U /U	722.4	0.67	863.1	0.54	1585.5	0.35	24.6%	14.4	11.2%	10.1%
	T /S /N / N /U	627.9	0.66	644.3	0.56	1272.1	0.36	0.0%	14.2	10.7%	10.0%
	T /S /N /N /N	632.0	0.67	675.0	0.55	1307.0	0.39	2.7%	13.5	10.7%	9.5%
N(105, 300)	T /S /N /O+U /N	1056.3	0.71	1120.4	0.46	2176.7	0.37	28.5%	19.5	9.6%	11.0%
	T /S /N /O+U /U	1010.1	0.67	1022.5	0.55	2032.6	0.37	20.0%	18.5	9.9%	10.4%
	T /S /N / N /U	917.8	0.67	842.8	0.50	1760.5	0.39	3.9%	19.8	9.9%	11.2%
	T /S /N /N /N	887.2	0.71	807.1	0.49	1694.3	0.42	0.0%	15.2	9.0%	8.6%

*Coefficient of variation (CV) = Standard deviation/Average

4.5.4 Traditional supply chain with direct emergency deliveries from the DC

We have also compared the results of the simulation of the model without emergency deliveries with the same model with the possibility of emergency deliveries from the DC to the place of consumption, if the inventory at the ward is not enough to fulfil all demand, for the four generated demands (the two models are described in section 4.3.3). We present some descriptive measures of the results of the simulation concerning the demand faced at each supply chain echelon in Table 4.14. Figure 4.16 and Figure 4.17 present graphical representations of the series of the demand faced by the ward (demand 1), the DC and the supplier when the systems with the possibility of emergency deliveries from the DC and without this possibility are considered (similar graphs with the possibility of emergency deliveries from the DC for demands 2 to 4 are presented in Appendix 4.14).

Table 4.14 Traditional SC, one DC, one ward: comparison of the daily demand faced at the various supply chain echelons without or with emergency deliveries from the DC

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Demand 1	T /S /N /O+U /N	103.7	144.8	1.40	101.3	162.8	1.61	112.2	81.5	0.73
	T /S /P /O+U /N	111.7	173.7	1.55	101.0	158.9	1.57			
	T /S /N /N /N	99.4	131.8	1.33	99.1	134.5	1.36			
	T /S /P /N /N	110.7	148.0	1.34	100.3	128.0	1.28			
Demand 2	T /S /N /O+U /N	102.9	160.7	1.56	101.8	172.5	1.69	110.3	99.2	0.90
	T /S /P /O+U /N	111.5	181.0	1.62	102.4	183.0	1.79			
	T /S /N /N /N	100.6	148.7	1.48	98.4	146.0	1.48			
	T /S /P /N /N	110.1	168.8	1.53	99.9	142.1	1.42			
Demand 3	T /S /N /O+U /N	136.7	307.8	2.25	131.2	356.9	2.72	141.8	186.8	1.32
	T /S /P /O+U /N	148.6	326.9	2.20	135.6	334.2	2.47			
	T /S /N /N /N	131.7	254.1	1.93	129.8	270.4	2.08			
	T /S /P /N /N	150.7	273.3	1.81	130.1	274.2	2.11			
Demand 4	T /S /N /O+U /N	116.4	228.5	1.96	114.0	230.4	2.02	123.4	131.4	1.06
	T /S /P /O+U /N	123.1	298.8	2.43	112.9	258.5	2.29			
	T /S /N /N /N	111.3	191.5	1.72	111.0	193.7	1.75			
	T /S /P /N /N	124.3	225.8	1.82	112.6	201.4	1.79			

*Coefficient of variation (CV) = Standard deviation/Average

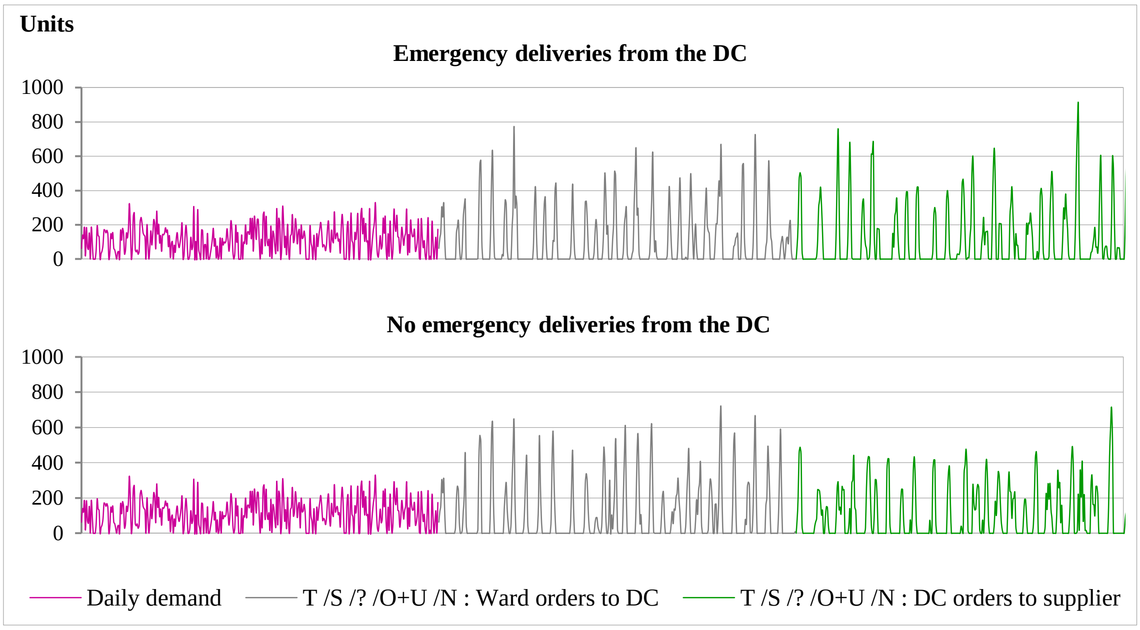

Figure 4.16 Traditional SC, one DC, one ward, over and under-ordering effects at the ward (no ordering effects at the DC): demand faced by the ward (*demand 1*), by the DC and by the supplier – system with emergency deliveries from the DC versus system with no emergency deliveries

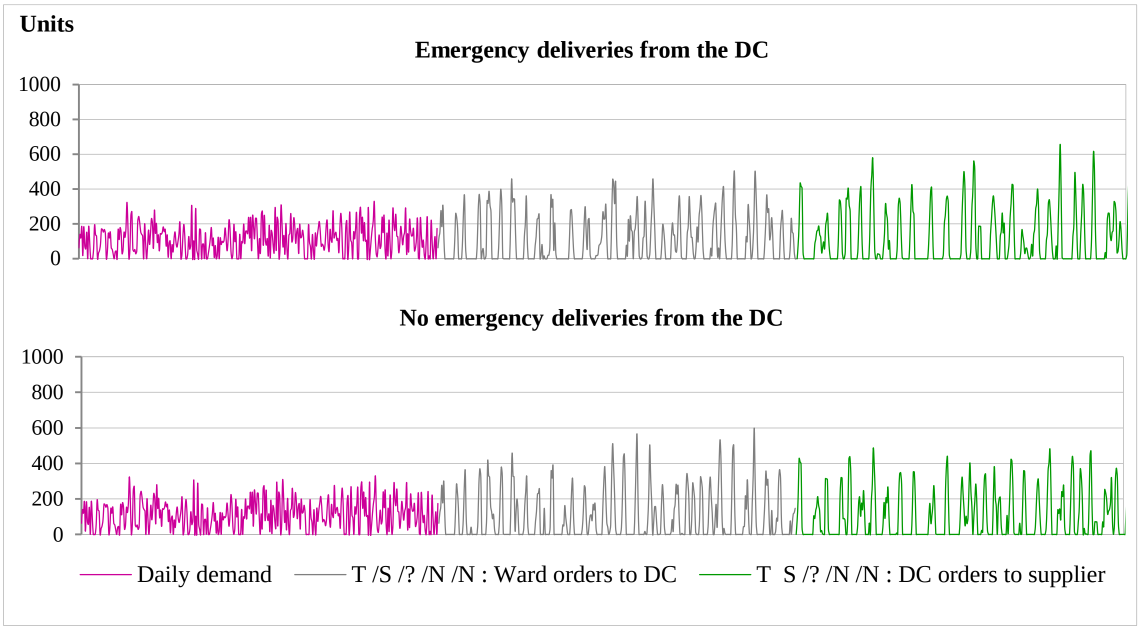

Figure 4.17 Traditional SC, one DC, one ward, no over ordering effects: demand faced by the ward (*demand 1*), by the DC and by the supplier – system with emergency deliveries from the DC versus system with no emergency deliveries

As can be observed in the graphs, the level and the variability of the demand faced by the supplier increased with the possibility of emergency deliveries from the DC.

Descriptive measures calculated from the supply chain inventory levels resulting from the simulations are presented in Table 4.15. We present graphs representing the accumulated differences[49] between the inventory levels in the two systems under analysis, i.e., between the system with the possibility of emergency deliveries from the DC and a similar system without such possibility, considering over and under-ordering effects at the wards (Figure 4.18) and without ordering effects (Figure 4.19), for demand 1. Similar graphs for demand 2 and demand 4 and graphs representing the inventory levels evolution at the ward and at the DC for all generated demands can be seen in Appendix 4.15.

Table 4.15 Traditional SC, one DC, one ward: comparison of inventory level(s) and lost demand without or with emergency deliveries

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital			Average (units per day)	% days w/ lost demand	% of lost demand
	Model	Average	CV*	Average	CV*	Average	CV*	Difference to lowest			
Demand 1	T/ S /N /O+U /N	441.2	0.65	565.3	0.58	1006.6	0.34	29.6%	10.4	14.0%	9.3%
	T/ S /P /O+U /N	462.7	0.75	495.1	0.52	957.8	0.42	23.3%	1.8	2.7%	1.6%
	T/ S /N /N /N	362.3	0.65	453.9	0.59	816.3	0.33	5.1%	13.3	15.9%	11.9%
	T/ S /P /N /N	381.6	0.72	394.9	0.40	776.5	0.41	0.0%	2.5	4.7%	2.2%
Demand 2	T/ S /N /O+U /N	527.3	0.69	664.1	0.55	1191.4	0.38	23.6%	9.7	9.3%	8.8%
	T/ S /P /O+U /N	606.5	0.68	636.2	0.52	1242.7	0.42	28.9%	0.1	0.3%	0.0%
	T/ S /N /N /N	480.3	0.61	539.6	0.58	1019.9	0.37	5.8%	11.9	11.8%	10.8%
	T/ S /P /N /N	483.1	0.72	481.2	0.51	964.3	0.46	0.0%	1.9	3.3%	1.7%
Demand 3	T/ S /N /O+U /N	1740.0	0.69	1472.7	0.47	3212.8	0.40	37.2%	16.2	6.0%	11.5%
	T/ S /P /O+U /N	1563.3	0.75	1454.4	0.52	3017.7	0.49	28.8%	2.5	0.8%	1.8%
	T/ S /N /N /N	1216.6	0.69	1125.6	0.58	2342.2	0.47	0.0%	15.6	7.1%	11.0%
	T/ S /P /N /N	1322.9	0.73	1111.5	0.57	2434.5	0.50	3.9%	1.2	0.3%	0.9%
Demand 4	T/ S /N /O+U /N	890.4	0.75	869.2	0.54	1759.6	0.45	15.7%	13.3	7.9%	10.7%
	T/ S /P /O+U /N	1155.8	0.79	1038.9	0.55	2194.7	0.53	44.3%	2.7	2.5%	2.2%
	T/ S /N /N /N	734.6	0.72	786.4	0.53	1521.0	0.42	0.0%	14.6	9.3%	11.8%
	T/ S /P /N /N	790.7	0.81	758.5	0.51	1549.1	0.48	1.8%	2.3	2.2%	1.8%

*Coefficient of variation (CV) = Standard deviation/Average

As expected, the possibility of emergency deliveries from the DC improved the service level (i.e., decreased the level and the frequency of the lost demand occurrences) considerably. In general, with the introduction of emergency deliveries, the average inventory at the DC decreased and the average inventory at the ward increased, being the impact on total inventory uncertain. This is easily visible in the graphs presented in Figure 4.18, Figure 4.19. In the graphs, if a line is below the horizontal axis, the inventory of the system under analysis (with the possibility of emergency deliveries from the DC) resulted in lower inventory levels since the beginning of the simulation than the system with which it is being compared to (i.e., without the possibility of emergency deliveries); if the line is above the horizontal axis, the system under

[49] Positive differences are added (therefore, the curve goes up) in the periods when the inventory of the system with the possibility of emergency deliveries from DC is higher than the inventory of the system without that possibility

analysis has resulted in higher inventory levels. When *demand 3* and *demand 4* with over and under-ordering effects at the ward and no ordering effects at the DC were simulated, the behaviour was different: with *demand 3* the inventory levels both at the ward and at the DC were lower with emergency deliveries; with *demand 4* the opposite results were obtained. Finally, with the introduction of emergency deliveries from the DC, the variability of the inventory level at the ward increased.

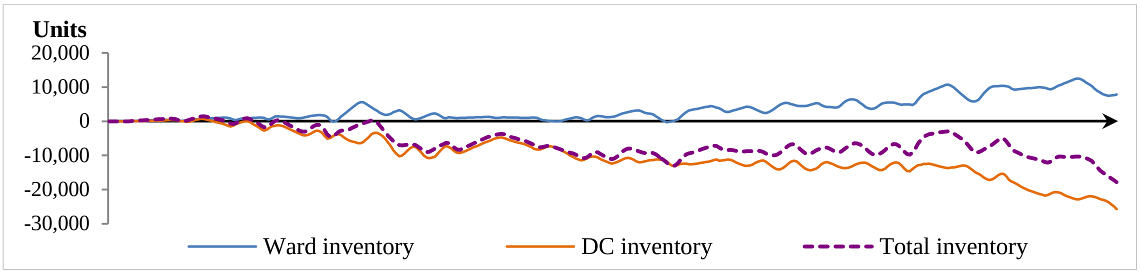

Figure 4.18 Traditional SC, one DC, one ward, *demand 1*, over and under-ordering effects at the ward (no ordering effects at the DC): Accumulated differences between the inventory levels in the system with the possibility of emergency deliveries from the DC and without such possibility

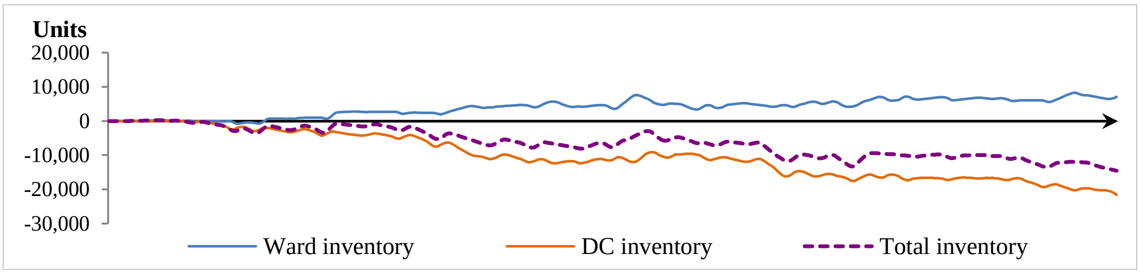

Figure 4.19 Traditional SC, one DC, one ward, *demand 1*, no ordering effects: Accumulated differences between the inventory levels in the system with the possibility of emergency deliveries from the DC and without that possibility

4.5.5 Centralised inventory control and inventory visibility

Table 4.16 presents some measures comparing the demand at the various supply chain echelons of the supply chain models with centralised inventory control and inventory visibility throughout the entire supply chain and with traditional supply chain management. In Figure 4.20, we present the corresponding graphs when the daily demand simulated was generated demand 1 (similar graphs for the centralised system with the other generated demands are available in Appendix 4.16). We can observe that, in conformity of what has been described in previous literature (e.g., Eppen 1979, Berman et al. 2011), the demand amplification effect was lower in the models simulating a supply chain with centralised inventory control and inventory visibility (as, for example, can be confirmed by the comparison of the coefficient of variation of the C/ S/ P /N /N models with the other two models for the four simulated daily demands). In accordance, we can observe in Figure 4.20 that the demand level and variability at the various echelons were much lower when the model with centralised inventory control was simulated (consistent results were observed when the other generated daily demands were used in the models, as can be seen in Appendix 4.16).

Table 4.16 Traditional SC, one DC, one ward: comparison of the daily demand faced at the various supply chain echelons – centralised versus decentralised inventory control

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Demand 1	T/ S/ P /O+U /N	111.7	173.7	1.55	101.0	158.9	1.57	112.2	81.5	0.73
	T/ S/ P /N /N	110.7	148.0	1.34	100.3	128.0	1.28			
	C/ S/ P /N /N	112.7	107.3	0.95	112.2	81.5	0.73			
Demand 2	T/ S/ P /O+U /N	111.5	181.0	1.62	102.4	183.0	1.79	110.3	99.2	0.90
	T/ S/ P /N /N	110.1	168.8	1.53	99.9	142.1	1.42			
	C/ S/ P /N /N	111.6	132.4	1.19	110.3	99.2	0.90			
Demand 3	T/ S/ P /O+U /N	148.6	326.9	2.20	135.6	334.2	2.47	141.8	186.8	1.32
	T/ S/ P /N /N	150.7	273.3	1.81	130.1	274.2	2.11			
	C/ S/ P /N /N	144.5	215.9	1.49	141.8	186.8	1.32			
Demand 4	T/ S/ P /O+U /N	123.1	298.8	2.43	112.9	258.5	2.29	123.4	131.4	1.06
	T/ S/ P /N /N	124.3	225.8	1.82	112.6	201.4	1.79			
	C/ S/ P /N /N	126.5	158.1	1.25	123.4	131.4	1.06			

*Coefficient of variation (CV) = Standard deviation/Average

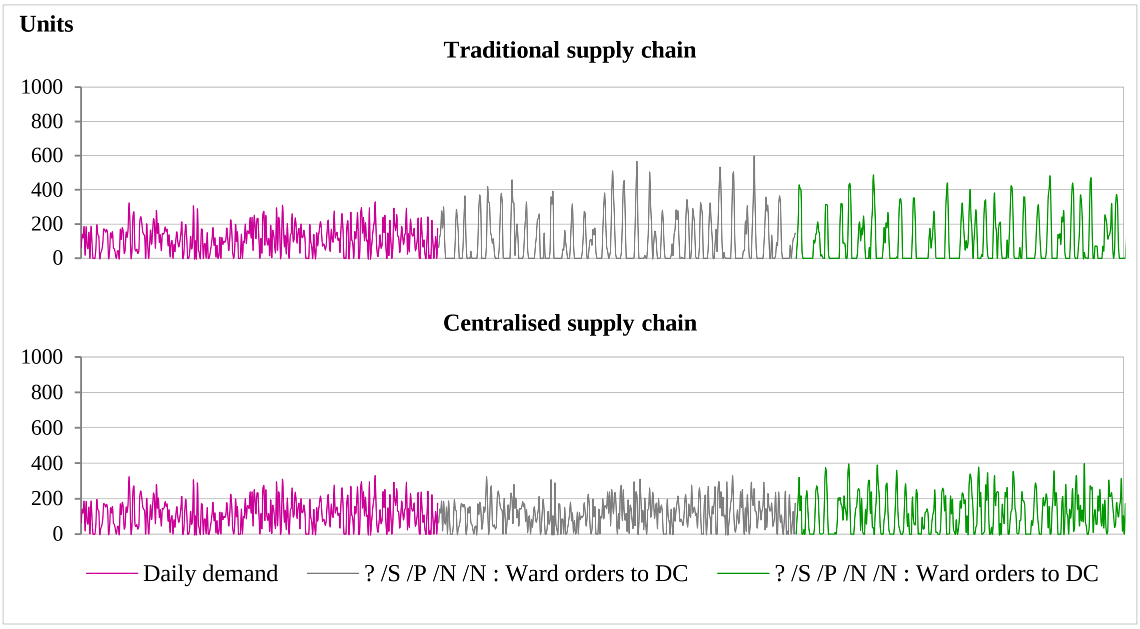

Figure 4.20 SC with one DC and one ward, with centralised inventory control and inventory visibility: demand faced by the ward and by the DC (both equal to *demand 1*) and by the supplier (with emergency deliveries from the DC and no ordering effects)

Table 4.17 contains measures concerning the inventory levels at the various echelons.

Table 4.17 Traditional SC, one DC, one ward: comparison of inventory level(s) and lost demand – centralised versus decentralised inventory control

		Inventory level							**Lost demand**		
		At the ward		At the DC		At the whole hospital			Average (units per day)	% days w/ lost demand	% of lost demand
	Model	Average	CV*	Average	CV*	Average	CV*	Difference to lowest			
Demand 1	T/ S /P /O+U /N	462.7	0.75	495.1	0.52	957.8	0.42	31.7%	1.8	2.7%	1.6%
	T/ S /P /N /N	381.6	0.72	394.9	0.40	776.5	0.41	6.8%	2.5	4.7%	2.2%
	C/ S /P /N /N	442.0	0.31	285.2	0.45	727.1	0.28	0.0%	0.7	1.1%	0.6%
Demand 2	T/ S /P /O+U /N	606.5	0.68	636.2	0.52	1242.7	0.42	28.9%	0.2	0.3%	0.0%
	T/ S /P /N /N	483.1	0.72	481.2	0.51	964.3	0.46	0.0%	1.9	3.3%	1.7%
	C/ S /P /N /N	688.8	0.27	358.5	0.47	1047.2	0.25	8.6%	0.9	0.5%	0.8%
Demand 3	T/ S /P /O+U /N	1563.3	0.75	1454.4	0.52	3017.7	0.49	72.1%	2.5	0.8%	1.8%
	T/ S /P /N /N	1322.9	0.73	1111.5	0.57	2434.5	0.50	38.9%	1.2	0.3%	0.9%
	C/ S /P /N /N	1131.9	0.42	621.4	0.49	1753.3	0.32	0.0%	2.2	1.1%	1.5%
Demand 4	T/ S /P /O+U /N	1155.8	0.79	1038.9	0.55	2194.7	0.53	60.5%	2.7	2.5%	2.2%
	T/ S /P /N /N	790.7	0.81	758.5	0.51	1549.1	0.48	13.3%	2.3	2.2%	1.8%
	C/ S /P /N /N	920.8	0.29	446.2	0.43	1367.0	0.25	0.0%	1.5	1.6%	1.2%

*Coefficient of variation (CV) = Standard deviation/Average

In Figure 4.21, we present a graph of the accumulated differences between the inventory levels in the various echelons for the centralised and the traditional systems (similar graphs for the other generated demands are available in Appendix 4.17). We can see that overall inventory level is lower in the centralised system, since the final accumulated differences are negative. Similar results were obtained when generated demands 3 and 4 were simulated. For generated demand 2, the rise on the inventory level at the ward that resulted from the centralised system was bigger than the fall of the inventory level at the DC. For generated demand 3 (the one with the higher variability), the inventory levels were lower both at the ward and at the DC. However, this had a negative impact on the service level, since this was the only generated demand relatively to which the service level obtained was worse than that of the traditional supply chain with no ordering effects.

For generated demands 1, 2 and 4, the service level obtained with the centralised supply chain was better than the one obtained with the traditional supply chain with no ordering effects, and for generated demands 1, 3 and 4 it was better than the one obtained with the traditional supply chain with no over and under-ordering effects at the ward.

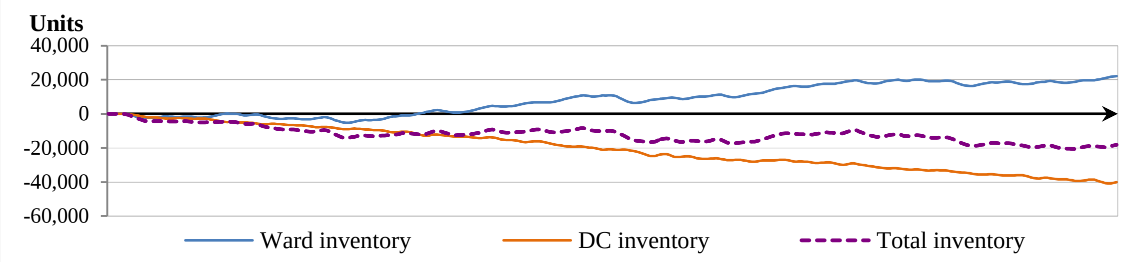

Figure 4.21 SC, one DC, one ward, *demand 1*, no ordering effects: Accumulated differences between the inventory levels in the centralised system and in the traditional system

The evolution of the inventory level in the supply chain, in the ward and in the DC when generated daily demand 1 was simulated is presented in Figure 4.22, Figure 4.23 and Figure 4.24, respectively (similar graphs for the other generated demands are available in Appendix 4.17). Observing these graphs we can see that, being the inventory variability lower with the centralised systems, the maximum inventory peaks are significantly lower in this systems than in the traditional ones (this is particularly visible for the most variable daily demands, i.e., generated demand 3 and 4).

Because of the pooling effect caused by the fact that each ward stores several different items, the overall needed inventory space variability would, for the two systems, be lower than that observed for a single product. Nevertheless, mainly at a ward, where the inventory variability is higher and, in practical situations, the variety of different items stored is much lower than that observed at a DC, the storage space needed in a centralised system for all the items with the characteristics of the one analysed would possibly (depending on the number of different items stored) be lower than that needed in a traditional system. The variability will always be lower in the centralised systems, but, if the number of different items stored is high, the difference between the variability of the two systems becomes irrelevant from a practical point of view, and the inventory level of each system will be closer to its average.

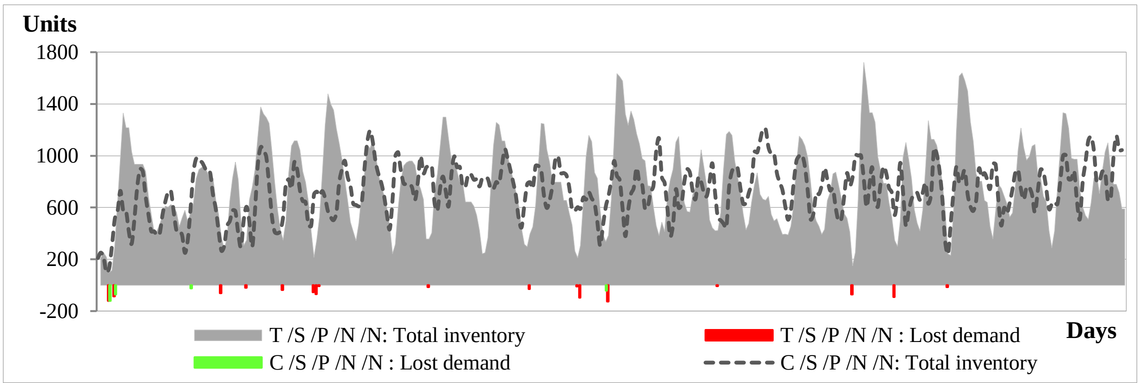

Figure 4.22 Simple SC, one DC, one ward, *demand 1*, no ordering effects (possibility of emergency deliveries from the DC): total SC inventory level - centralised versus traditional inventory control

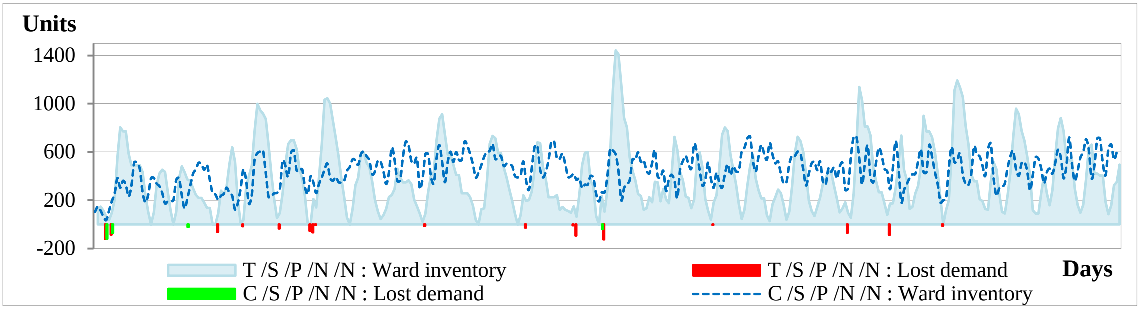

Figure 4.23 Simple SC, one DC, one ward, *demand 1*, no ordering effects (possibility of emergency deliveries from the DC): inventory level at the ward - centralised versus traditional inventory control

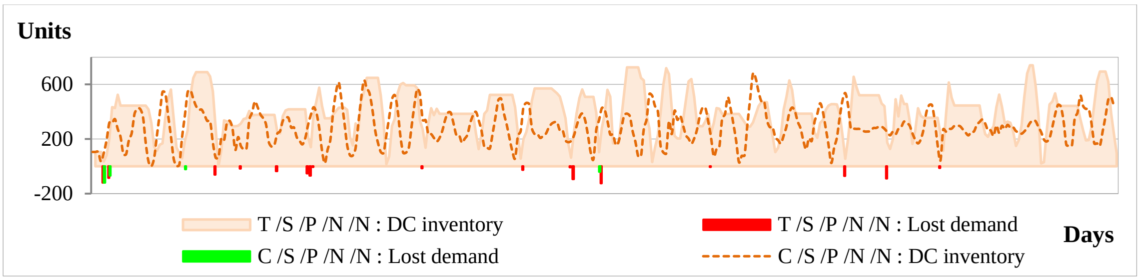

Figure 4.24 Simple SC, one DC, one ward, *demand 1*, no ordering effects (possibility of emergency deliveries from the DC): inventory level at the DC - centralised versus traditional inventory control

For example, if we imagine that 20 independent items similar to the one analysed are stored in the system, comparing the centralised system with the traditional system with no ordering effects, with the centralised system:

- the maximum inventory level[50] at the ward would be approximately 6% lower for generated demand 1, 14% higher for generated demand 2 (in this case, the inventory average at the ward is relatively high in the centralised system), 26% lower for generated demand 3 and 10% lower for generated demand 4;
- the maximum inventory level at the whole system would be approximately 13% lower for generated demand 1, 3% lower for generated demand 2, 24% lower for generated demand 3 and 32% lower for generated demand 4.

If 1000 independent items similar to the one analysed are stored, with the centralised system:

- at the ward, the maximum inventory level would be lower only when the daily demand is generated demand 3 (17% lower); for the other (more stable) generated

[50] *Maximum inventory level of n items = average of inventory of the item × n + 3 × corrected standard deviation of the inventory of n items*, where corrected *standard deviation of the inventory of n items = (n × (variance of the inventory of the item × (no. of days simulated/(no. of days simulated-1)))^(1/2)*; the central limit theorem was applied to make these calculations; according to the characteristics of the Normal distribution, the daily inventory level will be below the determined maximum inventory level around 99,73% of the days.

demands, the fact that the inventory average is higher at the ward becomes more determinant;

- the maximum inventory level at the whole system would be approximately 7% lower for generated demand 1, 29% lower for generated demand 3 and 14% lower for generated demand 3; for generated demand 2, it would be 7% higher, because the inventory average at the whole hospital is higher with the centralised system.

4.6 Results for quasi-arborescent supply chains with one DC and three wards

4.6.1 Introduction

All the models of quasi-arborescent supply chains were simulated considering the possibility of direct emergency deliveries from the DC to the wards, because of the improvements on the service level of the ward that were obtained on previous simulations (see subsection 4.5.4).

In Figure 4.25, we summarise the model alternatives considered for simulating quasi-arborescent supply chains with one DC and three wards that are identical in terms of the daily demand they face. For supply chains with decentralised inventory control, the existence of ordering effects at the wards is compared with a situation without such effects. When the inventory control is centralised, we consider that the health professionals at the wards do not have enough inventory related decision margin to cause ordering effects. In terms of the rules for DC on hand inventory allocation, we make simulations considering that the ER has priority over the other wards and that the available inventory is distributed by the wards proportionally to the relation between their pending orders and total wards' pending orders.

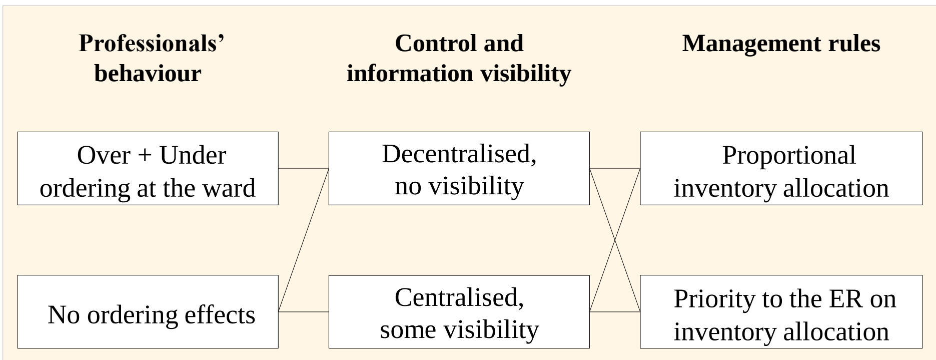

Figure 4.25 Characteristics of the simulated models of quasi-arborescent supply chains with one DC and three identical wards

In Figure 4.26, we summarise the model alternatives considered for simulating quasi-arborescent supply chains with one DC and three wards, different in terms of the daily demand faced. In this case, besides the simulations performed using models of quasi-arborescent supply chains with identical wards, we consider the possibility of lateral transshipments from the other wards to the ER.

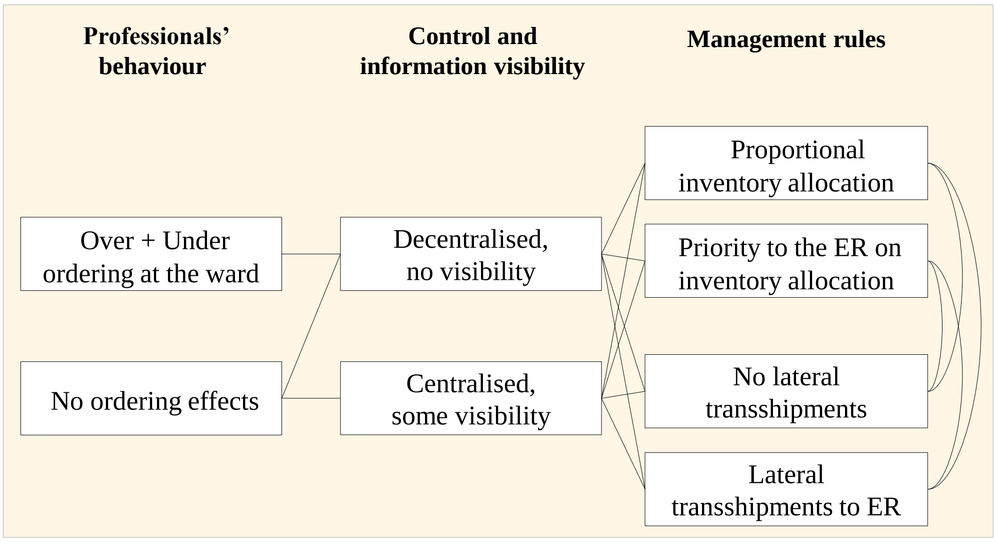

Figure 4.26 Characteristics of the simulated models of quasi-arborescent supply chains with one DC and three different wards

4.6.2 Traditional supply chain with identical wards

To simulate a traditional quasi-arborescent supply chain model with one DC and N wards, we considered an example with 3 wards. The daily demands of the wards were generated using the processes described in section 4.4 (p.113). The same (simple or compounded) distribution was used to generate the demands of the three wards (a description of the resulting daily demands is presented in Appendix 4.18). The generated demands for ward 1 are equal to the generated demands of the ward in the models of simple serial supply chains simulated in previous sections, so that some comparability between the obtained simulation results is possible. For generating the daily demands of wards 2 and 3, the same distributions (but different seeds) were used. We designate the modelled supply chain as *quasi-arborescent* because it includes the possibility of direct deliveries from the DC to satisfy final demand at a ward when the inventory available at that ward is insufficient, thus having a dual-role DC, which differs from a pure arborescent supply chain.

In Table 4.18, we present some descriptive measures relative to the demand faced at the various supply chain echelons obtained from running a model of a quasi-arborescent supply chain with three identical wards and models of three comparable simple serial supply chains (with the same daily demand distributions and a dual-role DC). The quasi-arborescent supply chain is compared with a situation with the same demand, originated at three different locations, served through three independent serial supply chains, each of them with one DC and one ward. In the table, demand measures concerning the aggregated demand are presented at the points where there is an upstream supply chain member that faces the pooled demand (in the case of the quasi-arborescent supply chain this happens at the DC; in the case of the serial supply chains, at the supplier, assuming that all the supply chains will be fulfilled by only one supplier).

Analysing the values in the table, as expected, we can observe a pooling effect at the DC, since the variability of the demand at the entry of the DC is significantly lower that the variability of the orders placed by each ward.

It can also be observed that, although the average of the quantity ordered to the supplier is lower in the quasi- arborescent supply chain, the variability of the demand passed to the supplier is higher than when the supplier receives the pooled requests of the three parallel serial supply chains that could serve the same final demand.

In Figure 4.27 and Figure 4.28, we present graphs representing the demand faced by ward 1, by the DC and by the supplier, with no ordering effects or with over and under-ordering effects at the wards (no ordering effects at the DC), when the ward daily demands are simulated using Process 1 (similar graphs for ward 2 and 3 and for the various echelons when daily demands is generated using processes 2, 3 and 4 are available in Appendix 4.19). As observed in the traditional serial supply chains, the ordering effects at the ward increase significantly the variability of the demand at the various echelons.

Table 4.18 Traditional SC: comparison of the daily demand faced at the various supply chain echelons – three serial supply chains versus quasi-arborescent SC with three identical wards

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Process 1	3 (T /S /P /O+U /N)	338.5	337.0	1.00						
		111.7	173.7	1.55	101.0	158.9	1.57	112.2	81.5	0.73
		109.3	191.6	1.75	96.6	174.2	1.80	106.8	84.4	0.79
		117.5	177.9	1.51	105.3	164.6	1.56	115.8	85.4	0.74
	T /AI /P /O+U /N	330.6	443.6	1.34	303.7	323.7	1.07			
					100.8	174.2	1.73	112.2	81.5	0.73
					96.7	171.6	1.77	106.8	84.4	0.79
					106.2	166.8	1.57	115.8	85.4	0.74
	3 (T /S /P /N /N)	330.2	307.6	0.93						
		110.7	148.0	1.34	100.3	128.0	1.28	112.2	81.5	0.73
		105.4	164.1	1.56	95.1	139.8	1.47	106.8	84.4	0.79
		114.2	173.0	1.52	103.9	136.8	1.32	115.8	85.4	0.74
	T /AI /P /N /N	328.9	379.7	1.15	294.0	243.1	0.83			
					98.4	140.9	1.43	112.2	81.5	0.73
					93.5	140.4	1.50	106.8	84.4	0.79
					102.1	148.3	1.45	115.8	85.4	0.74
Process 2	3 (T /S /P /O+U /N)	336.5	310.4	0.92						
		111.5	181.0	1.62	102.4	183.0	1.79	110.3	99.2	0.90
		116.0	178.4	1.54	105.7	176.9	1.67	115.0	96.5	0.84
		109.0	178.2	1.63	98.2	190.5	1.94	110.1	101.1	0.92
	T /AI /P /O+U /N	338.4	449.5	1.33	307.1	322.0	1.05			
					103.7	188.5	1.82	110.3	99.2	0.90
					104.3	185.1	1.77	115.0	96.5	0.84
					99.1	174.0	1.76	110.1	101.1	0.92
	3 (T /S /P /N /N)	330.6	289.7	0.88						
		110.1	168.8	1.53	99.9	142.1	1.42	110.3	99.2	0.90
		114.9	160.4	1.40	101.8	150.6	1.48	115.0	96.5	0.84
		105.7	181.8	1.72	96.7	156.3	1.62	110.1	101.1	0.92
	T /AI /P /N /N	328.0	412.4	1.26	298.9	272.2	0.91			
					99.8	147.0	1.47	110.3	99.2	0.90
					100.0	152.7	1.53	115.0	96.5	0.84
					99.0	144.5	1.46	110.1	101.1	0.92
Process 3	3 (T /S /P /O+U /N)	418.3	561.0	1.34						
		148.6	326.9	2.20	135.6	334.2	2.47	141.8	186.8	1.32
		124.2	282.5	2.27	112.9	284.3	2.52	125.4	159.6	1.27
		145.4	328.7	2.26	126.1	328.4	2.60	140.9	172.0	1.22
	T /AI /P /O+U /N	413.9	616.9	1.49	377.7	508.4	1.35			
					133.9	331.2	2.47	141.8	186.8	1.32
					114.0	280.3	2.46	125.4	159.6	1.27
					129.9	310.2	2.39	140.9	172.0	1.22
	3 (T /S /P /N /N)	420.6	439.2	1.04						
		150.7	273.3	1.81	130.1	274.2	2.11	141.8	186.8	1.32
		126.7	254.4	2.01	114.3	227.7	1.99	125.4	159.6	1.27
		143.2	278.7	1.95	126.2	255.3	2.02	140.9	172.0	1.22
	T /AI /P /N /N	408.0	548.9	1.35	370.8	427.4	1.15			
					131.1	271.0	2.07	141.8	186.8	1.32
					112.8	230.4	2.04	125.4	159.6	1.27
					126.9	240.2	1.89	140.9	172.0	1.22
Process 4	3 (T /S /P /O+U /N)	371.8	453.6	1.22						
		123.1	298.8	2.43	112.9	258.5	2.29	123.4	131.4	1.06
		120.8	232.9	1.93	108.4	228.0	2.10	118.1	138.5	1.17
		128.0	290.9	2.27	116.5	289.3	2.48	125.3	156.6	1.25
	T /AI /P /O+U /N	367.1	521.2	1.42	337.3	428.4	1.27			
					111.8	237.5	2.12	123.4	131.4	1.06
					107.9	218.3	2.02	118.1	138.5	1.17
					117.6	294.5	2.50	125.3	156.6	1.25
	3 (T /S /P /N /N)	370.1	391.3	1.06						
		124.3	225.8	1.82	112.6	201.4	1.79	123.4	131.4	1.06
		116.6	209.9	1.80	104.9	184.0	1.75	118.1	138.5	1.17
		129.3	262.5	2.03	114.7	234.9	2.05	125.3	156.6	1.25
	T /AI /P /N /N	358.4	477.5	1.33	331.0	338.2	1.02			
					112.6	193.4	1.72	123.4	131.4	1.06
					105.3	183.4	1.74	118.1	138.5	1.17
					113.1	223.5	1.98	125.3	156.6	1.25

*Coefficient of variation (CV) = Standard deviation/Average

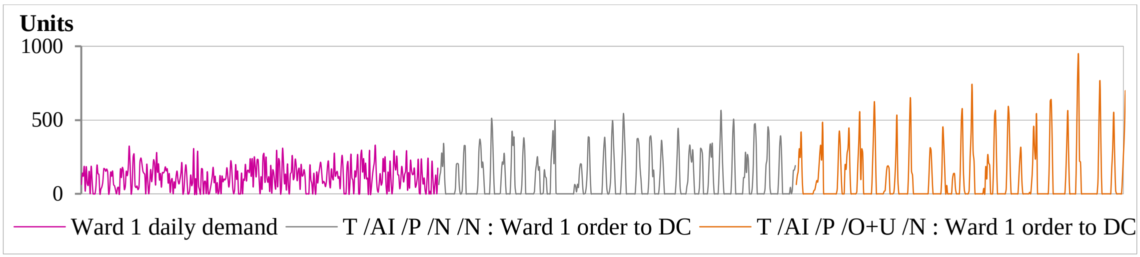

Figure 4.27 Traditional quasi-arborescent (N identical wards) SC (demands generated using Process 1), ward 1: demand faced and orders to DC – no ordering effects versus over and under-ordering effects at the ward

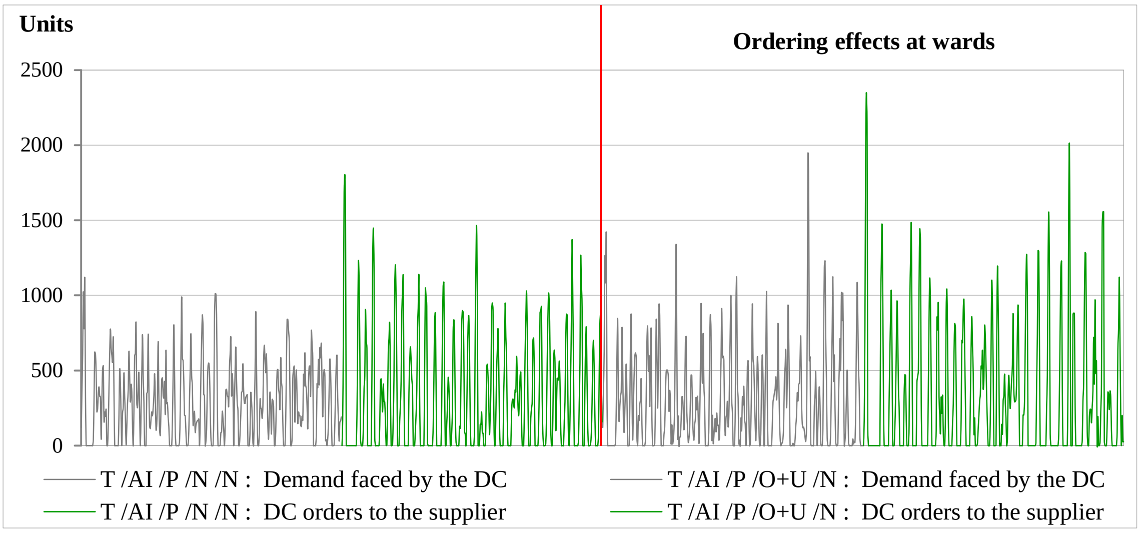

Figure 4.28 Traditional quasi-arborescent (N identical wards) SC (demand generated using Process 1): demand faced by the DC (sum of ward orders) and orders by the DC to the supplier – no ordering effects versus over and under-ordering effects at the ward

In Table 4.19, measures concerning the inventory levels at the various echelons and the service level at the wards are presented. As expected (see e.g., Yang and Wee 2001), the quasi-arborescent system resulted in lower total inventory levels for all daily demand generating processes and for both systems with over and under-ordering effects at the wards and systems with no ordering effects, mainly because the obtained inventory levels at the DC were significantly lower. In terms of service level, in general, the quasi-arborescent systems resulted in worst results (i.e., higher and more frequent lost demand) than the corresponding serial supply chains.

Table 4.19 Traditional SC: comparison of inventory level(s) and lost demand - three serial supply chains versus quasi-arborescent SC with three identical wards

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital					
		Average	CV*	Average	CV*	Average	CV*	Difference to lowest	Average (units per day)	% days w/ lost demand	% of lost demand
Process 1	3 (T /S /P /O+U /N)			1795.7		3291.2		45.6%			
		462.7	0.75	495.1	0.52	957.8	0.42		1.8	2.7%	1.6%
		528.3	0.77	699.0	0.58	1227.3	0.48		0.9	1.6%	0.9%
		504.6	0.70	601.5	0.54	1106.1	0.43		1.6	2.5%	1.4%
	T /AI /P /O+U /N	547.9	0.76						4.7	5.5%	4.2%
		521.0	0.76	1166.3	0.51	2747.3	0.38	21.6%	2.2	2.7%	2.0%
		512.1	0.73						1.8	2.5%	1.6%
	3 (T /S /P /N /N)			1379.0		2665.9		17.9%			
		381.6	0.72	394.9	0.40	776.5	0.41		2.5	4.7%	2.2%
		450.2	0.72	494.0	0.52	944.1	0.45		1.7	3.3%	1.6%
		455.2	0.75	490.1	0.47	945.3	0.46		3.0	4.1%	2.6%
	T /AI /P /N /N	444.5	0.72						4.3	5.8%	3.8%
		456.4	0.72	897.4	0.50	2260.2	0.36	0.0%	4.2	5.5%	3.9%
		461.9	0.71						2.9	4.4%	2.5%
Process 2	3 (T /S /P /O+U /N)			1884.1		3701.3		41.1%			
		606.5	0.68	636.2	0.52	1242.7	0.42		0.1	0.3%	0.0%
		567.4	0.77	601.6	0.53	1169.0	0.45		0.9	1.1%	0.8%
		643.3	0.79	646.3	0.59	1289.6	0.48		1.7	1.9%	1.6%
	T /AI /P /O+U /N	661.7	0.68						3.4	4.7%	3.1%
		598.0	0.75	1159.9	0.55	3134.2	0.39	19.5%	2.7	2.2%	2.3%
		714.7	0.80						1.3	1.1%	1.1%
	3 (T /S /P /N /N)			1415.3		2980.3					
		483.1	0.72	481.2	0.51	964.3	0.46		1.9	3.3%	1.7%
		495.3	0.71	461.4	0.42	956.7	0.41	13.6%	1.6	1.6%	1.4%
		586.6	0.80	472.7	0.47	1059.3	0.50		4.9	4.9%	4.5%
	T /AI /P /N /N	528.3	0.74						4.2	4.1%	3.8%
		514.5	0.68	1047.7	0.56	2623.8	0.38	0.0%	2.8	2.5%	2.5%
		533.3	0.73						3.1	3.3%	2.8%
Process 3	3 (T /S /P /O+U /N)			3824.8		8101.8		65.1%			
		1563.3	0.75	1454.4	0.52	3017.7	0.49		2.5	0.8%	1.8%
		1282.8	0.81	1137.3	0.45	2420.1	0.49		3.9	2.2%	3.1%
		1430.9	0.85	1233.1	0.44	2664.0	0.51		2.2	1.1%	1.5%
	T /AI /P /O+U /N	1532.3	0.79						3.2	2.5%	4.4%
		1278.7	0.70	1890.7	0.50	5960.7	0.33	21.5%	2.0	1.4%	1.6%
		1258.8	0.92						2.9	1.4%	1.1%
	3 (T /S /P /N /N)			2977.0		6539.0		33.3%			
		1322.9	0.73	1111.5	0.57	2434.5	0.50		1.2	0.3%	0.9%
		1092.1	0.74	832.1	0.48	1924.1	0.53		1.2	1.9%	1.0%
		1147.0	0.87	1033.4	0.54	2180.4	0.56		2.6	1.4%	1.8%
	T /AI /P /N /N	1275.9	0.69						3.2	1.4%	2.2%
		1036.2	0.64	1529.9	0.55	4906.5	0.34	0.0%	3.0	2.2%	2.4%
		1064.5	0.78						3.2	1.9%	2.2%
Process 4	3 (T /S /P /O+U /N)			3147.3		6618.6		77.8%			
		1155.8	0.79	1038.9	0.55	2194.7	0.53		2.7	2.5%	2.2%
		862.3	0.78	969.5	0.53	1831.8	0.44		0.4	1.1%	0.3%
		1453.2	0.79	1138.9	0.59	2592.1	0.57		2.9	1.9%	2.3%
	T /AI /P /O+U /N	950.4	0.74						1.7	2.2%	1.3%
		833.2	0.77	1464.3	0.48	4651.0	0.34	24.9%	2.3	1.9%	2.0%
		1403.0	0.83						3.0	1.6%	2.4%
	3 (T /S /P /N /N)			2201.3		4874.0		30.9%			
		790.7	0.81	758.5	0.51	1549.1	0.48		2.3	2.2%	1.8%
		742.8	0.80	673.1	0.53	1415.9	0.52		2.8	1.9%	2.4%
		1139.2	0.85	769.7	0.58	1908.9	0.61		4.4	3.3%	3.5%
	T /AI /P /N /N	741.0	0.76						4.0	2.5%	3.2%
		774.1	0.79	1149.6	0.48	3722.6	0.36	0.0%	5.9	4.9%	5.0%
		1058.0	0.80						4.6	2.5%	3.7%

*Coefficient of variation (CV) = Standard deviation/Average

The systems with over-ordering effects resulted always in higher inventory levels than the systems with no ordering effects (comparisons of inventory evolution at ward 1 and at the DC when demand was simulated using process 1 can be seen in Figure 4.29 and Figure 4.30, respectively; similar graphs for ward 2 and 3 and the various supply chain storage locations when the daily demands are generated through processes 2, 3 and 4 are available in Appendix 4.20).

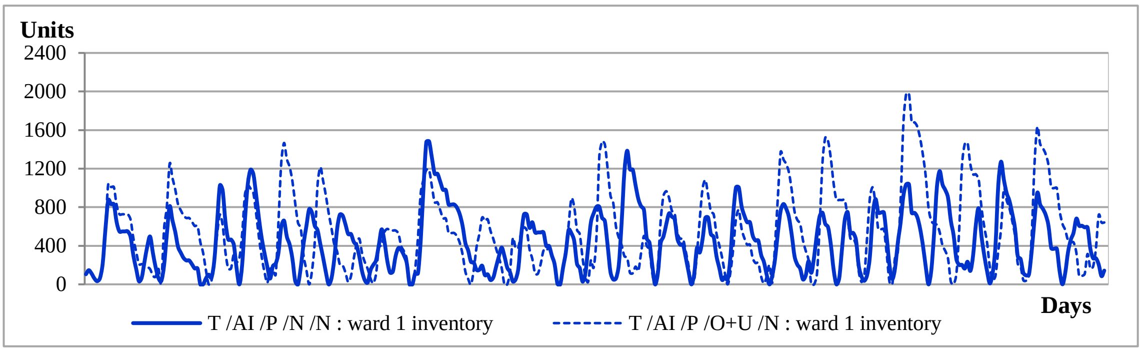

Figure 4.29 Traditional quasi-arborescent (N identical wards) SC (demand generated using Process 1): ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects

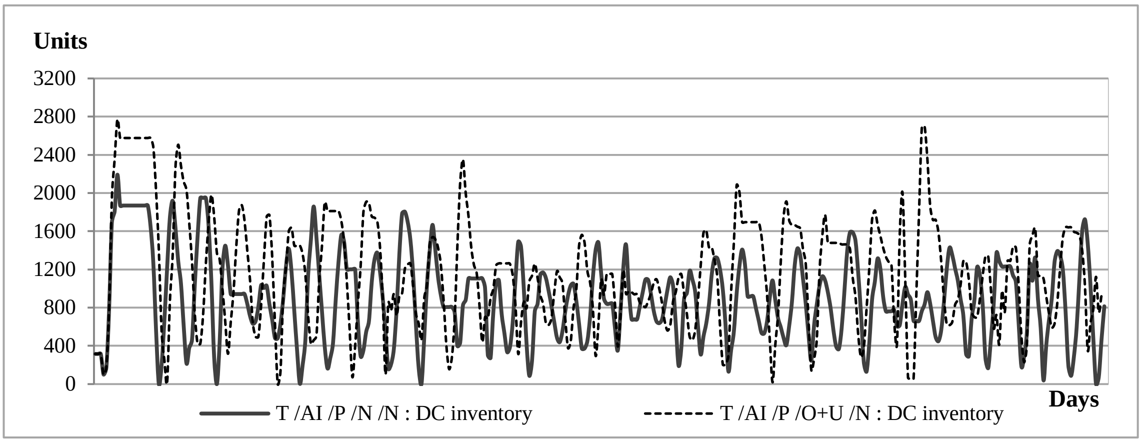

Figure 4.30 Traditional quasi-arborescent (N identical wards) SC (demand generated using Process 1): DC inventory level – over and under-ordering effects at the wards versus no ordering effects

4.6.3 Traditional supply chain with identical wards, one of which an ER

In Table 4.20, we present some measures describing the demand at the various echelons for the two models representing quasi-arborescent supply chains with identical daily demands at the wards and with the possibility of emergency deliveries from the DC to fulfil end demand if the inventory available at the ward is insufficient. The two models differ relatively to rules used to allocate the available DC inventory to the wards when existing units are not enough to fulfil all wards' requests, as described in section 4.3.1 (p.99).

Figure 4.31 and Figure 4.32 present graphs comparing the evolution of demand at the DC and passed to the supplier in the system that gives priority to the ER over the other wards in the allocation of the inventory available at the DC, in case of inventory insufficiency at the DC, and in the system with all the wards having the same priority, and thus receiving a quantity proportional the weight of their pending requests on total requests, considering daily demands generated using Process 4. We present the graph relative to Process 4 because the differences are more easily visualised in the systems with more variable daily demands (the graphs relative to the wards and to simulations performed with daily demands generating processes 1, 2 and 3 are presented at Appendix 4.21). In general, when models considering higher variability of the daily demand at the wards were simulated (demands generated through processes 2, 3 and 4), the systems with an ER resulted in higher demand variability faced by the DC and the supplier.

In terms of demand evolution, the differences between the systems using the two inventory allocation (rationing) rules under analysis at the entry and exit of the wards are not easily identified through graph visualisation.

Table 4.20 Traditional SC, one DC and three identical wards (with emergency deliveries from the DC): demand at the various SC echelons – ER with priority in the replenishments from the DC versus all wards with equal priority

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Process 1	T /AI /P /O+U /N	330.6	443.6	1.34	303.7	323.7	1.07			
					100.8	174.2	1.73	112.2	81.5	0.73
					96.7	171.6	1.77	106.8	84.4	0.79
					106.2	166.8	1.57	115.8	85.4	0.74
	T /AI+ER /P /O+U /N	336.1	423.4	1.26	306.0	304.5	1.00			
					101.9	166.0	1.63	112.2	81.5	0.73
					96.3	179.1	1.86	106.8	84.4	0.79
					107.7	162.6	1.51	115.8	85.4	0.74
	T /AI /P /N /N	328.9	379.7	1.15	294.0	243.1	0.83			
					98.4	140.9	1.43	112.2	81.5	0.73
					93.5	140.4	1.50	106.8	84.4	0.79
					102.1	148.3	1.45	115.8	85.4	0.74
	T /AI+ER /P /N /N	322.7	383.6	1.19	291.8	229.6	0.79			
					96.4	139.6	1.45	112.2	81.5	0.73
					93.0	141.9	1.53	106.8	84.4	0.79
					102.5	143.8	1.40	115.8	85.4	0.74

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Process 2	T /AI /P /O+U /N	338.4	449.5	1.33	307.1	322.0	1.05			
					103.7	188.5	1.82	110.3	99.2	0.90
					104.3	185.1	1.77	115.0	96.5	0.84
					99.1	174.0	1.76	110.1	101.1	0.92
	T /AI+ER /P /O+U /N	328.7	455.8	1.39	304.0	328.9	1.08			
					100.2	190.8	1.90	110.3	99.2	0.90
					104.6	180.5	1.73	115.0	96.5	0.84
					99.2	187.6	1.89	110.1	101.1	0.92
	T /AI /P /N /N	328.0	412.4	1.26	298.9	272.2	0.91			
					99.8	147.0	1.47	110.3	99.2	0.90
					100.0	152.7	1.53	115.0	96.5	0.84
					99.0	144.5	1.46	110.1	101.1	0.92
	T /AI+ER /P /N /N	325.4	392.8	1.21	295.5	277.4	0.94			
					98.5	154.5	1.57	110.3	99.2	0.90
					101.7	150.2	1.48	115.0	96.5	0.84
					95.4	161.7	1.69	110.1	101.1	0.92
Process 3	T /AI /P /O+U /N	413.9	616.9	1.49	377.7	508.4	1.35			
					133.9	331.2	2.47	141.8	186.8	1.32
					114.0	280.3	2.46	125.4	159.6	1.27
					129.9	310.2	2.39	140.9	172.0	1.22
	T /AI+ER /P /O+U /N	415.2	663.2	1.60	376.5	530.3	1.41			
					135.0	310.42	2.30	141.8	186.8	1.32
					112.2	286.38	2.55	125.4	159.6	1.27
					129.2	319.36	2.47	140.9	172.0	1.22
	T /AI /P /N /N	408.0	548.9	1.35	370.8	427.4	1.15			
					131.1	271.0	2.07	141.8	186.8	1.32
					112.8	230.4	2.04	125.4	159.6	1.27
					126.9	240.2	1.89	140.9	172.0	1.22
	T /AI+ER /P /N /N	403.0	552.0	1.37	367.2	407.0	1.11			
					133.3	266.5	2.00	141.8	186.8	1.32
					110.5	234.6	2.12	125.4	159.6	1.27
					123.4	253.8	2.06	140.9	172.0	1.22
Process 4	T /AI /P /O+U /N	367.1	521.2	1.42	337.3	428.4	1.27			
					111.8	237.5	2.12	123.4	131.4	1.06
					107.9	218.3	2.02	118.1	138.5	1.17
					117.6	294.5	2.50	125.3	156.6	1.25
	T /AI+ER /P /O+U /N	368.8	535.7	1.45	335.9	455.8	1.36			
					113.5	235.25	2.07	123.4	131.4	1.06
					107.5	217.59	2.02	118.1	138.5	1.17
					114.9	312.40	2.72	125.3	156.6	1.25
	T /AI /P /N /N	358.4	477.5	1.33	331.0	338.2	1.02			
					112.6	193.4	1.72	123.4	131.4	1.06
					105.3	183.4	1.74	118.1	138.5	1.17
					113.1	223.5	1.98	125.3	156.6	1.25
	T /AI+ER /P /N /N	358.1	499.7	1.40	326.4	350.0	1.07			
					111.9	198.3	1.77	123.4	131.4	1.06
					105.6	187.3	1.77	118.1	138.5	1.17
					108.9	233.0	2.14	125.3	156.6	1.25

*Coefficient of variation (CV) = Standard deviation/Average

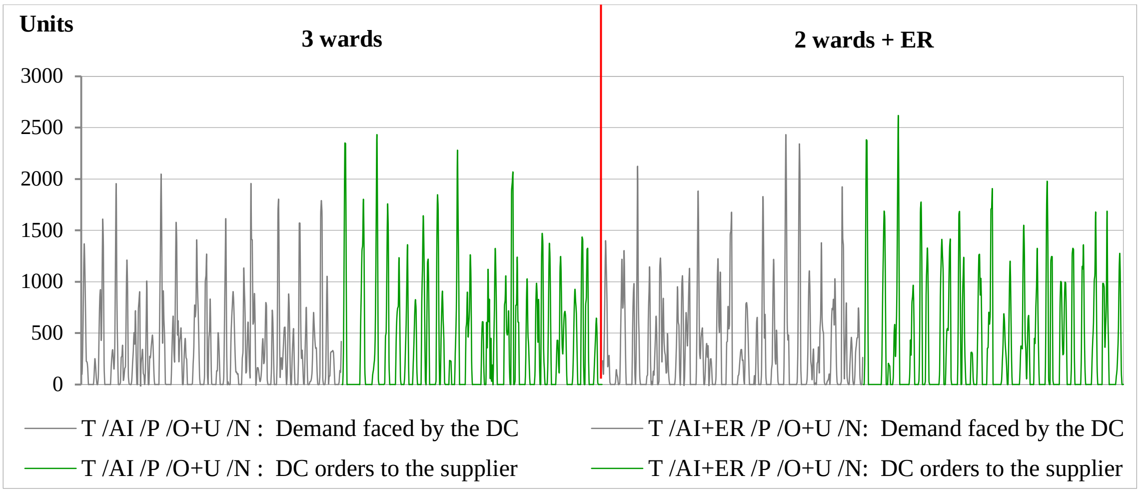

Figure 4.31 Traditional quasi-arborescent SC with 3 identical wards: SC with an ER plus 2 wards versus all wards with equal priority in inventory allocation (demands generated using Process 4), over and under-ordering effects at the ward – demand faced by the DC and orders to the supplier

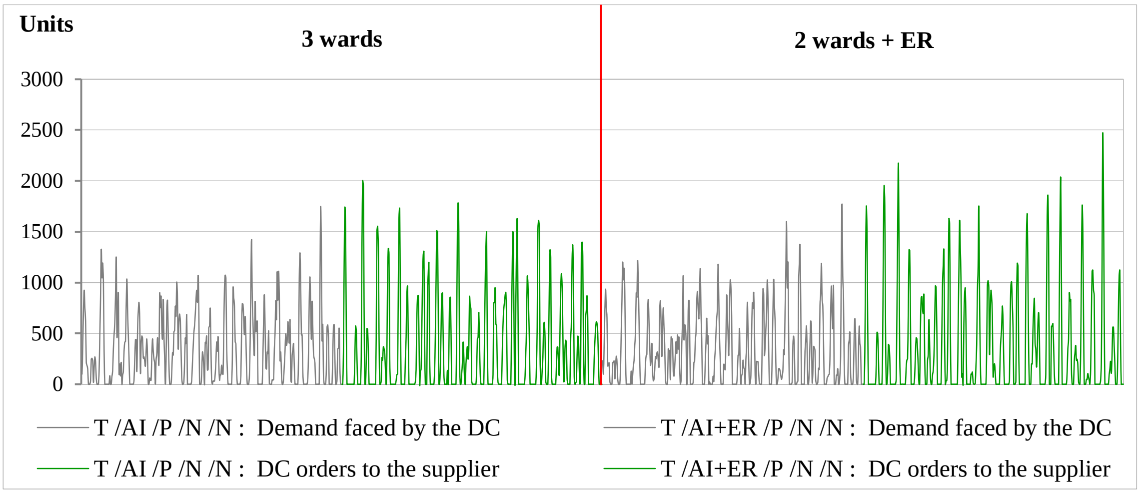

Figure 4.32 Traditional quasi-arborescent SC with 3 identical wards: SC with an ER plus 2 wards versus all wards with equal priority in inventory allocation (demands generated using Process 4), no ordering effects – demand faced by the DC and orders to the supplier

Once more, the systems with over and under-ordering effects at the wards presented higher demand level and variability at the various supply chain echelons.

Table 4.21 Traditional SC, one DC and three identical wards (with emergency deliveries from the DC): inventory levels and lost demand – ER with priority in the replenishments from the DC versus all wards with equal priority

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital			Average (units per day)	% days w/ lost demand	% of lost demand
		Average	CV*	Average	CV*	Average	CV*	Difference to lowest			
Process 1	T /AI /P /O+U /N	547.9	0.76						4.7	5.5%	4.2%
		521.0	0.76	1166.3	0.51	2747.3	0.38	21.6%	2.2	2.7%	2.0%
		512.1	0.73						1.8	2.5%	1.6%
	T /AI+ER /P /O+U /N	552.1	0.83						3.4	4.4%	3.0%
		627.2	0.76	1186.6	0.55	2873.4	0.41	27.1%	1.8	2.2%	1.7%
		507.5	0.74						1.1	2.5%	1.0%
	T /AI /P /N /N	444.5	0.72						4.3	5.8%	3.8%
		456.4	0.72	897.4	0.50	2260.2	0.36	0.0%	4.2	5.5%	3.9%
		461.9	0.71						2.9	4.4%	2.5%
	T /AI+ER /P /N /N	441.7	0.74						5.2	6.3%	4.6%
		469.3	0.73	907.2	0.54	2275.5	0.37	0.7%	5.5	6.3%	5.2%
		457.3	0.67						3.0	3.6%	2.6%
Process 2	T /AI /P /O+U /N	661.7	0.68						3.4	4.7%	3.1%
		598.0	0.75	1159.9	0.55	3134.2	0.39	19.5%	2.7	2.2%	2.3%
		714.7	0.80						1.3	1.1%	1.1%
	T /AI+ER /P /O+U /N	742.4	0.80						4.5	4.9%	4.1%
		616.8	0.78	1211.6	0.56	3258.6	0.40	24.2%	3.0	2.5%	2.6%
		687.8	0.77						1.0	1.1%	0.9%
	T /AI /P /N /N	528.3	0.74						4.2	4.1%	3.8%
		514.5	0.68	1047.7	0.56	2623.8	0.38	0.0%	2.8	2.5%	2.5%
		533.3	0.73						3.1	3.3%	2.8%
	T /AI+ER /P /N /N	569.1	0.74						4.7	5.8%	4.2%
		546.2	0.73	970.6	0.49	2663.3	0.34	1.5%	5.7	4.7%	4.9%
		577.4	0.70						2.5	2.7%	2.3%
Process 3	T /AI /P /O+U /N	1532.3	0.79						3.2	2.5%	4.4%
		1278.7	0.70	1890.7	0.50	5960.7	0.33	23.9%	2.0	1.4%	1.6%
		1258.8	0.92						2.9	1.4%	1.1%
	T /AI+ER /P /O+U /N	1430.1	0.73						2.3	0.8%	1.7%
		1324.3	0.71	1974.1	0.50	6153.7	0.36	28.0%	3.9	1.9%	3.1%
		1425.1	1.01						1.5	1.1%	1.1%
	T /AI /P /N /N	1275.9	0.69						3.2	1.4%	2.2%
		1036.2	0.64	1529.9	0.55	4906.5	0.34	2.0%	3.0	2.2%	2.4%
		1064.5	0.78						3.2	1.9%	2.2%
	T /AI+ER /P /N /N	1268.5	0.74						7.4	2.5%	5.2%
		985.1	0.66	1403.6	0.50	4809.4	0.33	0.0%	3.1	2.7%	2.4%
		1152.3	0.83						6.0	3.3%	4.2%
Process 4	T /AI /P /O+U /N	950.4	0.74						1.7	2.2%	1.3%
		833.2	0.77	1464.3	0.48	4651.0	0.34	24.9%	2.3	1.9%	2.0%
		1403.0	0.83						3.0	1.6%	2.4%
	T /AI+ER /P /O+U /N	949.1	0.70						3.3	3.0%	2.7%
		801.0	0.85	1580.4	0.49	4734.9	0.34	27.2%	3.6	3.6%	3.1%
		1404.4	0.82						3.2	1.9%	2.5%
	T /AI /P /N /N	741.0	0.76						4.0	2.5%	3.2%
		774.1	0.79	1149.6	0.48	3722.6	0.36	0.0%	5.9	4.9%	5.0%
		1058.0	0.80						4.6	2.5%	3.7%
	T /AI+ER /P /N /N	856.6	0.80						4.8	4.1%	3.9%
		770.9	0.76	1158.4	0.51	3815.7	0.36	2.5%	5.2	4.4%	4.4%
		1029.8	0.83						8.1	4.7%	6.5%

*Coefficient of variation (CV) = Standard deviation/Average

At the graphs presented in Figure 4.33 and Figure 4.34, we represented the accumulated differences of the inventory level at ward 1 in the system with the ER being served from the DC with priory relatively to the inventory level in the system with all wards having equal priority, considering over and under-ordering effects or no ordering effects, respectively (similar graphs for systems generating demands using processes 2, 3 and 4 are available in Appendix 4.22). In general, the systems that give priority to the ER resulted in higher inventory levels (the only exception was when process 3 was used to simulate the daily demand and no ordering effects were considered).

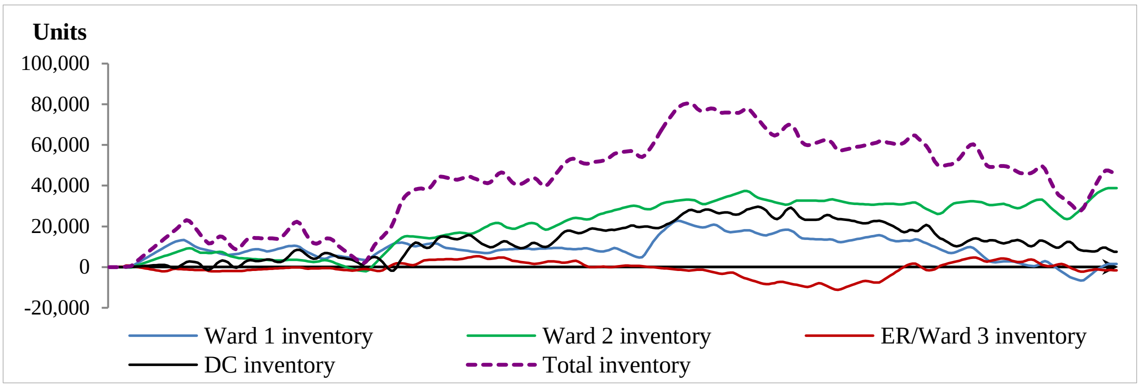

Figure 4.33 Traditional quasi-arborescent SC with 3 identical wards (demands generated using Process 1), over and under-ordering effects at the wards (no ordering effects at the DC): Accumulated differences between the inventory levels in the 2 wards and an ER system and in the system with 3 wards

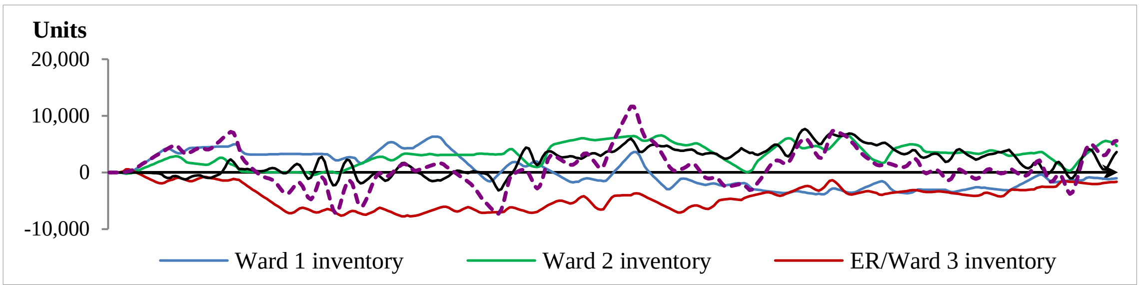

Figure 4.34 Traditional quasi-arborescent SC with 3 identical wards (demands generated using Process 1), no ordering effects: Accumulated differences between the inventory levels in the 2 wards and an ER system and in the system with 3 wards

In Appendix 4.22, we present graphs of the evolution the inventory level at the wards and at the DC, with and without over and under-ordering effects at the wards, resulting from the simulation of the inventory allocation rule that gives priority to the ER.

In Figure 4.35 and Figure 4.36, we present examples of graphs of the accumulated differences between the lost demand in the system with the system that gives priority to the ER in inventory allocation and in the system that allocates inventory to the wards proportionally to their pending orders, considering over and under-ordering effects at the wards (no ordering effects at the DC), respectively, when generated demand was simulated using process 2 (similar graphs for daily demands generated using the other processes are available in Appendix 4.22). In terms of service level, the system giving priority to the ER generally resulted in higher and more frequent lost demand at ward 1 and ward 2, or at least at one of these wards. It frequently resulted in lower lost demand at the ER. Nevertheless, in the system with daily demands generated using process 2, the magnitude of the service level deterioration at ward 1 or 2 was greater than that of the improvements at the ER (see Figure 4.35 and Figure 4.36) and there were several cases with the lost demand at the ER being higher than in the system with no priority given to the ER (namely, systems with no ordering effects and with daily demand generated using processes 1 or 3 and systems with daily demand generated using process 4).

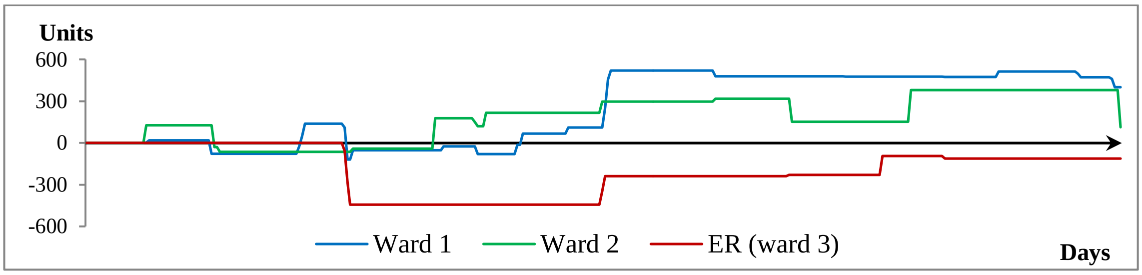

Figure 4.35 Traditional quasi-arborescent SC (demand generated using Process 2), over and under-ordering effects at the wards: accumulated differences between lost demand in the system with 2 identical wards and an ER and in the system with 3 identical wards

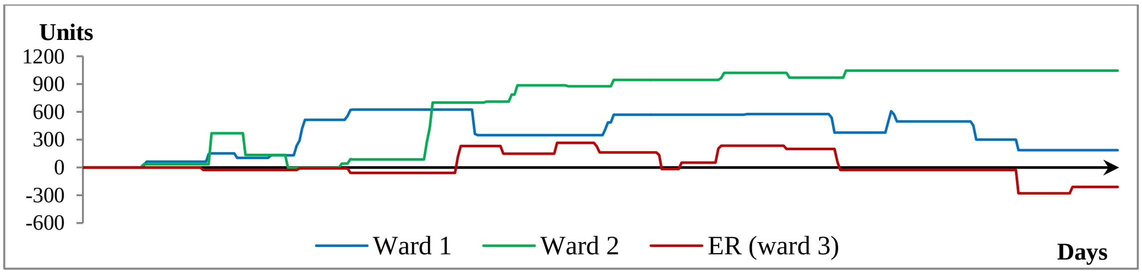

Figure 4.36 Traditional quasi-arborescent SC (demand generated using Process 2), no ordering effects: accumulated differences between lost demand in the system with 2 identical wards and an ER and in the system with 3 identical wards

4.6.4 Centralised inventory control and inventory visibility in a supply chain with identical wards

In Table 4.22 and Table 4.23, we compare, respectively, the demands and the inventory levels at the various echelons obtained from the simulation of centralised supply chains with three identical wards with the results of the simulation of alternative traditional supply chains with the same structure and also with the results of the simulation of the models of three parallel centralised serial supply chains with daily demands equal to those of the wards. The pattern of the inventory evolution at the wards and at the DC is similar to that observed on the serial supply chains (compare Figure 4.37 and Figure 4.38 with Figure 4.23 and Figure 4.24, p.136), namely, in the centralised systems, the ward inventory variability and the DC inventory level are significantly lower than in the corresponding traditional systems (the graphs representing the comparison of inventory evolution for other wards and generated demands are available in Appendix 4.24).

In Figure 4.39, we present a graph comparing the demand faced by the DC with the demand passed to the supplier in the centralised quasi-arborescent system with 3 identical wards, when daily demand was simulated using Process 1. The variability of the demand faced by the supplier was significantly higher than that faced at the DC. It was, however, significantly lower than in traditional quasi-arborescent systems. In Figure 4.40, a graph comparing the demand passed to the supplier in the centralised quasi-arborescent system with three identical wards with that passed to the supplier by three parallel serial centralised supplies chains is presented. We can note that the variability faced by the supplier was lower in the three serial supply chains (the total inventory average was similar in the two systems) – this may be an interesting indication concerning the hypothesis of studying other supply chain configurations[51]. Similar, and consistent, graphs for the other generated demands are presented in Appendix 4.23.

In terms of inventory level, in general, at the wards the inventory average was higher in the centralised systems than in the traditional ones. However, this resulted in a significant improvement in the service level. At the DC, the inventory average was significantly lower than in the traditional systems and, as a consequence, in general, the average of the total inventory level was slightly lower at the centralised systems (when demand was generated using Process 4, it was slightly higher).

[51] We will not do that in this chapter, though.

Table 4.22 Centralised SC, one DC and three wards (with emergency deliveries from the DC): demand faced at the various SC echelons - comparison with alternative traditional quasi-arborescent SC and 3 centralised serial supply chains

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Process 1	3 (C/ S/ P /N /N)	337.2	225.3	0.67						
		112.7	107.3	0.95	112.2	81.5	0.73	112.2	81.5	0.73
		107.2	126.4	1.18	106.8	84.4	0.79	106.8	84.4	0.79
		117.3	131.8	1.12	115.8	85.4	0.74	115.8	85.4	0.74
	T /AI /P /N /N	328.9	379.7	1.15	294.0	243.1	0.83			
					98.4	140.9	1.43	112.2	81.5	0.73
					93.5	140.4	1.50	106.8	84.4	0.79
					102.1	148.3	1.45	115.8	85.4	0.74
	C /AI /P /N /N	338.7	307.1	0.91	334.7	144.9	0.43			
					112.2	81.5	0.73	112.2	81.5	0.73
					106.8	84.4	0.79	106.8	84.4	0.79
					115.8	85.4	0.74	115.8	85.4	0.74
Process 2	3 (C/ S/ P /N /N)	337.0	225.1	0.67						
		111.6	132.4	1.19	110.3	99.2	0.90	110.3	99.2	0.90
		115.1	137.2	1.19	115.0	96.5	0.84	115.0	96.5	0.84
		110.3	140.9	1.28	110.1	101.1	0.92	110.1	101.1	0.92
	T /AI /P /N /N	328.0	412.4	1.26	298.9	272.2	0.91			
					99.8	147.0	1.47	110.3	99.2	0.90
					100.0	152.7	1.53	115.0	96.5	0.84
					99.0	144.5	1.46	110.1	101.1	0.92
	C /AI /P /N /N	337.8	315.6	0.93	335.3	169.4	0.51			
					110.3	99.2	0.90	110.3	99.2	0.90
					115.0	96.5	0.84	115.0	96.5	0.84
					110.1	101.1	0.92	110.1	101.1	0.92
Process 3	3 (C/ S/ P /N /N)	416.4	357.8	0.86						
		144.5	215.9	1.49	141.8	186.8	1.32	141.8	186.8	1.32
		127.9	181.1	1.42	125.4	159.6	1.27	125.4	159.6	1.27
		143.9	200.7	1.39	140.9	172.0	1.22	140.9	172.0	1.22
	T /AI /P /N /N	408.0	548.9	1.35	370.8	427.4	1.15			
					131.1	271.0	2.07	141.8	186.8	1.32
					112.8	230.4	2.04	125.4	159.6	1.27
					126.9	240.2	1.89	140.9	172.0	1.22
	C /AI /P /N /N	414.1	474.7	1.15	408.1	302.7	0.74			
					141.8	186.8	1.32	141.8	186.8	1.32
					125.4	159.6	1.27	125.4	159.6	1.27
					140.9	172.0	1.22	140.9	172.0	1.22
Process 4	3 (C/ S/ P /N /N)	373.0	282.0	0.76						
		126.5	158.1	1.25	123.4	131.4	1.06	123.4	131.4	1.06
		118.9	161.4	1.36	118.1	138.5	1.17	118.1	138.5	1.17
		127.6	172.6	1.35	125.3	156.6	1.25	125.3	156.6	1.25
	T /AI /P /N /N	358.4	477.5	1.33	331.0	338.2	1.02			
					112.6	193.4	1.72	123.4	131.4	1.06
					105.3	183.4	1.74	118.1	138.5	1.17
					113.1	223.5	1.98	125.3	156.6	1.25
	C /AI /P /N /N	373.1	387.3	1.04	366.8	245.6	0.67			
					123.4	131.4	1.06	123.4	131.4	1.06
					118.1	138.5	1.17	118.1	138.5	1.17
					125.3	156.6	1.25	125.3	156.6	1.25

*Coefficient of variation (CV) = Standard deviation/Average

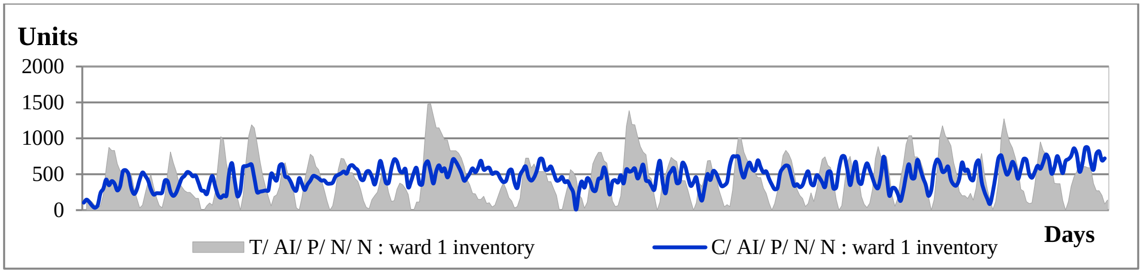

Figure 4.37 Quasi-arborescent (N identical wards) SC (demand generated using Process 1): ward 1 inventory level – centralised inventory control versus traditional SC

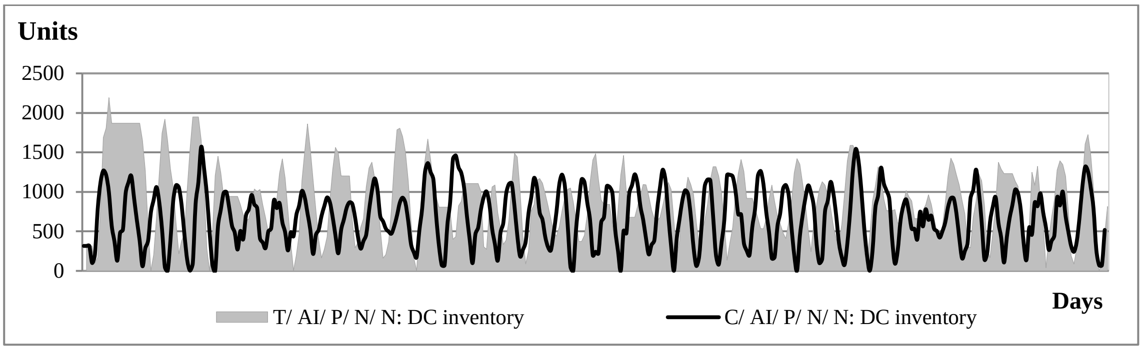

Figure 4.38 Quasi-arborescent (N identical wards) SC (demand generated using Process 1): DC inventory level – centralised inventory control versus traditional SC

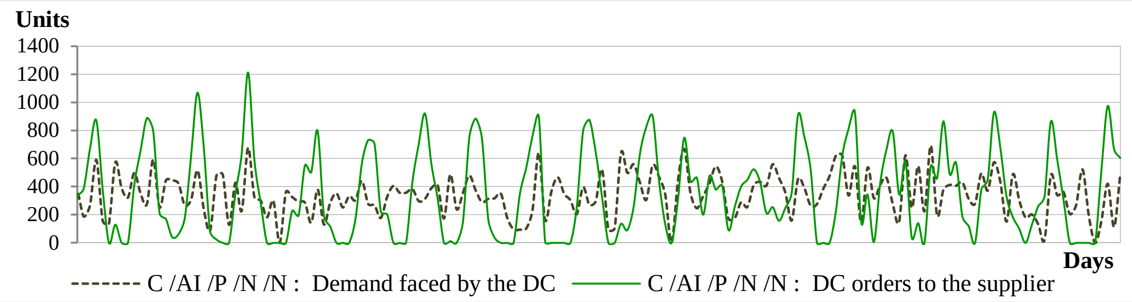

Figure 4.39 Centralised SC, one DC and three wards (with emergency deliveries from the DC), demand generated using process 1: comparison of the demand faced by the DC with the demand passed to the supplier

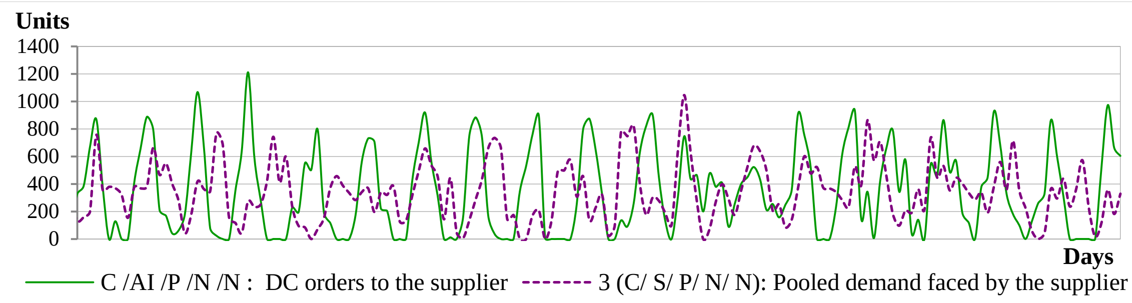

Figure 4.40 Demand passed to the supplier – comparison of the centralised quasi-arborescent system with 3 identical wards with 3 parallel serial centralised supplies chains serving the same demand (generated using process 1)

Table 4.23 Centralised SC, one DC and three wards (with emergency deliveries from the DC): inventory levels at the various echelons and lost demand - comparison with alternative traditional quasi-arborescent SC and 3 centralised serial supply chains

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital			Average (units per day)	% days w/ lost demand	% of lost demand
		Average	CV*	Average	CV*	Average	CV*	Difference to lowest			
Process 1				918.8		2438.1		8.3%			
	3 (C /S /P /N /N)	442.0	0.31	285.2	0.45	727.1	0.28		0.7	1.1%	0.6%
		563.9	0.29	307.9	0.49	871.8	0.27		1.1	1.9%	1.1%
		513.5	0.31	325.7	0.50	839.2	0.29		1.2	2.5%	1.0%
	T /AI /P /N /N	444.5	0.72						4.3	5.8%	3.8%
		456.4	0.72	897.4	0.50	2260.2	0.36	0.4%	4.2	5.5%	3.9%
		461.9	0.71						2.9	4.4%	2.5%
	C /AI /P /N /N	468.5	0.34						1.5	1.6%	1.3%
		524.2	0.29	661.2	0.54	2250.3	0.24	0.0%	1.3	2.2%	1.2%
		596.5	0.29						1.3	2.2%	1.2%
Process 2				1046.7		2995.6		22.4%			
	3 (C /S /P /N /N)	688.8	0.27	358.5	0.47	1047.2	0.25		0.9	0.5%	0.8%
		606.8	0.32	353.0	0.46	959.9	0.28		1.3	1.4%	1.2%
		653.3	0.32	335.3	0.49	988.6	0.30		1.4	2.2%	1.3%
	T /AI /P /N /N	528.3	0.74						4.2	4.1%	3.8%
		514.5	0.68	1047.7	0.56	2623.8	0.38	0.0%	2.8	2.5%	2.5%
		533.3	0.73						3.1	3.3%	2.8%
	C /AI /P /N /N	460.3	0.35						0.6	0.8%	0.5%
		677.7	0.37	727.7	0.51	2447.7	0.25	0.0%	1.7	1.1%	1.5%
		582.0	0.30						1.0	1.1%	0.9%
Process 3				1759.3		5417.5		13.2%			
	3 (C /S /P /N /N)	1131.9	0.42	621.4	0.49	1753.3	0.32		2.2	1.1%	1.5%
		1343.6	0.29	543.3	0.45	1886.9	0.28		2.4	2.5%	1.9%
		1182.6	0.32	594.7	0.44	1777.3	0.28		2.6	1.6%	1.8%
	T /AI /P /N /N	1275.9	0.69						3.2	1.4%	2.2%
		1036.2	0.64	1529.9	0.55	4906.5	0.34	2.5%	3.0	2.2%	2.4%
		1064.5	0.78						3.2	1.9%	2.2%
	C /AI /P /N /N	1228.3	0.44						3.5	1.6%	2.4%
		1103.4	0.30	1217.7	0.52	4785.0	0.26	0.0%	1.4	1.6%	1.1%
		1235.5	0.31						2.7	2.2%	1.9%
Process 4				1395.4		4205.5		13.0%			
	3 (C /S /P /N /N)	920.8	0.29	446.2	0.43	1367.0	0.25		1.5	1.6%	1.2%
		1016.6	0.30	480.9	0.47	1497.5	0.27		1.8	1.9%	1.5%
		872.7	0.40	468.3	0.49	1341.0	0.35		1.8	1.1%	1.4%
	T /AI /P /N /N	741.0	0.76						4.0	2.5%	3.2%
		774.1	0.79	1149.6	0.48	3722.6	0.36	0.0%	5.9	4.9%	5.0%
		1058.0	0.80						4.6	2.5%	3.7%
	C /AI /P /N /N	921.3	0.28						1.5	0.8%	1.2%
		986.1	0.32	940.2	0.53	3802.6	0.25	2.1%	0.9	0.8%	0.8%
		955.0	0.36						1.4	1.4%	1.1%

*Coefficient of variation (CV) = Standard deviation/Average

4.6.5 Centralised inventory control and inventory visibility in a supply chain with identical wards, one of which an ER

The models of centralised quasi-arborescent supply chains with an ER (i.e., a ward that is given priority in case of insufficient inventory on hand at the DC) and two identical ordinary wards are very similar to those of quasi-arborescent supply chains with three identical wards, because, in both cases, the quantity ordered by the wards to the DC equals the daily demand at the ward. Therefore, no matter what happens in terms of the need to ration the inventory distributed at the DC, the wards will maintain their ordering policy (that is the same on the two systems). This is why the demands passed to the DC are exactly the same in the two models of centralised supply chains (see Table 4.24). Another reason for the similarities between the results of the two systems is the fact that, at the DC, the unfulfilled orders are back-ordered, therefore if the orders of ward 1 or 2 are prevailed relatively to those of the ER on a given day, they will receive the requested units a few (around three) days later, as can be observed in Figure 4.41 (similar, and consistent, graphs obtained from simulations of the models with daily demands generated using processes 2 to 4 are presented in Appendix 4.25). Thus, when priority was given to the ER, occasional delays of approximately three days in the fulfilment of some units to the ordinary wards were caused. At the traditional systems, such regularity cannot be found because the quantities ordered by the wards are adjusted depending on the inventory on hand they have. Therefore, if less quantity is received, a higher quantity will be ordered, and, if there are over-ordering effects, these can be triggered.

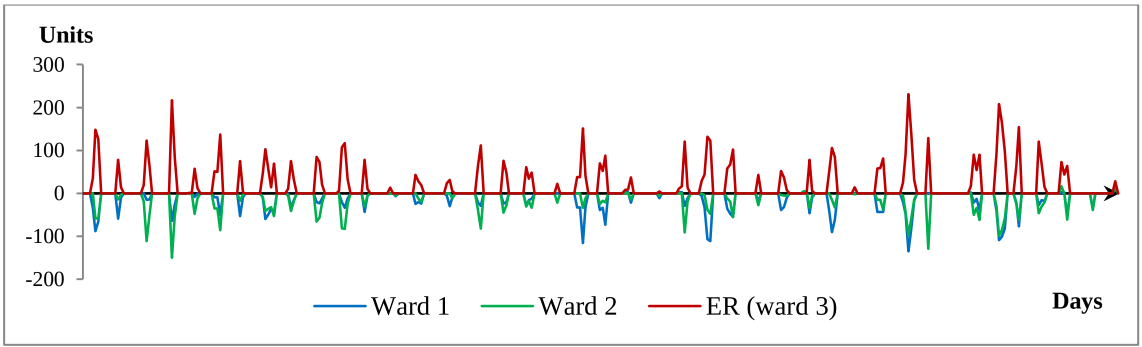

Figure 4.41 Centralised quasi-arborescent SC, demands generated with process 1: accumulated differences between quantities supplied to the wards (*Ward orders fulfilment*) on the system with one ER and two wards and in a similar system with three identical wards

Table 4.24 Centralised inventory control in a SC with one DC and three identical wards (with emergency deliveries from the DC): demand at the various SC echelons – ER with priority in the replenishments from the DC versus all wards with equal priority

		DC orders to the supplier			Ward orders to the DC			Daily demand		
		Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
Process 1	T /AI+ER /P /N /N	322.7	383.6	1.19	291.8	229.6	0.79			
					96.4	139.6	1.45	112.2	81.5	0.73
					93.0	141.9	1.53	106.8	84.4	0.79
					102.5	143.8	1.40	115.8	85.4	0.74
	C /AI /P /N /N	338.7	307.1	0.91	334.7	144.9	0.43			
					112.2	81.5	0.73	112.2	81.5	0.73
	C /AI+ER /P /N /N	338.5	306.8	0.91	106.8	84.4	0.79	106.8	84.4	0.79
					115.8	85.4	0.74	115.8	85.4	0.74
Process 2	T /AI+ER /P /N /N	325.4	392.8	1.21	295.5	277.4	0.94			
					98.5	154.5	1.57	110.3	99.2	0.90
					101.7	150.2	1.48	115.0	96.5	0.84
					95.4	161.7	1.69	110.1	101.1	0.92
	C /AI /P /N /N	337.8	315.6	0.93	335.3	169.4	0.51			
					110.3	99.2	0.90	110.3	99.2	0.90
	C /AI+ER /P /N /N	337.8	315.6	0.93	115.0	96.5	0.84	115.0	96.5	0.84
					110.1	101.1	0.92	110.1	101.1	0.92
Process 3	T /AI+ER /P /N /N	403.0	552.0	1.37	367.2	407.0	1.11			
					133.3	266.5	2.00	141.8	186.8	1.32
					110.5	234.6	2.12	125.4	159.6	1.27
					123.4	253.8	2.06	140.9	172.0	1.22
	C /AI /P /N /N	414.1	474.7	1.15	408.1	302.7	0.74			
					141.8	186.8	1.32	141.8	186.8	1.32
	C /AI+ER /P /N /N	414.5	478.6	1.15	125.4	159.6	1.27	125.4	159.6	1.27
					140.9	172.0	1.22	140.9	172.0	1.22
Process 4	T /AI+ER /P /N /N	358.1	499.7	1.40	326.4	350.0	1.07			
					111.9	198.3	1.77	123.4	131.4	1.06
					105.6	187.3	1.77	118.1	138.5	1.17
					108.9	233.0	2.14	125.3	156.6	1.25
	C /AI /P /N /N	373.1	387.3	1.04	366.8	245.6	0.67			
					123.4	131.4	1.06	123.4	131.4	1.06
	C /AI+ER /P /N /N	374.5	382.9	1.02	118.1	138.5	1.17	118.1	138.5	1.17
					125.3	156.6	1.25	125.3	156.6	1.25

*Coefficient of variation (CV) = Standard deviation/Average

In Figure 4.42, we compare the accumulated lost demand resulting from the centralised systems with priority given to the ER with the lost demand when inventory is allocated proportionally to wards pending orders simulated with daily demands generated through process 1 (similar graphs obtained from simulations of the models with daily demands generated using processes 2 to 4 are available in Appendix 4.25). We can observe that the system giving priority to the ER resulting in a worst service level at ward 1 and ward 2 and a better service level at the ER. When daily demand was generated using process 2 the results were similar to those of process 1. With process 3 the same patterns was observed, but the improvement of the service level at the ER is minimal, being much lower than the negative impact obtained at ward 1 and 2. Finally, when simulations with demand generated through process 4 were run, the service level decreased at all the wards with the priority given to the ER in inventory allocation.

Table 4.25 Centralised inventory control in a SC with one DC and three identical wards (with emergency deliveries from the DC): inventory levels and lost demand – ER with priority in the replenishments from the DC versus all wards with equal priority

		Inventory level							Lost demand		
		At the ward		At the DC		At the whole hospital			Average (units per day)	% days w/ lost demand	% of lost demand
		Average	CV*	Average	CV*	Average	CV*	Difference to lowest			
Process 1	T /AI+ER /P /N /N	441.7	0.74						5.2	6.3%	4.6%
		469.3	0.73	907.2	0.54	2275.5	0.37	1.1%	5.5	6.3%	5.2%
		457.3	0.67						3.0	3.6%	2.6%
	C /AI /P /N /N	468.5	0.34						1.5	1.6%	1.3%
		524.2	0.29	661.2	0.54	2250.3	0.24	0.0%	1.3	2.2%	1.2%
		596.5	0.29						1.3	2.2%	1.2%
	C /AI+ER /P /N /N	543.4	0.32						1.8	2.2%	1.6%
		571.9	0.29	660.8	0.53	2326.1	0.23	3.4%	1.6	1.4%	1.5%
		550.1	0.27						1.1	1.1%	1.0%
Process 2	T /AI+ER /P /N /N	569.1	0.74						4.7	5.8%	4.2%
		546.2	0.73	970.6	0.49	2663.3	0.34	8.8%	5.7	4.7%	4.9%
		577.4	0.70						2.5	2.7%	2.3%
	C /AI /P /N /N	460.3	0.35						0.6	0.8%	0.5%
		677.7	0.37	727.7	0.51	2447.7	0.25	0.0%	1.7	1.1%	1.5%
		582.0	0.30						1.0	1.1%	0.9%
	C /AI+ER /P /N /N	523.2	0.33						0.8	0.5%	0.7%
		728.9	0.40	728.2	0.51	2580.3	0.25	5.4%	2.0	1.1%	1.7%
		600.0	0.29						0.9	0.8%	0.8%
Process 3	T /AI+ER /P /N /N	1268.5	0.74						7.4	2.5%	5.2%
		985.1	0.66	1403.6	0.50	4809.4	0.33	0.5%	3.1	2.7%	2.4%
		1152.3	0.83						6.0	3.3%	4.2%
	C /AI /P /N /N	1228.3	0.44						3.5	1.6%	2.4%
		1103.4	0.30	1217.7	0.52	4785.0	0.26	0.0%	1.4	1.6%	1.1%
		1235.5	0.31						2.7	2.2%	1.9%
	C /AI+ER /P /N /N	1310.5	0.48						3.9	1.6%	2.8%
		1160.1	0.30	1221.7	0.52	4939.4	0.27	3.2%	1.6	1.6%	1.3%
		1247.1	0.31						2.6	1.9%	1.8%
Process 4	T /AI+ER /P /N /N	856.6	0.80						4.8	4.1%	3.9%
		770.9	0.76	1158.4	0.51	3815.7	0.36	0.7%	5.2	4.4%	4.4%
		1029.8	0.83						8.1	4.7%	6.5%
	C /AI /P /N /N	921.3	0.28						1.5	0.8%	1.2%
		986.1	0.32	940.2	0.53	3802.6	0.25	0.4%	0.9	0.8%	0.8%
		955.0	0.36						1.4	1.4%	1.1%
	C /AI+ER /P /N /N	917.7	0.29						1.7	1.1%	1.4%
		985.8	0.31	929.0	0.50	3787.8	0.2	0.0%	1.1	1.1%	0.9%
		955.3	0.37						1.6	1.9%	1.2%

*Coefficient of variation (CV) = Standard deviation/Average

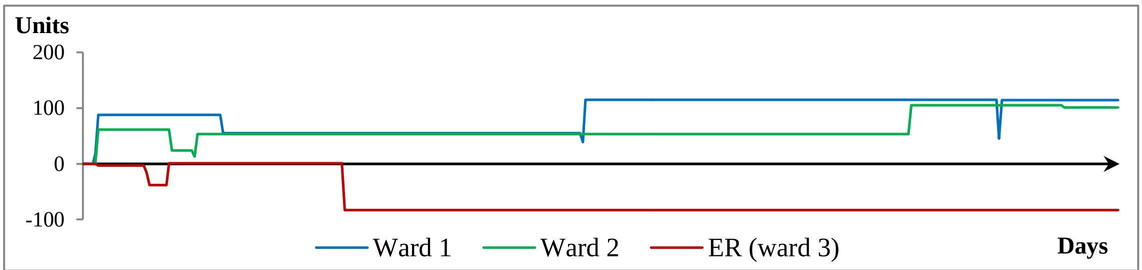

Figure 4.42 Centralised quasi-arborescent SC, demands generated with process 1: accumulated differences between lost demand in the system with one ER and two wards and in a similar system with three identical wards

4.6.6 Supply chain with different wards

In this subsection, we describe the results of the performed simulations relative to the application of alternative supply chain management processes to an hospital supply chain with three different wards, the daily demands of which are based on the characteristics of the samples collected from a real hospital system (see Appendix 4.9) and were generated using the processes described at the end of section 4.1 (p.115). It must be noted that the two simulated centralised models without lateral transshipments do not differ relatively to the way the orders to the DC are made: order daily a quantity equal to the demand faced.

The alternatives simulated include systems with reactive lateral transshipment from ward 1 or ward 2 to the ER when the inventory on hand at the ER is not enough to fulfil all demand faced there. Considering that, in the simulated systems, stock-outs (and lost demand) at the wards are relatively rare events, mainly when we simulate systems with centralised inventory control, in addition to the simulations for a period of 365 days (1 year), that are comparable with the simulations described in the previous subsections for ward 1, we performed simulations for periods of 1100 days (around 3 years), so that data series with a higher number of such events could be obtained.

In Table 4.26, we compare the impacts upon the ward that has the same daily demand in the quasi-arborescent model with identical and different wards (i.e., ward 1). In most of the traditional systems, the fact that the wards are considered different resulted in higher and more frequent stock-outs at ward 1 (the ward with lower and less variable daily demand of the three considered). On the centralised systems, when different demands are considered, the service level at ward 1 improves (i.e., the stock-outs' frequency and level decrease). In the traditional systems, when lateral transshipments to the ER are simulated, the service level at ward 1 decreases, which was expectable, since the lateral transshipments scheme modelled assumes that lost demand at the ER is more serious than at the other wards, and thus, may involve the fulfilment of ER demand using ward 1 inventory. Nevertheless, in the centralised systems with transshipments, the service level at ward 1 is not harmed (this can be confirmed by comparison of the data in Table 4.28, where results from simulations of all centralised models considering 1100 days are available).

Table 4.26 Quasi-arborescent supply chain with one DC and 3 wards: comparison of the inventory levels at ward 1 in the systems with identical and different wards

	Inventory		Lost demand		
	At the ward				
	Average	CV*	Average (units per day)	% days w/ lost demand	% of lost demand
Traditional systems with over and under-ordering effects at the wards:					
T /AI /P /O+U /N	547.9	0.76	4.7	5.5%	4.2%
T /AD /P /O+U /N	532.9	0.75	4.2	4.7%	3.8%
T /AD+L /P /O+U /N	547.7	0.84	7.0	5.2%	6.2%
T /AI+ER /P /O+U /N	552.1	0.83	3.4	4.4%	3.0%
T /AD+ER /P /O+U /N	639.1	0.76	6.4	5.5%	5.7%
T /AD+ER+L /P /O+U /N	780.0	0.93	9.0	8.5%	8.0%
Traditional systems with no ordering effects:					
T /AI /P /N /N	444.5	0.72	4.3	5.8%	3.8%
T /AD /P /N /N	422.6	0.77	6.2	6.8%	5.5%
T /AD+L /P /N /N	411.3	0.76	5.6	7.1%	5.0%
T /AI+ER /P /N /N	441.7	0.74	5.2	6.3%	4.6%
T /AD+ER /P /N /N	517.8	0.77	8.3	8.2%	7.4%
T /AD+ER+L /P /N /N	520.6	0.91	10.1	7.9%	9.0%
Centralised systems with no ordering effects:					
C /AI /P /N /N	468.5	0.34	1.5	1.6%	1.3%
C /AD /P /N /N	435.5	0.32	0.5	0.8%	0.4%
C /AD+L /P /N /N†	524.0	0.29	0.2	0.4%	0.1%
C /AI+ER /P /N /N	543.4	0.32	1.8	2.2%	1.6%
C /AD+ER /P /N /N	558.0	0.31	0.9	1.1%	0.8%
C /AD+ER+L /P /N /N†	676.5	0.31	0.3	0.6%	0.3%

* Coefficient of variation (CV) = Standard deviation/Average

† Unlike all other results in the table, that were obtained from simulations considering periods of 365 days, the results for these models were obtained considering periods of 1100 days, so that a minimum number of lost sales occurrences could be obtained.

In Table 4.27 and Table 4.28, we present, respectively, some measures analysing the demands faced describing the resulting inventory levels at the various supply chain echelons.

Table 4.27 Quasi-arborescent supply chain with one DC and 3 different wards: demand at the various supply chain echelons – comparison of different SC processes

	DC orders to the supplier			Ward orders to the DC			Daily demand		
	Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
T /AD /P /O+U /N	1088.1	1822.2	1.67	990.4	1424.5	1.44			
				100.9	170.9	1.69	112.2	81.5	0.73
				182.7	360.5	1.97	203.8	184.1	0.90
				706.8	1291.4	1.83	764.2	762.8	1.00
T /AD /P /O+U /N (1100 days)	1037.1	1806.6	1.74	947.9	1472.8	1.55			
				99.5	184.1	1.85	112.3	85.6	0.76
				182.3	355.1	1.95	204.8	182.2	0.89
				666.0	1369.4	2.06	740.5	733.2	0.99
T /AD+L /P /O+U /N (1100 days)	1050.5	1713.7	1.63	978.8	1479.2	1.51			
				113.6	191.5	1.69	112.3	85.6	0.76
				208.5	383.2	1.84	204.8	182.2	0.89
				656.6	1309.8	1.99	740.5	733.2	0.99

	DC orders to the supplier			Ward orders to the DC			Daily demand		
	Average	Standard deviation	CV*	Average	Standard deviation	CV*	Average	Standard deviation	CV*
T /AD /P /N /N	1081.8	1563.3	1.45	968.4	1292.9	1.34			
				99.0	137.9	1.39	112.2	81.5	0.73
				179.2	289.5	1.62	203.8	184.1	0.90
				690.2	1188.3	1.72	764.2	762.8	1.00
T /AD /P /N /N (1100 days)	1033.9	1524.1	1.47	932.5	1206.9	1.29			
				97.6	142.3	1.46	112.3	85.6	0.76
				179.6	285.6	1.59	204.8	182.2	0.89
				655.3	1136.7	1.73	740.5	733.2	0.99
T /AD+L /P /N /N (1100 days)	1045.9	1527.5	1.46	962.1	1205.5	1.25			
				111.3	147.5	1.33	112.3	85.6	0.76
				206.9	292.0	1.41	204.8	182.2	0.89
				644.0	1050.3	1.63	740.5	733.2	0.99
T /AD+ER /P /O+U /N	1070.5	1745.8	1.63	969.2	1486.2	1.53			
				97.6	182.8	1.87	112.2	81.5	0.73
				184.9	340.5	1.84	203.8	184.1	0.90
				686.7	1412.4	2.06	764.2	762.8	1.00
T /AD+ER /P /O+U /N (1100 days)	1043.3	1654.5	1.59	944.9	1438.7	1.52			
				98.2	191.5	1.95	112.3	85.6	0.76
				180.0	375.7	2.09	204.8	182.2	0.89
				666.7	1371.3	2.06	740.5	733.2	0.99
T /AD+ER+L /P /O+U /N (1100 days)	1037.0	1582.8	1.53	986.0	1378.2	1.40			
				117.2	199.3	1.70	112.3	85.6	0.76
				212.1	392.3	1.85	204.8	182.2	0.89
				656.7	1252.9	1.91	740.5	733.2	0.99
T /AD+ER /P /N /N	1078.8	1521.6	1.41	961.0	1206.9	1.26			
				95.4	145.6	1.53	112.2	81.5	0.73
				178.4	287.7	1.61	203.8	184.1	0.90
				687.2	1167.6	1.70	764.2	762.8	1.00
T /AD+ER /P /N /N (1100 days)	1032.4	1488.5	1.44	928.9	1148.7	1.24			
				96.3	148.2	1.54	112.3	85.6	0.76
				177.3	285.9	1.61	204.8	182.2	0.89
				655.3	1122.9	1.71	740.5	733.2	0.99
T /AD+ER+L /P /N /N (1100 days)	1026.6	1519.1	1.48	949.1	1222.0	1.29			
				110.2	155.0	1.41	112.3	85.6	0.76
				199.9	306.6	1.53	204.8	182.2	0.89
				638.9	1041.5	1.63	740.5	733.2	0.99
C /AD /P /N /N	1091.8	1266.4	1.16	1080.2	785.8	0.73			
				112.2	81.5	0.73	112.2	81.5	0.73
C /AD+ER /P /N /N	1091.5	1259.8	1.15	203.8	184.1	0.90	203.8	184.1	0.90
				764.2	762.8	1.00	764.2	762.8	1.00
C /AD /P /N /N (1100 days)	1060.6	1184.2	1.12	1057.7	752.8	0.71			
				112.3	85.6	0.76	112.3	85.6	0.76
C /AD+ER /P /N /N (1100 days)	1060.5	1184.7	1.12	204.8	182.2	0.89	204.8	182.2	0.89
				740.5	733.2	0.99	740.5	733.2	0.99
C /AD+L /P /N /N (1100 days)	1059.4	1182.1	1.12	1057.7	752.8	0.71			
				112.7	85.5	0.76	112.3	85.6	0.76
				206.6	185.2	0.90	204.8	182.2	0.89
				738.4	729.8	0.99	740.5	733.2	0.99
C /AD+ER+L /P /N /N (1100 days)	1059.3	1191.0	1.12	1057.7	752.8	0.71			
				112.7	85.5	0.76	112.3	85.6	0.76
				207.8	187.3	0.90	204.8	182.2	0.89
				737.2	726.2	0.99	740.5	733.2	0.99

*Coefficient of variation (CV) = Standard deviation/Average

Table 4.28 Quasi-arborescent supply chain with one DC and 3 different wards: inventory levels at the various supply chain echelons – comparison of different SC processes

	Inventory level							Lost demand		
	At the ward		At the DC		At the whole hospital			Average (units per day)	% days w/ lost demand	% of lost demand
	Average	CV*	Average	CV*	Average	CV*	% difference no transship.			
T /AD /P /O+U /N	532.9	0.75						4.2	4.7%	3.8%
	1260.7	0.77	5038.4	0.50	11782.6	0.46	-	4.4	2.7%	2.2%
	4950.6	0.80						19.9	2.2%	2.6%
T /AD /P /O+U /N (1100 days)	622.0	0.78						4.3	4.1%	3.8%
	1262.2	0.74	5254.5	0.50	12510.6	0.45	0.0%	4.0	2.7%	2.0%
	5371.9	0.83						19.3	2.2%	2.6%
T /AD+L /P /O+U /N (1100 days)	569.3	0.78						5.3	4.1%	4.7%
	1283.2	0.79	5186.4	0.50	11888.2	0.44	-5.0%	6.8	3.3%	3.3%
	4849.3	0.79						3.9	0.8%	0.5%
T /AD /P /N /N	422.6	0.77						6.2	6.8%	5.5%
	985.5	0.68	4471.4	0.48	10061.4	0.42	-	8.2	3.8%	4.0%
	4182.0	0.74						19.6	3.3%	2.6%
T /AD /P /N /N (1100 days)	446.9	0.73						4.7	4.7%	4.2%
	954.8	0.70	4331.9	0.49	10140.8	0.44	0.0%	5.0	2.5%	2.4%
	4407.3	0.78						19.5	3.0%	2.6%
T /AD+L /P /N /N (1100 days)	443.3	0.75						4.7	5.3%	4.2%
	922.5	0.75	4245.8	0.48	9519.0	0.42	-6.1%	6.9	4.5%	3.4%
	3907.3	0.79						8.1	1.4%	1.1%
T /AD+ER /P /O+U /N	639.1	0.76						6.4	5.5%	5.7%
	1403.9	0.80	5481.7	0.51	12671.9	0.44	-	6.4	3.3%	3.1%
	5147.1	0.74						7.9	2.2%	1.0%
T /AD+ER /P /O+U /N (1100 days)	742.6	0.86						5.4	4.5%	4.8%
	1561.0	0.84	5262.0	0.50	12638.3	0.41	0.0%	7.8	3.2%	3.8%
	5072.7	0.75						8.0	1.6%	1.1%
T /AD+ER+L /P /O+U /N (1100 days)	773.5	0.91						7.8	6.8%	6.9%
	1526.6	0.92	5263.3	0.53	12113.8	0.43	-4.2%	10.6	4.8%	5.2%
	4550.5	0.81						3.4	0.6%	0.5%
T /AD+ER /P /N /N	517.8	0.77						8.3	8.2%	7.4%
	1060.7	0.78	4338.1	0.51	10201.9	0.51	-	10.5	5.8%	5.1%
	4285.4	0.78						17.3	2.2%	2.3%
T /AD+ER /P /N /N (1100 days)	518.0	0.76						5.1	4.9%	4.6%
	1059.6	0.80	4151.1	0.51	10034.5	0.43	0.0%	9.8	4.5%	4.8%
	4305.7	0.79						18.4	2.2%	2.5%
T /AD+ER+L /P /N /N (1100 days)	600.8	0.91						10.5	8.3%	9.3%
	1177.7	0.88	4579.7	0.53	10184.0	0.45	1.5%	17.2	7.3%	8.4%
	3825.7	0.79						8.8	1.4%	1.2%
C /AD /P /N /N	435.5	0.32						0.5	0.8%	0.4%
	977.7	0.33	3233.0	0.53	10026.2	0.25	-	1.2	0.8%	0.6%
	5380.0	0.27						10.6	1.4%	1.4%
C /AD /P /N /N (1100 days)	514.3	0.28						0.2	0.3%	0.1%
	1163.3	0.28	3074.4	0.50	10344.6	0.21	0.0%	0.4	0.3%	0.2%
	5592.7	0.22						3.5	0.5%	0.5%
C /AD+L /P /N /N (1100 days)	524.0	0.29						0.2	0.4%	0.1%
	1374.0	0.23	3109.3	0.51	10228.4	0.22	-1.1%	1.1	0.5%	0.6%
	5221.1	0.24						3.9	0.4%	0.5%
C /AD+ER /P /N /N	558.0	0.31						0.9	1.1%	0.8%
	1053.3	0.34	3219.9	0.52	10217.7	0.25	-	1.5	1.1%	0.7%
	5386.5	0.26						10.6	1.4%	1.4%
C /AD+ER /P /N /N (1100 days)	705.4	0.28						0.4	0.5%	0.4%
	1190.9	0.28	3106.6	0.51	10624.7	0.20	0.0%	0.5	0.4%	0.2%
	5621.7	0.21						3.5	0.5%	0.5%
C /AD+ER+L /P /N /N (1100 days)	676.5	0.31						0.3	0.6%	0.3%
	1639.2	0.22	3082.1	0.50	10285.4	0.22	-3.2%	1.4	0.6%	0.7%
	4887.6	0.25						3.7	0.4%	0.5%

*Coefficient of variation (CV) = Standard deviation/Average

In Figure 4.43, we present a graph comparing the average total inventory level and the average lost demand of the alternative systems simulated (the alternatives in the graph are sorted by ascending order of the average total inventory.

We could expect that systems with higher inventory levels would result in better service levels. However, this was not always the case. Observing Figure 4.43 in combination with Table 4.27 and Table 4.28, we can highlight the following results:

- a significant rise in the average total inventory can be observed when over and under-ordering effects are simulated;
- the models with centralised inventory control are the ones that achieve the best results in terms of service level at the wards, without very significant increases in terms of the average inventory level (the system that resulted in the lowest inventory level had, on average, 8.8 days of inventory on hand in the whole hospital, while the centralised systems resulted in, on average, 9.5 to 9.8 days of inventory on hand in the whole hospital).
- in general, the systems with priority given to the ER resulted in an improvement of the service level at the ER, but this was achieved through a higher inventory in the whole system and, as expected, a lower service level in the other wards;
- the centralised systems resulted in higher average inventory at the wards, although with lower variability, and lower average inventory at the DC;
- the variability of the inventory level at the wards is much lower at the centralised systems, which results in fewer and lower stock-outs;
- at the centralised systems, the ward with higher and more frequent stock-outs was the one with the higher daily demand level and variability (ER or ward 3); when priority in inventory allocation was given to this ward, the stock-outs at the other wards increased but at this ward they were not reduced;
- in general, the simulation of lateral transshipments resulted in an improvement of the service level at the ER (the exception of the centralised systems will be further analysed, and the results of this analysis will show that it was due to instability in an initial phase of the simulation), without a very significant increase in the average inventory level;
- the simulation of lateral transshipments without giving priority to the ER in the allocation of inventory has always outperformed the systems with priority given to the ER (with or without lateral transshipments), both in terms of total inventory level and service level.

The system that resulted in the lowest average inventory level was the traditional one, with the wards having the same priority in inventory allocation, with lateral transshipments to the ER and emergency direct deliveries of the DC (to satisfy demand at all wards) and no ordering effects (T /AD+L /P /N/ N), but the centralised systems resulted in best service levels (see Figure 4.43).

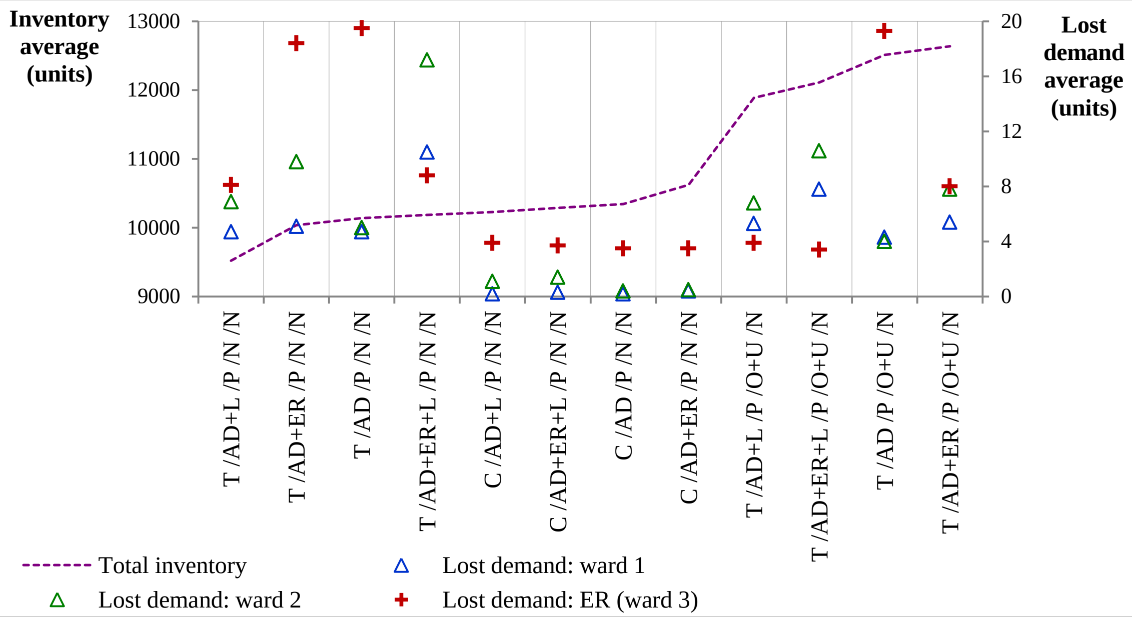

Figure 4.43 Quasi-arborescent supply chain with 3 different wards: comparison of the various systems in terms of total inventory level and lost demand.

In Figure 4.44, Figure 4.45 and Figure 4.46, we compare the lost demand at the three wards obtained with the centralised systems with lateral transshipments and with the same systems without lateral transshipments: if the lines are above the horizontal axis line, the accumulated[52] lost demand of the system with lateral transshipments to the ER has been higher than the accumulated lost demand of the same system without lateral transshipments. In Figure 4.47, we present a similar comparison of the total inventory level.

In Figure 4.45 and Figure 4.46, we can observe that the difference between the most significant changes in the accumulated differences between the systems with lateral transshipments and the system without that possibility occur at the beginning of the simulation (before period 75). We can also observe in Figure 4.47 that the behaviour pattern of the series before day 75 is different from that observed after that day. This was a consequence of the initiation of the simulation. As a consequence, we decided to compare the results of the models that attained better results – model T/AD+L/ P/ N/ N and the models with centralised inventory control - only after this initial period (from day 76 to day 1100). The obtained results are summarised in Table 4.29.

[52] Since the beginning of the simulation.

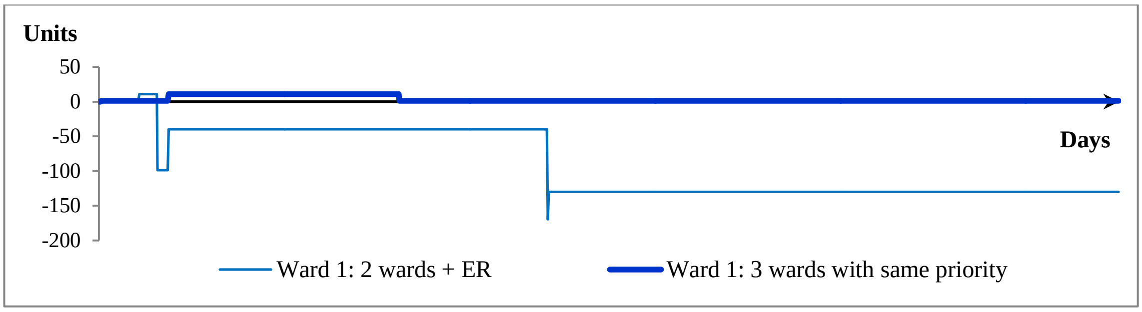

Figure 4.44 Quasi-arborescent supply chain with 3 different wards: accumulated differences between lost demand at ward 1 in the centralised systems with lateral transshipments and the same systems without lateral transshipments

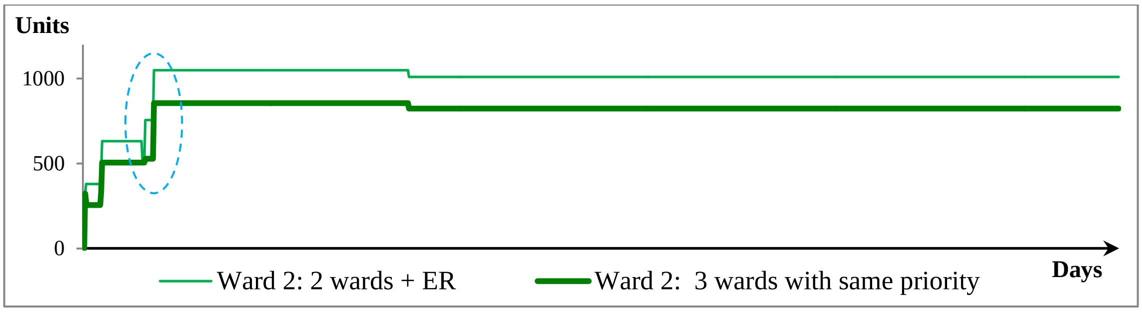

Figure 4.45 Quasi-arborescent supply chain with 3 different wards: accumulated differences between lost demand at ward 2 in the centralised systems with lateral transshipments and the same systems without lateral transshipments

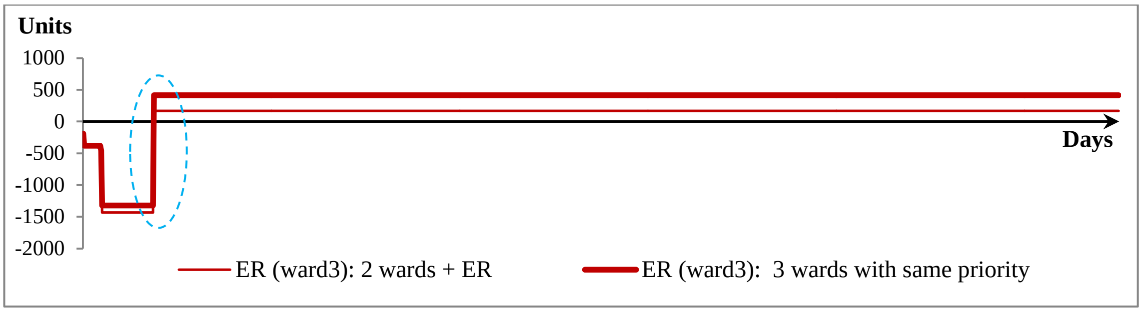

Figure 4.46 Quasi-arborescent supply chain with 3 different wards: accumulated differences between lost demand at the ER (ward 3) in the centralised systems with lateral transshipments and the same systems without lateral transshipments

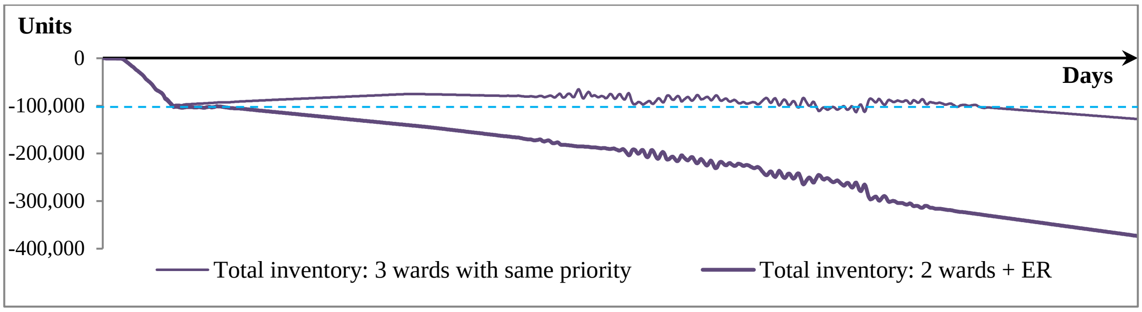

Figure 4.47 Quasi-arborescent supply chain with 3 different wards: accumulated differences the total inventory in the centralised systems with lateral transshipments and the same systems without lateral transshipments

Table 4.29 Quasi arborescent supply chain with 3 different wards: total inventory and lost demand, excluding the first 75 days of simulation, resulting from the best models

		Simulated system				
		Traditional/ Same priority/ Lateral transshipments	Centralised control/ Same priority/ Lateral transshipments	Centralised control/ Priority to the ER/ Lateral transshipments	Centralised control/ Same priority/ No lateral transshipments	Centralised control/ Priority to the ER/ No lateral transshipments
		T/AD+L/P/N/N	C/AD+L/P/N/N	C/AD+ER+L/P/N/N	C/AD/P/N/N	C/AD+ER /P/N/N
Total inventory average		9499.2	10473.1	10538.0	10500.6	10801.8
% difference to the lowest		0.0%	10.3%	10.9%	10.5%	13.7%
Days of inventory on hand (whole system)		8.8	9.7	9.8	9.7	10.0
Lost demand average	Ward 1	4.2	0.005	0.039	0.015	0.127
	Ward 2	5.2	0.000	0.000	0.032	0.039
	ER (ward 3)	7.3	0.000	0.000	0.000	0.000

The traditional systems with all the wards having the same type of probability and lateral transshipments to the ward (T /AD+L /P /N /N) was the one resulting in the lower total inventory average. The results of the models assuming centralised inventory control do not vary much: although they resulted in higher inventory averages than the T /AD+L /P /N /N model, the obtained service level at the three wards was significantly lower. The model with centralised inventory with all the wards having the same type of priority in inventory allocation and lateral transshipments to the ward (C /AD+L /P/ N /N) was the model with centralised inventory control that resulted in the lowest average inventory level.

Afterwards, we determined an approximate estimate of the maximum total inventory level at the wards and in the whole system if the supply chain supplied 20 items similar to the one considered in our analysis (see the details of the calculations performed in subsection 4.5.5, p.136), i.e., items with the same daily demand distribution and approximately the same size, considering the T /AD+L /P /N /N and the C /AD+L /P/ N /N systems. The relative difference of the maximum inventory level with the centralised system relatively to the traditional one is presented in Table 4.30. The lost demand is a sum of the lost demand for the 20 items, assuming that they are independent (e.g., there are not substitute items in the lot of 20).

Table 4.30 Quasi arborescent supply chain with 3 different wards: total inventory and lost demand, excluding the first 75 days of simulation, comparison of the maximum total inventory resulting from the best models if there are 20 items similar to the one analysed in the supply chain

		Simulated system				
		Traditional/ Same priority/ Lateral transshipments	Centralised control/ Same priority/ Lateral transshipments	Centralised control/ Priority to the ER/ Lateral transshipments	Centralised control/ Same priority/ No lateral transshipments	Centralised control/ Priority to the ER/ No lateral transshipments
		T/AD+L/P/N/N	C/AD+L/P N/N	C/AD+ER+L/P/N/N	C/AD/P/N/N	C/AD+ER /P/N/N
Maximum total inventory (% difference to the lowest, % DL)		0.0%	-3.1%	-2.7%	-3.0%	-0.4%
Maximum inventory (% DL)	Ward 1	0.0%	-5.9%	23.4%	-8.1%	25.7%
	Ward 2	0.0%	21.6%	43.7%	6.6%	8.9%
	ER (ward 3)	0.0%	2.6%	-3.3%	7.6%	7.8%
Total inventory average (% DL)		0.0%	10.3%	10.9%	10.5%	13.7%
Lost demand average (units)	Ward 1	84.6	0.1	0.8	0.3	2.5
	Ward 2	103.2	0.0	0.0	0.6	0.8
	ER (ward 3)	146.7	0.0	0.0	0.0	0.0

If the number of items considered was higher than 38, the C /AD+L /P/ N /N system would always have a higher maximum inventory level in the whole hospital (thus requiring more storage space) than the T /AD+L /P /N /N system.

4.7 Summary of results and discussion

Models of serial supply chains with one ward, one DC and at least one external supplier

In Figure 4.48, we present a summary of the results of the simulations of models representing serial supply chains with one ward, one DC and at least one external supplier. In the figure, the symbols represent a comparison of systems with an added feature (above) relatively to systems without that feature (below). It must be noted that, relatively to ordering effects on the DC and the systems with no possibility of emergency deliveries from the DC, we have performed simulation experiments for the traditional systems (i.e., systems with decentralised inventory control).

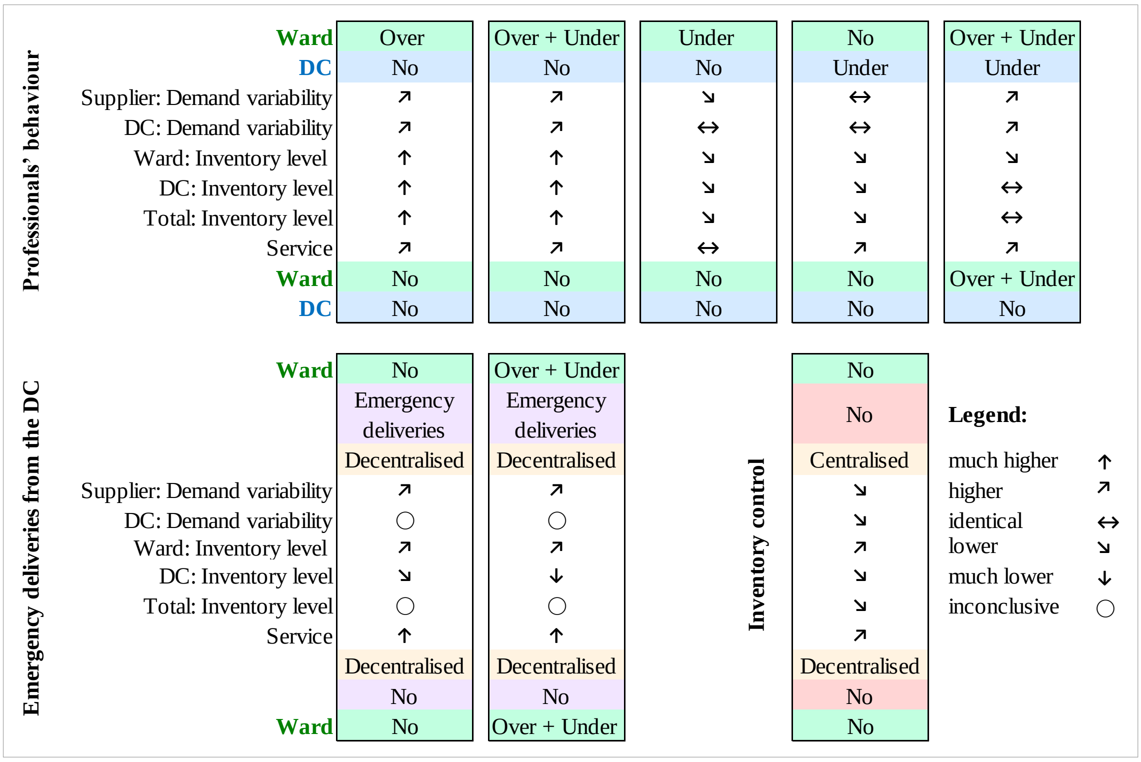

Figure 4.48 Summary of the simulation results of the models of serial supply chains

From the obtained results, we emphasise the following:

- over-ordering effects at the wards, even when combined with under ordering effects at the ward, have resulted in significant increases in the inventory levels both at the ward and at the DC; these increases resulted in improvements in terms of service level, but these improvements were modest relatively to the inventory increases observed; when generated demands with higher variability were used to perform the simulations, the over-ordering effects resulted in significantly higher average inventory levels without the corresponding benefit in terms of increased service level;
- the modelled under-ordering effects at the DC seem to have positive consequences in terms of inventory level and service level;
- the possibility of emergency deliveries from the DC resulted in a significant improvement in the service level, without significantly increasing the total inventory level in the system; since in a hospital supply chain a high service level is considered important, these feature was maintained in subsequent models (e.g., the models of supply chains with centralised inventory control).
- the centralisation of inventory control resulted in a significant decrease of the inventory levels at the DC and in an increase of the inventory levels at the wards, which generally caused a decrease on the total inventory level on the whole system; additionally, an increase in the service level was also observed.

Models of quasi-arborescent supply chains with three identical wards, one DC and at least one external supplier

In Figure 4.49, we present a summary of the results of the simulations of models representing quasi-arborescent supply chains with three identical wards (i.e., with daily demands with the same distribution), one DC and at least one external supplier (or three serial supply chains for serving the same three daily demands).

As was observed for the serial models, the models of quasi-arborescent supply chains with identical wards with over-ordering effects have always resulted in much higher average inventory levels. In terms of service level, improvements have been observed, but in the models that use the rule of allocating DC inventory to the wards proportionally to the ratio of the pending orders of each ward over the total pending orders, despite the significant increase in the inventory levels, the results in terms of service level were mixed.

The models of traditional supply chains (i.e., with decentralised inventory control) that serve the demand at the three wards through a quasi-arborescent supply chain instead of through three parallel and independent serial supply chains resulted in much lower inventory levels at the DC, but the service level at the wards decreased. In our simulation experiments, some policy parameters have not been change. In this case, possibly the service level at the wards could be improved through an increase in the *Ward protection level.* Such a change would increase the average inventory level at the wards, but some calibration could be made to assure that the increase is lower than the decrease of the average inventory level at the DC resulting from the use of a centralised system.

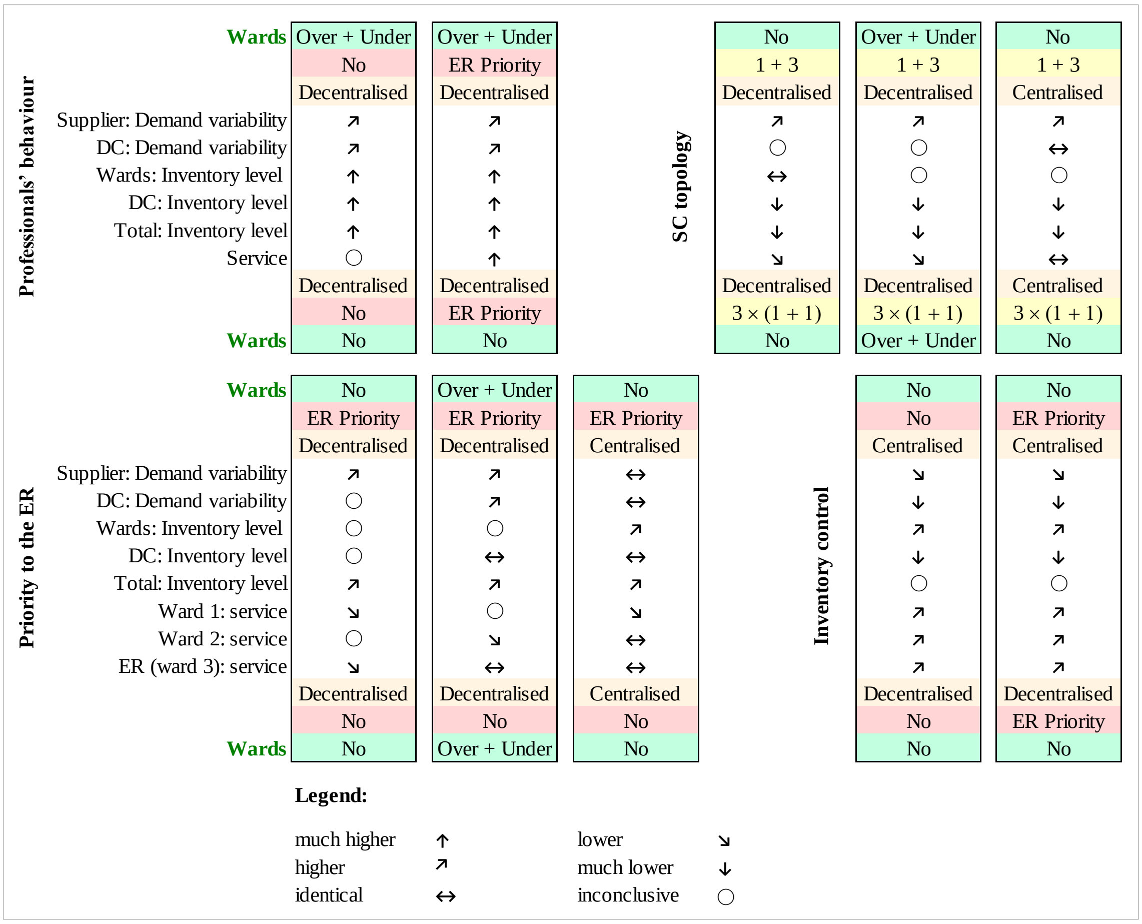

Figure 4.49 Summary of the simulation results of the models of quasi-arborescent supply chains with identical wards

Relatively to the comparison of the results of the simulations of the systems with priority in DC inventory allocation given to the ER versus the results of the simulations of the systems that allocate DC inventory to the wards proportionally to the ratio of the pending orders of each ward over the total pending orders, the total average inventory level obtained was higher in the systems that give priority to the ER. Additionally, the expected result in terms of service level was not observed: the service level at the ER did not improve.

In terms of the comparison of the models simulating supply chains with centralised inventory control versus the models simulating supply chains with decentralised inventory control, the obtained results were similar to those obtained with the models of serial supply chains: the models considering centralised inventory control resulted in a lower average inventory level at the DC and higher average inventory levels at the wards, being the results in terms of total inventory level uncertain; the service level was better in the simulations of models considering centralised inventory control.

Models of quasi-arborescent supply chains with three different wards, one DC and at least one external supplier

In Figure 4.50, we present a summary of the results of the simulations of models representing quasi-arborescent supply chains with three different wards (i.e., with daily demands with different distributions, based on samples of three real of a real hospital system), one DC and at least one external supplier.

Before commenting on the results obtained from the performed simulations, it is important to recall that the daily demands of the three modelled wards, that are based on samples of the daily demands of three wards of a real hospital system, are very diverse: for example, the average daily demand at the ER is roughly three times higher than the sum of the averages of the daily demands at the other two wards, and the average daily demand of ward 2 is slightly higher than the double of the average daily demand of ward 1.

Comparing the results of the simulation of models considering over and under-ordering effects at the wards with those of the models that do not consider ordering effects, we can observe once again that the average inventory level both at the ward and at the DC, and thus in the whole supply chain, was much higher when ordering effects at the wards were considered. As a trade-off, a better service level at the various wards was attained. It must, however, be noted that the simulation of the systems with centralised inventory control resulted in an even better service level with significantly less inventory.

In general, the systems with priority given to the ER resulted in an improvement of the service level at the ER. However, they resulted in a higher inventory in the whole system and, as expected, in a lower service level in the other wards. At the centralised systems, the ward with higher and more frequent stock-outs was the ER (or ward 3); when priority in inventory allocation was given to this ward, the stock-outs at the other wards increased but at this ward they were not reduced.

The models with centralised inventory control were those that resulted in a higher service level, without very significant increases in terms of the average inventory level relatively to the system that resulted in lower average total inventory level. In terms of inventory levels, they resulted in higher average inventory at the wards, although with lower variability, and lower inventory at the DC.

The simulation of lateral transshipments resulted in an improvement of the service level at the ER without a very significant increase in the average inventory level. The simulation of lateral transshipments without giving priority to the ER in the allocation of inventory has always outperformed the systems with priority given to the ER (with or without lateral transshipments), both in terms of total inventory level and of service level.

Professionals' behaviour

Wards	Over + Under	Over + Under	Over + Under	Over + Under
	No	No	ER Priority	ER Priority
	Decentralised	Decentralised	Decentralised	Decentralised
	No	Lateral Transshipments	No	Lateral Transshipments
Supplier: Demand variability	↗	↗	↗	↗
DC: Demand variability	↗	↗	↗	↗
Wards: Inventory level	↑	↑	↑	↑
DC: Inventory level	↑	↑	↑	↑
Total: Inventory level	↑	↑	↑	↑
Service	↗	↗	↗	↑
	No	Lateral Transshipments	No	Lateral Transshipments
	Decentralised	Decentralised	Decentralised	Decentralised
	No	No	ER Priority	ER Priority
Wards	No	No	No	No

Priority to the ER

Wards	No	Over + Under	No	No	Over + Under	No
	ER Priority	ER Priority	ER Priority	ER Priority	ER Priority	ER Priority
	Decentralised	Decentralised	Centralised	Decentralised	Decentralised	Centralised
	No	No	No	Lateral Transshipments	Lateral Transshipments	Lateral Transshipments
Supplier: Demand variability	↗	↘	↔	↔	↘	↔
DC: Demand variability	↘	↗	↔	↗	↘	↔
Wards: Inventory level	↗	↗	↗	↘	○	↔
DC: Inventory level	↘	↗	↔	↘	↗	↔
Total: Inventory level	↔	↗	↔	↘	↔	↔
Ward 1: service	↘	↘	↔	↓	↘	↔
Ward 2: service	↘	↘	↔	↓	↘	↔
ER (ward 3): service	↗	↗	↔	↔	↔	↔
	No	No	No	Lateral Transshipments	Lateral Transshipments	Lateral Transshipments
	Decentralised	Decentralised	Centralised	Decentralised	Decentralised	Centralised
	No	No	No	No	No	No
Wards	No	Over + Under	No	No	Over + Under	No

Lateral transshipments

Ward	No	Over + Under	No	Over + Under	No	No
	No	No	ER Priority	ER Priority	No	ER Priority
	Decentralised	Decentralised	Decentralised	Decentralised	Centralised	Centralised
	Lateral Transshipments	Lateral Transshipments	Lateral Transshipments	Lateral Transshipments	Lateral Transshipments	Lateral Transshipments
Supplier: Demand variability	↔	↘	↗	↘	↔	↔
DC: Demand variability	↔	↘	↗	↘	↔	↔
Ward: Inventory level	↔	↘	○	↘	↔	○
DC: Inventory level	↔	↘	↗	↔	↔	↔
Total: Inventory level	↔	↘	↗	↘	↔	↔
Ward 1: service	↔	↘	↓	↘	↔	↔
Ward 2: service	↘	↘	↓	↘	↔	↔
ER (ward 3): service	↗	↗	↗	↗	↔	↔
	No	No	No	No	No	No
	Decentralised	Decentralised	Decentralised	Decentralised	Centralised	Centralised
	No	No	ER Priority	ER Priority	No	ER Priority
Ward	No	Over + Under	No	Over + Under	No	No

Inventory control

Ward	No	No	No	No
	No	ER Priority	No	ER Priority
	Centralised	Centralised	Centralised	Centralised
	No	No	Lateral Transshipments	Lateral Transshipments
Supplier: Demand variability	↓	↓	↘	↘
DC: Demand variability	↓	↓	↓	↓
Ward: Inventory level	↗	↗	↑	↑
DC: Inventory level	↘	↘	↘	↓
Total: Inventory level	↔	↗	↗	↗
Ward 1: service	↑	↑	↑	↑
Ward 2: service	↑	↑	↑	↑
ER (ward 3): service	↗	↑	↑	↑
Ward	No	No	Lateral Transshipments	Lateral Transshipments
	Decentralised	Decentralised	Decentralised	Decentralised
	No	ER Priority	No	ER Priority
	No	No	No	No

Legend:

much higher	↑
higher	↗
identical	↔
lower	↘
much lower	↓
inconclusive	○

Figure 4.50 Summary of the simulation results of the models of quasi-arborescent supply chains with different wards

The system whose simulation resulted in the lowest average total inventory level assumed decentralised inventory control (i.e., that decisions at the wards are made locally), with the wards having the same priority in inventory allocation, with lateral transshipments to the ER and the possibility of emergency deliveries from the DC to satisfy unmet demand at all wards, and no ordering effects. On the other hand, the systems with centralised inventory control resulted in best service levels.

4.8 Conclusions and managerial implications

We have analysed alternative strategic supply chain processes and policy rules for a typical hospital *high volume, frequent and generalised use item*. The performed analysis contributes to the understanding of a hospital supply chain dynamics by focusing in some specificities of a material's hospital supply chain, namely the fact that at a hospital the service level assumes a high importance. As Tucker et al. (2013) have shown, in a hospital context, even small operational failures, like a local stock-out of an apparently unimportant material, that can be easily workaround have a relevant impact, and that impact can be more serious in critical services (e.g., at an emergency room). Therefore, it is desirable that a high service level is achieved through all hospital wards, while critical services are specially protected against stock-out situations. The analysis of the best (i.e., more efficient) processes to attain this objective is thus relevant.

By using System Dynamics based models to analyse various hospital supply chain relevant decision processes, we have highlighted the impacts and interactions among those processes. Moreover, this analysis resulted in simple management guidelines that can be easily considered by hospital supply chain managers.

It is generally acknowledged that "just-in-case" type behaviour at the wards leads to excess stock in hospital supply systems (see e.g., Ritchie et al. 2000, Burns et al. 2002: 13). The results of our simulations indicate that reinforcing orders when the inventory on hand falls significantly below the desired level results in much higher average inventory levels both at the wards and at the DC, even if lower orders are made when the inventory grows significantly above that level. Additionally, our results indicate that this increase in the inventory levels does not result in a proportional improvement in the service level at the wards. The simulations of systems with centralised inventory control resulted in better service levels while accumulating lower inventory levels throughout the system. Consequently, for high volume, frequent and generalised use items, the process to determine the quantities to be ordered by the wards should be more automatic and defined with the coordination of central inventory management. Some backup procedures to respond to stock-out situations should however be maintained or even increased: the possibility of emergency deliveries from the DC and, for more critical wards, that of receiving lateral transshipments from other wards.

Another practice that, according to the performed simulations, seems to have a negative impact on the average inventory levels in the system, without a clear indication that the intended results in terms of service level (i.e., an improvement of the service level at the ER) will be achieved, is giving priority to the ER in the allocation of DC inventory. In the performed simulations, better results, both in terms of average inventory levels and service level at the ER, were achieved through lateral transshipments from the other wards to the ER. There are, thus, indications that the hospital supply chain should not give preference to the orders of wards considered more critical in case of inventory insufficiency at the DC, since more efficient results may be obtained by distributing the inventory by the various wards with pending requests (in our models, this was done proportionally to the size of their requests) and, in case the inventory at the ER is insufficient to meet the demand faced there, by making a transshipment (possible within the same day) from another ward (in the case of our models, the ward with the lower probability of having a stock-out as a consequence of the transshipment was chosen).

The modelled lateral transshipments (i.e., from the ward with the lower probability of having a stock-out to the ER, in case of a stock-out at the ER) have given positive indications in terms of their effects on the service level at the ER, without harming the average inventory level at the whole hospital.

In this work, we have not made any attempt to optimise the management policy parameters used in all the models (e.g., the initial DC and ward inventory levels and the protection level at the DC and, in the models that use it, at the wards). Future insights may be gained if the influence of these parameters on the different models is further analysed.

The developed models can be modified in order to analyse other strategic hospital supply chain issues – e.g., more echelons or more entities in the considered tiers can be analysed, other network configurations can be considered, different inventory allocation rules can be analysed, etc.

5 A hybrid approach for integrated health care cooperative purchasing and supply chain configuration

This chapter is based on the following published paper:

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The work described in this chapter was partially financed by the ERDF - European Regional Development Fund, through the COMPETE Programme (operational programme for competitiveness) and by National Funds through FCT - Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) within the project Flexible Design of Networked Engineering Systems (PTDC/SEN-ENR/101802/2008).

5.1 Introduction

Hospital managers and other authorities have naturally been giving more importance to enhancing health care supply chains through cooperative purchasing strategies.

From a supply chain perspective, the improvement of purchasing strategies typically implies intensifying integration and increasing purchasing centralisation, supported by information and communication technologies for real-time information sharing, and promoting order consolidation to reduce unit costs (Monczka et al. 2010). Thus, spontaneous horizontal cooperation between neighbour hospitals, with the objective of controlling purchasing costs and sharing supply chain management knowledge, should be encouraged. However, purchasing groups often experience difficulties in their implementation, thus justifying additional support to maximise their chances of success (Schotanus et al. 2010).

In this chapter, we propose a flexible approach to recommend and evaluate a Group Purchasing Organisation (GPO) structure (i.e., the number of GPOs to form, their size and composition) for a set of hospitals willing to cooperate, while minimising their shared supply chain costs. Our approach combines the recommendation of a GPO structure with the use of an optimisation procedure to determine the supply chain configuration of the resulting GPOs (i.e., where, when and in which quantities supplied items are stored and flow in the supply chain). This integration enables the identification of synergies within each possible GPO.

The problem is solved by a two-module optimisation approach that incorporates a hybrid VNS / Tabu Search metaheuristc, and that can be adapted to the analysis of cooperative purchasing strategies in hospital supply chains involving the establishment of various types of GPOs.

Our approach can be easily used to support a group of hospitals intending to form a GPO, since the decision makers (the managers of the hospitals involved in a collaboration process) only need to provide information about the structure of their supply chains (suppliers, distribution centres, storage locations, places where demand occurs, and the possible supply links between these points) and some transactional data (e.g., the demand of items at relevant places, prices and discount schemes of alternative suppliers, fixed administrative costs of establishing commercial relations with these suppliers, an interest rate for inventory holding cost calculation, existing storage capacity constraints). In return, they get detailed reports comparing the costs of various cooperation alternatives.

Moreover, the approach is flexible enough to be applied to simplified versions of the problem, for example, by aggregating demand at upstream points in the supply chain, and by considering only some of the costs.

Schotanus (2007) points out that no instruments have yet been developed to determine the optimal size of purchasing groups under different circumstances (e.g., different markets, price elasticity, etc.), Schoenherr et al. (2012) highlight the need for research that improves the understanding of mechanisms for the design and control of processes which enable joint value creation and sharing (namely, sharing of cost savings resulting from joint cost reduction efforts), and Walker et al. (2013) state that developing tools for calculating the benefits of cooperative purchasing is an enabler of collaboration. The proposed approach links GPO formation with the optimisation of the resulting joint supply chain. This integration points out the supply chain design directions for the specific cooperative situation being evaluated. Additionally, it facilitates the analysis and negotiation processes for cooperative purchasing initiatives, by exposing financial impacts for the group and for individual hospitals, thus enhancing communication and fostering negotiations on the allocation of cooperation costs and gains.

This chapter is structured as follows. First, we relate our problematic situation to cooperative purchasing, namely in a health care setting and taking a supply chain perspective, and we frame that situation by describing the evolution of health care GPOs in Portugal. Second, we explain and formulate a model for the problem. We then solve our model using a two-module optimisation method and we present an illustrative example to show the benefits of the approach. Finally, we draw some conclusions and propose lines for further research.

5.2 Literature review

5.2.1 Cooperative purchasing

Cooperative purchasing (also referred to as group purchasing, collaborative purchasing, collective purchasing, joint purchasing, consortium purchasing, shared purchasing, bundled purchasing, pooled purchasing, alliance purchasing, etc.) is the horizontal cooperation between two or more organisations in one or more steps of the purchasing process, by pooling and/or sharing their purchasing volumes, information, market and demand risks and/or resources (Schotanus and Telgen 2007, Bakker et al. 2008, Burns and Lee 2008). The resulting initiatives have originated a wide diversity of cooperative organisations that range from informal/virtual arrangements to third party (formal) outsourcing, broadly designated as purchasing groups or group purchasing organisations (GPOs) (see a summary of possible typologies in Bakker et al. 2008).

In Table 5.1 we summarise the most frequently stated advantages and disadvantages of GPOs, as well as some areas where there are doubts about their benefits. Many of the existing research findings depend on the purchasing group type under analysis, and therefore it is important to clearly classify and define those types in order to identify which advantages, disadvantages, critical success factors, drivers and preconditions apply to which group type(s) (Schotanus 2007). Purchasing groups are much more frequent in the public sector (Essig 2000) and an important part of the existing research on cooperative purchasing focuses on health care GPOs. In general, results from other sectors may be transposed to health care, but the special characteristics of this industry may require some specific analysis. Accordingly, in subsection 5.2.3 we briefly discuss this topic further, focusing in a health care context.

The size of the purchasing group may have a significant impact on its financial performance since the involvement of many members may lead to higher set-up and transaction costs but, on the other hand, the involvement of few members may lead to smaller economies of scale. Nevertheless, research has indicated that in health care purchasing there is no direct relationship between higher volumes and lower prices (e.g., Ellison and Snyder 2011, Scanlon 2002).

Schotanus (2007) points out that no instruments have yet been developed to determine the optimal size of purchasing groups under different circumstances (e.g., different markets, price elasticity, etc.). However, it should be noted that the optimal purchasing group size strongly depends on the type of purchasing group under consideration (see, e.g., Schotanus and Telgen 2007, Bakker et al. 2008).

Table 5.1 Group purchasing advantages and disadvantages

At individual member level
Advantages • reduction of purchasing related costs (namely, acquisition costs (e.g., Burns and Lee 2008, Essig 2000, Hu and Schwarz 2011, Johnson 1999, Schneller 2009), transaction costs (e.g., Burns and Lee 2008, Johnson 1999, Schneller 2009, Tella and Virolainen 2005), administrative costs (e.g., Essig 2000, Schneller 2009, Huff-Rousselle 2012, Nollet and Beaulieu 2005) • human resources savings, since some purchasing effort is transferred to the group (Schneller 2000, Schneller 2009) • increased information on supply markets (Tella and Virolainen 2005) • increased focus on core operational activities (e.g., Schneller 2009, Schneller 2000)
Disadvantages • standardisation decreases the ability to fulfil the needs of decentralised users (e.g., Monczka et al. 2010) • lower innovation capabilities, at contract (Laing and Cotton 1997) and product/ service levels (Dimitri et al. 2006), due to compromise (Laing and Cotton 1997), standardisation, and reduction of direct contacts with suppliers (Dimitri et al. 2006) • lower responsiveness (Monczka et al. 2010), e.g., in case of a small scale emergency situation (Dimitri et al. 2006)
Doubts/ Concerns • prices negotiated by purchasing groups may be higher than those negotiated directly with vendors (Scanlon 2002)
At group/ supply chain level
Advantages • consolidation of purchase volumes enables the negotiation of more favourable terms with suppliers (Monczka et al. 2010, Schneller 2009, Tella and Virolainen 2005, Dimitri et al. 2006) • reduction of duplicated purchasing efforts (e.g., Monczka et al. 2010), namely, through reduction of the number of transactions (e.g., Essig 2000, Tella and Virolainen 2005) • development of purchasing expertise (Monczka et al. 2010) • rationalised choice through better-informed selection and standardisation (e.g., Huff-Rousselle 2012, Dimitri et al. 2006) • standardisation and consolidation of purchasing volumes increase economies of scale (e.g., at supplier level), lowering unit costs for the whole supply chain (Dimitri et al. 2006, Johnson 1999) • improved ability to respond to large scale emergency situations (Dimitri et al. 2006), due to increased flexibility of inventories (Tella and Virolainen 2005), coordination (Dimitri et al. 2006) and resource pooling (Dimitri et al. 2006)
Disadvantages • coordination costs (e.g., Johnson 1999, Dimitri et al. 2006), mainly when GPO size increases (Schotanus 2007)
At macro/ political level
Advantages • reduction of overall supply chain costs, that, in the public sector, implies that the amount paid by tax payers decreases (Huff-Rousselle 2012) • in the public sector, prevention/ reduction of corruption (Essig 2000, Ellison and Snyder 2011)
Disadvantages • consolidation of sales volumes may inhibit SMEs from participating in the tenders (Dimitri et al. 2006, Walker et al. 2013) • may be a barrier to innovation, because GPOs tend to favour suppliers with broad product lines rather than a single innovative product (Herzlinger 2006)
Doubts/ Concerns • risk of a negative effect in market dynamics due to excessive buyer concentration (Blair and Durrance 2013) • risk of a negative effect in market dynamics due to the introduction of an additional intermediary, in case of third party GPOs (e.g., Sethi 2006) • depending on the market at stake, an increase in the concentration of the buyers (demand side) may counterbalance the excess concentration on the supply side, improving competition conditions (Blair and Durrance 2013)

5.2.2 Cooperative purchasing in supply chains

Although cooperative purchasing initiatives have been widely applied, there is very little research concerning the integrated analysis of purchasing groups formation with the coordination of the supply chains of the cooperating organisations. Our approach links the evaluation of the potential purchasing groups with an optimisation procedure, in order to determine their common supply chain configuration. This integration takes into consideration not only the most recognised benefits of cooperation, such as obtaining quantity discounts or transaction and administrative costs savings, but also other possible supply chain synergies, achieved, for example, through inventory pooling, inventory lateral transshipments, or distribution consolidation. Moreover, it supports the operationalization of existing supply chains to the new cooperative situation.

From a supply chain point of view, our approach can be viewed as being related to the broad supply chain coordination literature (see Bahinipati et al. 2009, Arshinder et al. 2008) and to the literature on cooperative ordering / lot sizing models (see Meca and Timmer 2008, Drechsel 2010).

The main distinctive features of our approach in comparison with previous works are the following:

- The determination of the best GPO structure (subsection 5.3.2) for a group of cooperating organisations (in our case, hospitals) integrated with the multi-period optimisation of the resulting GPO supply chains, computing the costs of all participants and combining (for the first time, as far as we are aware of) the following characteristics: interrelated purchasing, distribution and inventory decisions; more than two echelons; multiple suppliers; multiple products; quantity discounts; fixed costs; path-dependent costs; and bundled storage and supply capacity constraints.
- Its flexibility, since it can be used to optimise problems with different supply chain configurations (e.g., number of echelons, suppliers, hospitals, hospital wards and/or products) as well as different cost types.

5.2.3 Cooperative purchasing in health care

Given the increasing need to rationalise health care services, there have been diverse attempts to improve the efficiency and effectiveness of hospital systems through vertical or horizontal, and direct or indirect supply chain collaboration. Besides cooperative purchasing, these efforts have included the stockless system (described in DeScioli 2005), Vendor Managed Inventory (VMI) systems (e.g., Bhakoo et al. 2012), resource sharing/pooling by neighbour health care providers (e.g., Pasin et al. 2002, Beaulieu and Patenaude 2004), e-commerce (e.g., Bhakoo and Chan 2011) and/or e-communication, namely, in the area of telemedicine (e.g., Wang et al. 2010), integrated care (Kodner and Spreeuwenberg 2002), and other integration initiatives (see Bazzoli et al. 2004).

The full success of many of these experiences has been hindered by difficulties in communication, leadership or conflicting interests conciliation (e.g., Bhakoo et al. 2012, Burns and Pauly 2002, Boonstra and Govers 2009, Ford et al. 2004, More and McGrath 2002), or by suspicions about the fair distribution of costs and benefits of the collaboration processes (e.g., Pasin et al. 2002, Ford et al. 2004). Communication problems (Laing and Cotton 1997, Schotanus et al. 2010) and the allocation of savings (Schotanus 2007) are two of the main difficulties of purchasing groups for *informally structured programme groups* (Schotanus and Telgen 2007), i.e., groups having the characteristics of the group of our research case (subsection 5.3.1).

In health care these difficulties may be larger as the supply chain is managed through a complex line of command, based on a sensitive balance of power relationships among diverse highly trained professional groups (managers, physicians, nurses, pharmacists, etc.) that work at autonomous units (de Vries et al. 1999). The system is also highly dependent on the role played by physicians (Schneller and Smeltzer 2006), as they develop long run relationships with suppliers and preferences on specific materials and products, reflecting, for example, their education in specific medical schools.

The knowledge about the supply chain, and the awareness of the impacts of certain decisions on its operation, may improve the willingness to discuss alternative actions to develop collaboration between supply chain members (e.g., van Donk 2003). Moreover, as stressed by Ford et al. (2004), understanding which individuals stand to lose or gain within a particular collaborative initiative can yield critical insights into the prospects for the success of a project.

Burns and Lee (2008) conducted an independent survey of materials managers for hospitals in the US, concerning their national purchasing alliance usage, and confirmed the conclusions of Schneller (2000) that GPOs help contain rising health care costs by reducing product prices in two ways: (1) through pooled purchasing leverage of hospitals buying products on nationwide contracts; and (2) through the establishment of price ceilings beneath which hospitals negotiate on their own. They also concluded that alliances may also benefit hospitals financially by reducing transaction costs.

In summary, previous research has confirmed that cooperative purchasing can significantly reduce costs related to hospital systems purchasing activities. However, it is also clear how important it is to incorporate a supply chain perspective into GPO analysis and to prepare potential cooperation processes, by analysing and negotiating possible forms of cooperation and their consequences to the group and also to individual participants, so that adequate incentive alignment and goal congruence can be reached. Since GPO size and characteristics may influence the extent and nature of achieved benefits, models to analyse GPO formation should take these aspects into account.

5.3 Problem

5.3.1 Research case

Our research was motivated by the observation of a group of neighbour public hospital systems that are physically close, and that have established some purchasing cooperation relations and launched several joint tenders. This group was formed by a core set of four neighbour hospital systems (totalizing 10 hospitals), responsible for more than 20% of the total pharmaceuticals consumption by public hospitals in Portugal (INFARMED 2012), but with time has involved the participation of other systems. One of the cooperating hospitals is widely recognised as a centre of knowledge and innovation, and its initiatives are easily followed by other hospitals (belonging or not to the purchasing group), and consequently, the possibility of not doing business with this hospital can be very negative to a supplier, especially when a prestigious brand is at stake. Thus, in some situations, this hospital can take the leading role in the negotiation of on-contract prices with suppliers. Representatives of the management teams of these hospitals meet weekly to discuss cooperative projects (e.g., the definition of a common master file of medical-surgical products, the standardisation of pharmaceuticals use, and the organisation of purchasing processes) or to share their experiences and opinions about supply chain best practices. The participating hospital systems do already share information as required by our approach (namely, demand and prices obtained from suppliers). Since all group members have strong relationships with each other and all can influence specifications, this purchasing group can be considered as an *informally structured programme group* (Schotanus and Telgen 2007).

It may be argued that the best solution for Portuguese public hospitals would be the establishment of a national GPO. In fact, over the years, we have seen repeated attempts from national health authorities to implement and manage national purchasing groups. However, the proportion of purchases channelled through these organisations has been quite small and they have recurrently experienced limited acceptance or even resistance from hospitals, especially when involving mandatory compliance rules. The introduction of health care GPOs in Portugal has in fact followed a path opposed to the commonly observed evolution phases of group purchasing development, as described by D'Aunno and Zuckerman (1987), Johnson (1999), Nollet and Beaulieu (2003) or Schotanus et al. (2010), and probably this is one of the reasons why the results achieved by these first attempts have been so disappointing. Other reasons may be the heterogeneity of Portuguese hospital systems in terms of dimension (and consequently, demand volume), financial situation (and consequently, payment period) and accessibility. Since suppliers had to present their price offers based on a forecast of potential annual sales, without knowing the locations of their client hospitals, or the payment dates, the prices offered to GPOs were often considerably higher than those obtained by individual hospital systems through direct negotiations.

These failed experiences further reflect the gap between policy goals and the realities of the hospital systems involved in these purchasing groups, as identified by Schotanus et al. (2010). Moreover, these authors concluded that “no enforced participation” is the most important success factor for managing a purchasing group, since the cost-effectiveness of a well-organised group should attract members without forcing them to formally cooperate (Schotanus et al. 2010).

The four hospital systems observed in this study meet many of the favourable conditions for increased purchasing centralisation (van Weele 2009, Schotanus et al. 2010): they are not direct competitors, since NHS hospitals access does not depend on patient choice, all members have a similar influence in the group and similar objectives, they are geographically near to each other, they have common consumption of items and purchasing requirements, their supply markets are often highly concentrated, the savings potential of purchasing cooperation is high, and their purchasing processes require high expertise.

At the current stage, the proposed solution for this set of hospitals is the consolidation of purchasing cooperation, without mandatory compliance, but they need to determine which are the best cooperation arrangements, to anticipate the global and individual savings they will achieve, and to find out how to organise their joint supply chain in order to take the maximum advantage from cooperation. The actual needs of this group of hospitals, as observed in practice, were the real motivation for the approach described in this work.

5.3.2 Model description

In this work we consider a cooperative game, defined on the real situation of a group of neighbour hospitals engaged in an information sharing process with the objective of purchasing items cooperatively. The motivation of these hospitals was to significantly decrease costs, while meeting quality and usability requirements. In past cooperation initiatives, they had already established some binding and benefits sharing agreements. In spite of these experiences and the intent to deepen cooperation, it was quite clear that the identification and sharing of cooperation costs and benefits was not a simple task.

The theory of cooperative games is concerned with situations in which players (in our case, hospitals) can negotiate effectively. I.e., if there is a feasible change in the strategies of the coalition members that might benefit all of them, then they would agree to actually make such a change, unless it contradicts agreements of some members of the coalition with other outside players (Myerson 2004). For this purpose, any of the 2^N-1 nonempty subsets of the total set of N players under consideration is a potential coalition.

The adoption of a cooperative game perspective makes sense in situations where the players have incentives to improve their game payoffs, by adding communication or (explicit or implicit) contract-signing options, providing some control over the actions of other players, with the objective of transforming the initial game into a game with equilibria that are better for all the players (Myerson 2004).

Cooperative games are based on three necessary conditions (Ford et al. 2004, Nash 1953): (1) every actor‘s motivation is known by the others; (2) legally binding agreements exist between the coalition members; and (3) all benefits derived from cooperation are returned to the members in a way they consider equitable. In case one of the previous conditions is absent, even if hospitals have the intention to cooperate, we have a non-cooperative game and, for the GPO to survive, each player should receive at least as much from participating in the group as he would receive by operating unilaterally.

In a cooperative game with more than two players, the possibility of cooperation among subsets of the players should be considered, and the resulting potential structure of the sequential negotiations between the participants of all possible coalitions is, in real situations, very complex (Myerson 2004).

As the problem under analysis represents a situation where an important part of the cooperation benefits can be measured by financial outcomes that can be transferred between purchasing group members, we can apply the commonly used transferable utility assumption.

For the purposes of this work, a GPO (coalition) is any nonempty subset of the set of hospitals (players) involved in the cooperative game (i.e., those with the intention to cooperate with each other), and a GPO structure is a partition of the hospitals (players) into disjoint, exhaustive GPOs (coalitions). Therefore each hospital belongs exactly to one GPO, and some GPOs may be composed of one single hospital.

Our approach compares all possible GPOs (coalitions) formed from a group of N hospitals (players), and recommends the GPO structure that minimizes the total cost for the global solution. It also provides information about alternative GPO structures and about the individual hospital participation in the final solution, thus supporting a possible negotiation phase to (re)allocate cooperation results.

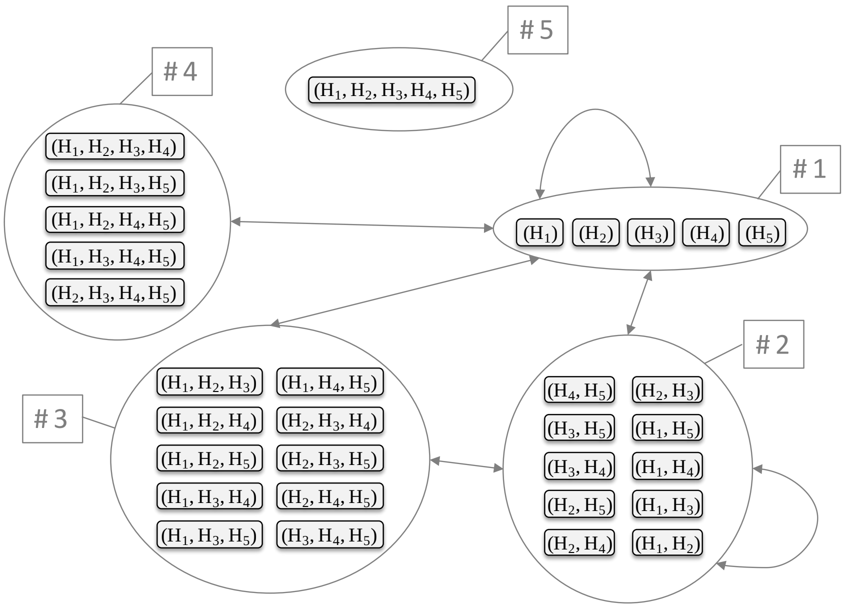

Figure 5.1 Potential GPOs originated from a group of 5 hospitals and how they form GPO structures

The number of possible GPO structures equals $\sum_{i=1}^{N} Z(N,i)$, where $Z(N,i)$, known as the Stirling number of the second kind, is the number of GPO structures with i GPOs formed from N hospitals willing to cooperate. The easiest approach to enumerate Stirling numbers is recursion, with $Z(N,i) = Z(N-1,i-1) + iZ(N-1,i)$, and $Z(N,N) = Z(N,1) = 1$. Figure 5.1 illustrates the case of a group of 5 individual hospitals, showing how the 31 (2^5-1) potential GPOs can be associated to form GPO structures.

Figure 5.2 lists the 52 possible GPO structures composed from those 31 potential GPOs. Nodes represent all possible GPO (coalition) structures. At the top of the figure, we have a coalition composed by all the five hospitals, and at the bottom, we have the five hospitals purchasing individually. Arcs represent mergers of two coalitions when going upwards, and splits of a coalition into two when going downwards (Sandholm et al. 1999). It is easy to see that the number of GPO structures grows exponentially with the number of hospitals (e.g., if we had 9 hospitals, we would have 21147 GPO structures).

Our approach consists of a recursive two-module method, where module 2 is a procedure performed inside module 1, as described in Figure 5.3.

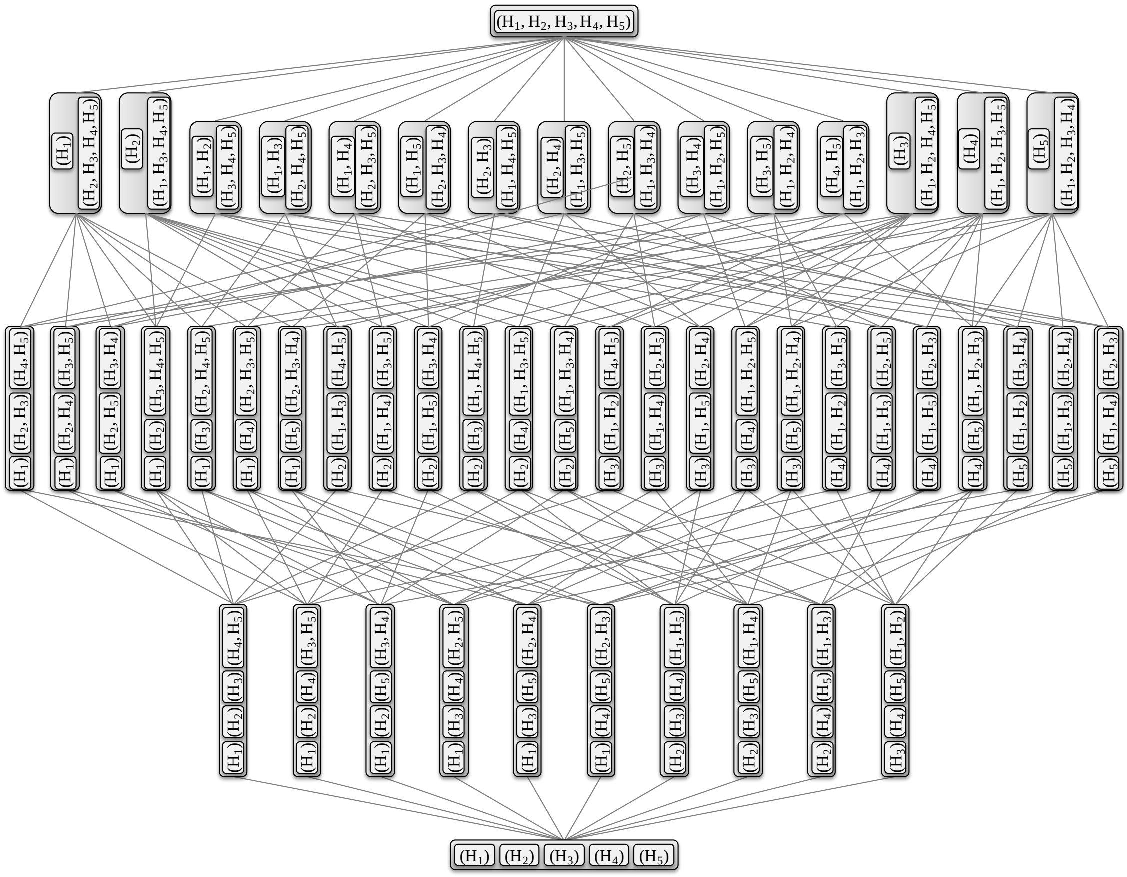

Figure 5.2 GPO structure graph for a 5-hospital game (adapted from Sandholm et al. 1999)

Module 2 is intended to optimise each potential GPO supply chain, by using a modified version of a model developed in a previous work (Rego and Pinho de Sousa 2009). This model was inspired by the formulation from Ahuja et al. (1993) considering a multi-stage, multi-level, multi-product production-distribution system planning problem, based on a graph representation of the problem. The multi-period dimension of the problem is taken into account in the model through the replication of the supply chain with "inventory edges" connecting storage areas (at hospital distribution centres and point of care units) in subsequent periods. A version of this problem considering one network entity at each supply chain echelon (as described in subsection 5.3.3) is NP-hard, if the model includes fixed supply costs that are independent from supplied quantities (Ahuja et al. 1993). Since our model considers this type of costs, while admitting more than one network entity at each supply chain echelon, it is also NP-hard.

Furthermore, the objective function of the problem is non-linear and non-convex (e.g., the number of edges in a solution varies), thus increasing the complexity of the problem.

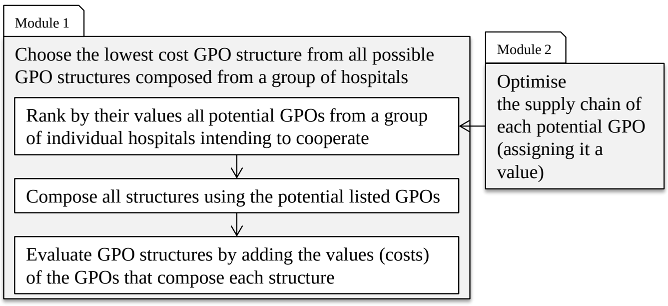

Figure 5.3 Optimisation approach

Figure 5.4 illustrates the application of this modelling logic to a very simple supply chain: two producers (P_1 and P_2), an informal GPO (i.e., a virtual organisation that centralises GPO purchases) and two cooperating hospitals with five *point of care units* each (U_{11}, U_{12}, ... U_{15}, and U_{21}, U_{22}, ... U_{25}), during five purchasing periods. A *point of care unit* is a location where final demand occurs (i.e., where it is traced). These locations may have a space for inventory storage. In practice, they may be wards or parts of wards. Solving this model means determining a relatively low cost way of fulfilling the demand of all the point of care units, by identifying all necessary network supply paths, i.e., sequences of consecutive supply and/or storage edges linking a producer to a point of care unit, and valued by the item quantity that is supplied through them.

A *supply edge* links one network entity to another in one time period (e.g., producer 1 in period 1 to hospital 1 in the same period), and represents physical (or virtual, if a GPO is involved) supplies of items between those two entities. The flexibility of the model allows the decision maker to consider the alternative of supplying the point of care units directly from the producer (as in a VMI scheme), as represented by the direct arcs from the producer to the point of care units in period 1. This possibility is not graphically represented in the following periods to preserve the readability of the figure.

A *storage edge* is represented by a dashed edge linking one network entity in one period to the same entity in the following period (e.g., hospital 1 in period 1 to hospital 1 in period 2) and represents the possibility of storing inventory at that location from one period to the next.

The model considers: (1) fixed administrative costs for establishing commercial relationships between a supplier and a customer, e.g., costs of negotiation and contracts; (2) fixed and (3) variable transaction costs; (4) acquisition costs, including GPO margins (or discounts); and (5) inventory carrying costs (Rego and Pinho de Sousa 2009). In line with what has been observed in practice, we added an acquisition cost scheme considering bundle supplier discounts depending on the aggregate sales of the GPO (or individual hospital) during the planning horizon under consideration.

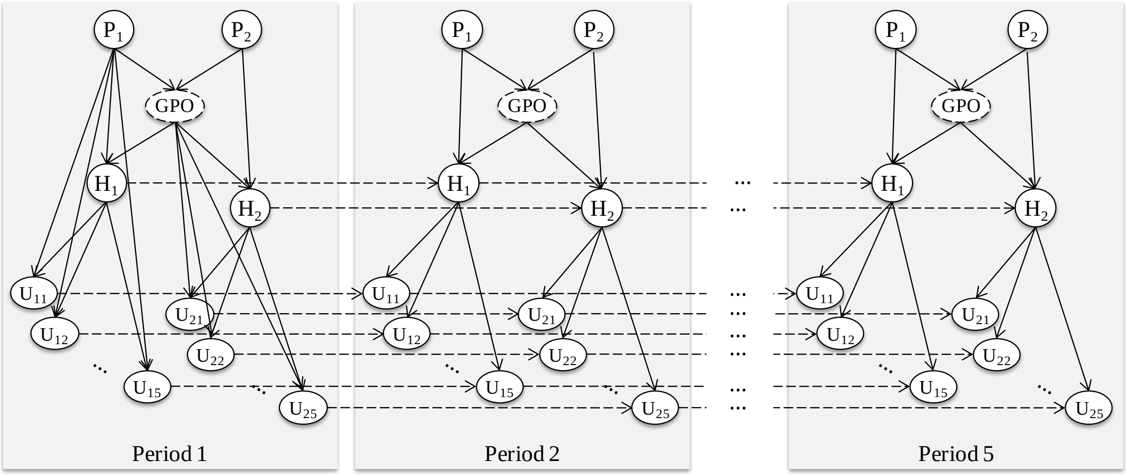

Figure 5.4 Illustration of the model (adapted from Rego and Pinho de Sousa 2009)

Due to the nature of the acquisition and inventory carrying costs considered, our mathematical formulation cannot be based on the structure that is frequently found in the literature (some examples can be found in Muriel and Simchi-Levi 2003), that associates the decision variables to the quantities that flow through the network edges. Therefore, as any item flowing through a specific edge can have different costs, depending on its previous path (see a few examples in Rego and Pinho de Sousa 2009), our formulation associates the supplied quantities to the network supply paths (several edges) that have been used.

In what follows we assume that all relevant data (costs, capacities, and other parameters) have been collected using appropriate estimation/forecasting methods and a hospital-specific business analysis.

5.3.3 Model formulation

Sets and indices

G = [1, 2, … g, ...] – items

C = [...,γ ,...] – potential GPOs (coalitions); #(C) = 2^N-1, where N is the number of potentially cooperating hospitals (e.g., in a 5 hospitals problem there are 31 potential GPOs)

R_γ *= [1, 2, ..., i, j, ...]* – network entities (suppliers, hospitals, intermediaries, and point of care units) in a potential GPO γ

K_γ *= [1, 2, … k, ...]* – network supply paths for potential GPO γ

H_γ *= [1, 2, … h, ...]* - hospitals; H_γ is a subset of R_γ

E_γ = *[1, 2, ... e, ...]* – demand entities (point of care units); E_γ is a subset of R_γ

E_γ^h – demand entities that are part of hospital *h*; E_γ^h are subsets of E_γ

L = [1, 2, ... l, ...] – suppliers; *L* is a subset of R_γ

θ_γ =organisation (maybe virtual or informal) that centralises potential GPO γ purchases; θ_γ is a subset of R_γ

S = [1, 2, ..., p, t, ... s_{max}*]* – periods of the planning horizon

CS = *[... χ, ...]* – GPO (coalition) structures (e.g., in a 5 hospitals problem we have 52 potential GPO structures)

Figure 5.5 illustrates the way each node or edge is identified. An edge can be classified as a "supply edge", if it links different entities in the same period, i.e., when $(i \neq j) \wedge (p = t)$, or as a "storage edge" if it links one entity in different, consecutive periods, i.e., when $(i = j) \wedge (t = p + 1)$.

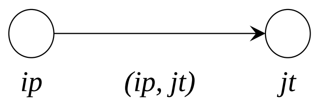

Figure 5.5 Edge *(ip, jt)* links entity *i* in period *p* to entity *j* in period *t*

Costs

a_{ij} = fixed administrative cost of establishing a commercial relationship between entity *i* and entity *j*

f_{ij} = fixed transaction cost from entity *i* to entity *j*

v_{gij} = cost of transacting one unit of item *g* from entity *i* to entity *j*

b_{gip} = rate (applied to the aggregated acquisition cost) used to calculate the cost of maintaining one unit of item *g* stored at entity *i* from period *p* until period *p + 1*

w_{glj} = price at which supplier *l* sells each unit of item *g* to entity *j*

m_{gij} = commercial margin that intermediary *j* adds to the acquisition cost of item *g* when he/she buys one unit of it from supplier *i*

Other parameters

d_{gjt} = demand of item *g* by entity *j* in period *t*

SC_i = storage capacity of entity *i*

FC_{gip} = supply capacity of item *g* by entity *i* in period *p*

Decision variables

Q_{gk} = quantity of item g that flows through path k

$$X_{ipjtk} = \begin{cases} 1, \text{if edge (ip, jt) belongs to path k, with } (j \geq i) \wedge (t \geq p) \\ 0, \text{otherwise} \end{cases}$$

χ = GPO structure

$$\phi_{\gamma\chi} = \begin{cases} 1, \text{if GPO } \gamma \text{ belongs to GPO structure } \chi \\ 0, \text{otherwise} \end{cases}$$

Intermediate variables

$$Y_{ipjt} = \begin{cases} 1, \text{if (ip, jt) is a supply edge, i.e., if } (p = t) \wedge (i \neq j) \\ 0, \text{otherwise} \end{cases}$$

$$Z_{ipjt} = \begin{cases} 1, \text{if (ip, jt) is a storage edge, i.e., if } (t = p+1) \wedge (i = j) \\ 0, \text{otherwise} \end{cases}$$

It must be noted that supply edges are never storage edges and the opposite is also true. Additionally, all edges in the model should be either supply or storage edges.

$$A_{ij} = \begin{cases} 1, \text{if the supply link between i and j is used, i.e., if } \sum_g \sum_p \sum_t X_{ipjtk} Y_{ipjt} Q_{gk} \geq 1, \forall (i,j) \text{ with } i, j \in R_\gamma \\ 0, \text{otherwise} \end{cases}$$

e_{gkrs} = acquisition cost of one unit of item g at the entry of node rs (i.e., at the entry of entity r at the beginning of period s) belonging to path k

q_{glj} = aggregated quantity of item g bought by entity j to supplier l

o_{gkrs} = aggregated inventory carrying cost of one unit of g at the entry of node rs (i.e., at the entry of entity r at the beginning of period s) belonging to path k

$$\text{Total fixed administrative cost} = \sum_i \sum_j A_{ij} a_{ij} \quad (1)$$

$$\text{Total fixed transaction cost} = \sum_k \sum_i \sum_p \sum_j \sum_t X_{ipjtk} Y_{ipjt} f_{ij} \quad (2)$$

$$\text{Total variable transaction cost} = \sum_k \sum_i \sum_p \sum_j \sum_t X_{ipjtk} Y_{ipjt} Q_{gk} v_{gij} \quad (3)$$

$$\text{Total acquisition cost} = \sum_g \sum_k \sum_i \sum_p e_{gkip} Q_{gk} \quad (4)$$

with:

$$e_{gkrs} = \begin{cases} e_{gkip}, \text{ if } Z_{iprs}=1, & (5) \\ \sum_i \sum_p \sum_j^{j<r} \sum_t^{t\leq s} (w_{glj} X_{ipjtk} Y_{ipjt}) \times \prod_i \prod_p \prod_j^{j<r} \prod_t^{t\leq s} \left[1+(m_{gij} X_{ipjtk} Y_{ipjt})\right], & (6) \\ \quad \text{if } Y_{iprs}=1, \quad \forall g \in G, \forall k \in K_\gamma, \forall r \in R_\gamma, \forall s \in S \end{cases}$$

where,

$$w_{glj} = \begin{cases} w^0_{glj}, & if \ \ 0 \leq q_{glk} < \delta_1 \\ w^1_{glj}, & if \ \ \delta_1 \leq q_{glk} < \delta_2 \\ \dots & \dots \\ w^n_{glj}, & if \ \ \delta_n \leq q_{glk} < +\infty \end{cases}$$

with:

$$q_{glj} = \begin{cases} \sum_k \sum_i \sum_p \sum_{j\in\theta_\gamma} \sum_t X_{ipjtk} Y_{ipjt} Q_{gk}, \quad \forall i \in L, \forall g \in G, \quad \text{if } j \in \theta_\gamma \\ \sum_k \sum_i \sum_p \sum_{j\in H_\gamma} \sum_t X_{ipjtk} Y_{ipjt} Q_{gk} + \sum_k \sum_i \sum_p \sum_{j\in E_h} \sum_t X_{ipjtk} Y_{ipjt} Q_{gk}, \\ \quad \forall g \in G, \forall i \in L, \quad \text{if } (j \in H_\gamma) \vee (j \in E^h_\gamma) \end{cases} \quad (7)$$

The above expressions allow us to model the following requirements. When passing through a storage edge (5), the acquisition cost of one unit of item g is maintained but, when passing through a supply edge (6), this cost is adjusted considering the price at which entity i sells item g, or the commercial margin that intermediary j adds to the cost at which he acquires one unit of that item. The value of the demand used to determine the price at which supplier l sells each unit of item g to entity j (7) is computed by aggregating all the demand channelled through the informal organisation that centralises each potential GPO purchases or all the demand channelled through the individual hospitals (including their point of care units) during the planning horizon considered. The model does not assume enforced GPO participation, i.e., hospitals can buy directly from suppliers.

Total inventory carrying cost = $\sum_g \sum_k \sum_i \sum_p o_{gkip} Q_{gk}$, with: (8)

$$o_{gkrs} = \begin{cases} o_{gkip}, \text{ if } Y_{iprs}=1, \\ \\ o_{gkip} + \left(e_{gkrs} + o_{gkip}\right) b_{grs} X_{iprsk} Z_{iprs}, \text{ if } Z_{iprs}=1, \\ \qquad \forall g \in G, \forall k \in K_\gamma, \forall r \in R_\gamma, \forall s \in S, \text{ with } i \in R_\gamma,\ p \in S \end{cases} \quad (9)$$

The unit inventory carrying cost (9) is maintained when passing through a supply edge, and it is adjusted when passing through a storage edge. This adjustment is done by using a rate (applied to the aggregated acquisition cost) that considers the cost of maintaining one unit of item *g* stored at entity *i* from period *p* until period *p + 1*.

Model

Module 1:

Minimise $$V(\chi) = \sum_{\gamma \in \chi} V(\gamma)\varphi_{\gamma\chi} \quad (10)$$

Module 2:

$$V(\gamma) = \text{Min} \left(\sum_i \sum_j A_{ij} a_{ij} + \sum_k \sum_i \sum_p \sum_j \sum_t X_{ipjtk} Y_{ipjt} f_{ij} + \right.$$

$$+ \sum_k \sum_i \sum_p \sum_j \sum_t X_{ipjtk} Y_{ipjt} Q_{gk} v_{gij} +$$

$$\left. \sum_g \sum_k \sum_i \sum_p e_{gkip} Q_{gk} + \sum_g \sum_k \sum_i \sum_p o_{gkip} Q_{gk} \right) \quad (11)$$

Subject to:

$$\sum_j \sum_t X_{00jtk} = 1, \quad \forall k \in K_\gamma \quad (12)$$

$$\sum_i \sum_p X_{iprsk} = 1, \quad \forall k \in K_\gamma, \forall r \in R_\gamma, \forall s \in S \quad (13)$$

$$\sum_j \sum_t X_{rsjtk} = 1, \quad \forall k \in K_\gamma, \forall r \in R_\gamma, \forall s \in S \quad (14)$$

$$\sum_k \sum_i \sum_p^{S_{max}} Q_{gk}.X_{iprsk} Y_{iprs} + \sum_k \sum_i \sum_p^{S_{max}} Q_{gk}.X_{iprsk} Z_{iprs} - \sum_k \sum_j \sum_t^{S_{max}} Q_{gk}.X_{rsjtk} Y_{rsjt} -$$

$$- \sum_k \sum_j \sum_t^{S_{max}} Q_{gk}.X_{rsjtk} Z_{rsjt} = d_{grs}, \quad \forall g \in G, \forall r \in R_\gamma, \forall s \in S \quad (15)$$

$$\sum_{k}\sum_{j}\sum_{p} Q_{gk}.X_{ipjtk}Y_{ipjt} \leq FC_{gip}, \quad \forall g \in G, \forall i \in R_{\gamma}, \forall p \in T \tag{16}$$

$$\sum_{g}\sum_{k}\sum_{i}\sum_{p} Q_{gk}.X_{ipjtk}Z_{ipjt} \leq SC_{i}, \quad \forall i \in R_{\gamma} \tag{17}$$

$$Q_{gk} \geq 0 \text{ and integer}, \quad \forall g \in G, \forall k \in K_{\gamma} \tag{18}$$

$$X_{ipjtk}, Y_{ipjt}, Z_{ipjt}, A_{ij}, \varphi_{\gamma\chi} \in \{0,1\}, \quad \forall i,j \in R, \forall p,t \in T, \forall k \in K, \forall \gamma \in C \tag{19}$$

Our objective is to find the GPO structure, χ*, with the minimum cost (10), with the cost of each GPO structure being the sum of the values of the GPOs that compose that structure.

The global cost of each GPO γ is obtained through the minimization (11) of the sum of fixed administrative costs (1), fixed (2) and variable (3) transaction costs, acquisition costs (4) and inventory carrying costs (8) of the solution obtained for the corresponding supply chain configuration problem.

Constraints (12) ensure that all paths begin at the network artificial node 00 (located upstream from the producers), and constraints (13) and (14) ensure that, for each path *k*, only one edge arrives at each node *rs* and only one edge departs from each node *rs*, guaranteeing that paths are formed to serve demand entities.

Constraints (15) ensure flow conservation at the different entities and impose that all demand is satisfied.

Constraints (16) and (17) impose capacity bundle restrictions: they ensure that all supply capacity (16) and warehouse storage (17) limitations are taken into account. Finally, constraints (18) and (19) define the domains for the decision variables.

5.4 Solving the model

Since we are studying a case with a limited number of hospitals, the optimisation of the GPO structure (module 1) is performed through the computation and comparison of all the costs of the structures under consideration. If we wanted to apply our approach to a case with a significantly larger number of hospital systems, module 1 would have to be modified to avoid determining and comparing the costs of all GPO structures. This could be done by using an algorithm for coalition structure generation. Voice et al. (2012) present brief descriptions of several available algorithms for this purpose.

To optimise the supply chain of each GPO (module 2), we use a hybrid algorithm based on Tabu Search (TS) (Glover 1989, 1990) and Variable Neighbourhood Search (VNS)

(Mladenovic and Hansen 1997). We use a metaheuristic to solve this problem because it is a NP-hard, non-convex mixed-integer, non-linear problem (MINLP). Additionally, we want our tool to be easily adaptable to solve real size problem instances with diverse cost characteristics. Due to their features, metaheuristics are well suited to solve complex cross-functional supply chain management problems (Griffis et al. 2012). Further details about the construction and parameterization of this algorithm are discussed in Rego and Pinho de Sousa (2009), but in this work, for self-containment reasons, we will only present the main characteristics of the adopted approach.

Our hybrid algorithm combines the search scheme of a Tabu Search, by incorporating a tabu list that forbids repetition of recent moves, with the diversification features of VNS, by changing the neighbourhood structure when the search seems unable to improve the current solution. This method provides the flexibility required to cope with a great diversity of problems (e.g., in terms of types and number of entities and/or types of costs and constraints considered), and is suitable to handle a great variety of real life, highly combinatorial situations.

5.4.1 Initial solution

An initial solution is constructed through an iterated creation of network supply paths, until all demand is satisfied. Each path is formed by starting at a point of care unit, and by adding supply or storage edges, until one of the producers is reached. The edge that arrives at the last node in the path is chosen by selecting randomly its node of origin from all possible origins. Feasibility was considered an important requirement, since the constrained nature of the problem may complicate the attainment of a feasible solution during the search. If the demand of the point of care unit cannot be fully fulfilled due to a supply or storage constraint, the path under construction will be valued with the feasible quantity and another path will be constructed for the remaining quantity.

5.4.2 Objective function

The objective function has two components: the original objective function of the problem (see subsection 5.3.3) plus a function P that penalizes infeasibility associated to the limits imposed by storage and supply constraints:

$$P = \left[\sum_{g} \sum_{k} (\text{capacity excess}_{gk} \times \eta_g) \right] \times \varepsilon \quad , \qquad (20)$$

where:

- capacity excess$_{gk}$ is the sum of the quantities in excess of item *g* flowing through network supply path *k* due to storage and supply constraints;
- η_g is a parameter that adjusts the penalization to the scale of the costs considered (in our algorithm, η_g is the higher unit price charged by the producers of item *g*); and
- ε is a dynamic parameter (updated every κ iterations) that is multiplied (divided) by 2 if the search stays in unfeasible (feasible) regions (in our case, the initial value of ε is 1, and κ =10).

5.4.3 Neighbourhood structures

Due to the specific characteristics of the costs considered in our model, where the cost of sending a given quantity through one edge depends on the network supply path that quantity travelled before, we could not define the neighbourhood of a solution by employing the most usual and simple moves, such as *insertion* or *swapping* of elements. Therefore, we move to a neighbour solution by swapping complete or partial network supply paths, as exemplified in Figure 5.6, where we highlight two partial paths that could be swapped (ending in H_2) and two complete paths that could be swapped (ending in U_{15}). During the search process we allow some temporary occurrences of infeasible solutions, and follow a best improvement strategy (i.e., the entire neighbourhood is searched).

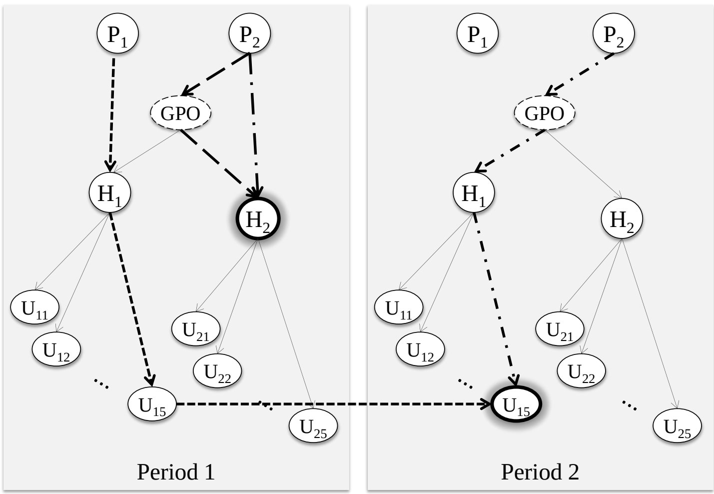

Figure 5.6 Examples of network supply paths swapping

We developed three neighbourhood structures: two cost based procedures (NS1 and NS2) and a random neighbourhood scheme. We combine all types of moves by running each of these three neighbourhood structures during a given number of iterations, p_{max} (in our case, we set p_{max} = 500).

NS1 selects the paths with the minimum unit cost, ignoring the current solution structure (i.e., the selection does not take into account the fact that other paths of the current solution may use edges that are common to the path under analysis). NS2 selects the paths with the minimum unit cost, but considering the current solution structure. Finally, the random neighbourhood structure selects a new path by randomly choosing a chain in a way that the capacity constraints are satisfied.

5.4.4 Tabu list

The tabu list stores the last combination edge × path × item of a number of recently replaced paths, so that it is not possible to include these edges in the paths that will be tested to form new solutions. The tenure of the tabu list is randomly determined using a uniform distribution - Uniform [λ; δ], where λ is 1/3 of the number of network elements, and δ is the number of network nodes. This way, the tenure of the tabu list is adapted to the size of the supply network of each GPO analysed.

5.4.5 Aspiration criterion

We use an aspiration criterion based on the global objective, by accepting a tabu solution if it yields the best solution ever found, even if it results from a tabu move.

5.5 Illustrative example

Assume that we want to design the GPO (coalition) structure for five potentially cooperating hospitals that intend to purchase two items offered by two competing suppliers, during five purchasing periods. They want to serve the demand of five point of care units per hospital, taking into account the specific features of the supply chains of these hospitals. Since small intensive purchasing groups are more successful when all members have a similar influence and similar objectives (Schotanus et al. 2010), we considered that the five hospitals are similar in terms of their size (measured through their demand volumes for both items 1 and 2).

These five hospitals[53], or subgroups of them, may form virtual/informal GPOs to aggregate demand volumes, thus obtaining lower item prices, and eventually a reduction of other purchasing costs. We have randomly generated demand, costs and constraints, using, as an inspiration, the characteristics of the supply systems of the research case under analysis (e.g., the types of costs). The point of care units were classified as units of high demand or units of low demand, according to a binomial distribution with $p = 0.5$. Demand was determined through a normal distribution: $N(\mu=100, \sigma=20)$ or $N(\mu=50, \sigma=20)$ for high or low demand, respectively. Costs were generated using the distributions shown in Table 5.2. The relative values of the various costs are realistic, and the generated demands and suppliers' prices represent well those from real items.

Table 5.2 Distributions used to generate data[54] (adapted from Rego and Pinho de Sousa 2009)

<table>
<tr><td rowspan="6">acquisition cost</td><td rowspan="6">Base cost
Item1:
Uniform [100, 120];
Item2:
Uniform [50, 70]</td><td colspan="4">Quantity discount structure</td></tr>
<tr><td colspan="2">Order quantity</td><td colspan="2">Discount</td></tr>
<tr><td colspan="2">[0, LS1[</td><td colspan="2">0%</td></tr>
<tr><td colspan="2">[LS1, LS2[</td><td colspan="2">Uniform [0%, 5%]</td></tr>
<tr><td colspan="2">[LS2, LS3[</td><td colspan="2">Uniform [5%, 10%]</td></tr>
<tr><td colspan="2">[LS3, +∞[</td><td colspan="2">Uniform [10%, 20%]</td></tr>
<tr><td>inventory carrying cost</td><td colspan="5">Uniform [1/1000, 3/1000]</td></tr>
<tr><td>commercial margin</td><td>producer→GPO
Uniform [-10%,-1%]</td><td colspan="2">producer→care unit
GPO→care unit
hospital→hospital or care unit of other hospital
Uniform [5%,10%]</td><td colspan="2">GPO →hospital
hospital→hospital
Uniform [2%,7%]</td></tr>
<tr><td>fixed administrative cost</td><td>producer→GPO
producer→hospital
GPO →hospital
Uniform[1000,1500]</td><td colspan="2">producer→care unit
GPO→care unit
hospital→hospital or care unit of other hospital
distribution identical to the one of the hospital where the care unit belongs</td><td colspan="2">hospital→hospital
Uniform [500,1000]</td></tr>
<tr><td>fixed transaction cost</td><td>producer→GPO
producer→hospital
GPO →hospital
hospital→hospital
Uniform [200, 500]</td><td colspan="2">producer→care unit
GPO→care unit
hospital→hospital or care unit of other hospital
distribution identical to the one of the hospital where the care unit belongs</td><td colspan="2">hospital→care unit of the same hospital
care unit→care unit of the same hospital
Uniform [10,20]</td></tr>
<tr><td>variable transaction cost</td><td>producer→GPO
GPO →hospital
hospital→hospital
Uniform [1,10]</td><td>producer→ hospital
hospital→ care unit of other hospital
Uniform [5,10]</td><td>producer→ care unit
Uniform [10,15]</td><td>GPO→care unit
Uniform [5,15]</td><td>hospital→care unit of the same hospital
care unit→care unit of the same hospital
Uniform [5,15]</td></tr>
</table>

Note: LS1=25% of total demand / no. of periods
LS2=50% of total demand / no. of periods
LS3=75% of total demand / no. of periods

[53] A network with 2 suppliers, 1 GPO, 5 hospitals and 5 point of care units per hospital, and a planning horizon of 5 purchasing periods has 165 nodes.
[54] The detailed data sets are available in electronic format upon request.

The developed algorithms were implemented in C++ and executed on a PC Intel Core 2 CPU 7200 2.2 Ghz.

In 30 runs to optimise the *grand GPO* (i.e., the GPO that aggregates the five hospitals), the hybrid VNS / Tabu Search algorithm took 5 minutes and 19 seconds on average, to perform an average of 7728 iterations to reach the best solution. The average run time (until the activation of the stopping criterion) was 8 minutes and 4 seconds, and the coefficient of variation of the solution values was 0.012.

To determine how the five hospitals should cooperate, we analysed the outcomes of the 31 possible GPOs (coalitions) they could form. For each GPO, we considered the solution corresponding to the best of 10 runs of the hybrid algorithm. Then, we compared all the 52 possible GPO structures composed from the 31 GPOs, in order to minimise the global costs of the five hospitals. Figure 5.7 shows the percentage of savings that could be achieved through the 51 different cooperative solutions, when compared to a situation of no cooperation, and Table 5.4 compares the three best solutions formed by all the five hospitals with a no-cooperation situation. In Table 5.4, we can also observe that, although the five hospitals have similar sizes in terms of their demand for items 1 and 2, their costs (e.g., average variable unitary cost), when in a no-cooperation situation, are not the same.

One of the advantages of our approach is the possibility of analysing not only the effects (e.g., in terms of costs) of the various cooperating strategies in the network as a whole but also the impact of the global optimisation on each of the hospitals and point of care units. This possibility, making the different impacts visible, is a pre-condition to a fair distribution of cooperation costs and gains, since all participants can analyse in advance the financial consequences, to the group and to the participants, of all possible cooperation arrangements. This will simultaneously determine which hospitals should cooperate when purchasing a specific set of items, according to up to date relevant market conditions. This can also be used to support the negotiation between these participants on how to allocate financial results of that cooperation.

Table 5.5 and Table 5.6 present the costs of the best cooperative solution: hospitals 1, 3 and 5, forming a purchasing group; and hospitals 2 and 4, forming another group. The fixed costs of these purchasing groups have not been allocated to individual hospitals as that distribution would imply the application of some subjective distribution criterion. In a real negotiation process, hospitals can decide which criteria to use. We can observe, in the example, the various impacts of cooperation on individual hospitals: see, for example, the average variable unitary cost of the hospitals within each purchasing group (Table 5.5). Similarly, we also have different percentages of reduction in variable costs.

Table 5.3 Best cooperative vs. non-cooperative solutions

Solution	Solution description	Total Cost	
		Amount	% of Savings
Initial Situation	No cooperation: each of the 5 hospitals has an isolated purchasing strategy / network: 1, 2, 3, 4, 5	2,153,115	-
Best cooperating solutions	All 5 hospitals cooperating: creation of 1 GPO, (1, 2, 3, 4, 5)	1,974,990	8,27%
	(1,2,5), (3,4) ⇒ 2 GPOs	1,974,770	8,28%
	(1,3,5), (2,4) ⇒ 2 GPOs	1,972,041	8,41%

Table 5.4 Best non-cooperative solutions: comparison of individual hospitals

Hospital	Demand		Average variable unitary cost		Variable costs	Fixed costs	Total cost
	Item 1	Item 2	Item 1	Item 2			
1	1536	1664	117.26	70.03	296,639	92,060	388,699
2	2088	1674	116.74	76.46	371,762	70,454	442,216
3	1769	2522	121.49	78.06	411,783	83,203	494,986
4	1120	1910	121.70	80.00	289,112	92,146	381,258
5	1832	1767	118.99	77.93	355,680	90,277	445,957
Total	-	-	-	-	1,724,975	428,140	2,153,115

Table 5.5 Best cooperative vs. best non-cooperative solutions: comparison of average variable unitary costs

Purchasing groups	Hospital	Average variable unitary costs					
		Item 1			Item 2		
		No cooperation	Cooperation	Reduction (%)	No cooperation	Cooperation	Reduction (%)
(1, 2, 3, 4, 5)	1	117.26	96.67	17.6%	70.03	59.59	14.9%
	2	116.74	98.67	15.5%	76.46	60.26	21.2%
	3	121.49	97.30	19.9%	78.06	57.95	25.8%
	4	121.7	99.95	17.9%	80	59.54	25.6%
	5	118.99	97.15	18.4%	77.93	60.03	23.0%
(1, 3, 5)	1	117.26	97.25	17.1%	70.03	68.84	1.7%
	3	121.49	99.21	18.3%	78.06	69.48	11.0%
	5	118.99	101.12	15.0%	77.93	67.77	13.0%
(2, 4)	2	116.74	115.37	1.2%	76.46	73.44	4.0%
	4	121.70	115.95	4.7%	80.00	73.54	8.1%

The information provided by the model should then be used by the five hospitals to decide how to allocate the financial results of their cooperation effort. For example, given the intentions to cooperate expressed by the five hospitals, and as a consequence of the results obtained, a negotiation may be initiated between groups (2, 4) and (1, 3, 5) aiming at implementing a solution where all five hospitals cooperate (with 8.27% savings instead of the global 8.41% of the optimal solution). In this situation, hospitals 2 and 4 may accept to transfer part of their savings to hospitals 1, 3, and 5, as long as they obtain a result that overcomes the

2.0% savings that they would attain if they stayed isolated in a group (see Table 5.6). Alternatively, the five hospitals may decide to organize their purchases through the two GPOs recommended in the optimal solution, thus maximizing their global savings, and simultaneously implement a share scheme that involves the transferral of some of the resulting financial gains from (1, 3, 5) to (2, 4).

Table 5.6 Best cooperative vs. best non-cooperative solutions: comparison of costs

Purchasing groups	Hospital	Variable costs			Fixed costs			Total costs		
		No cooperation	Cooperation	Reduction (%)	No cooperation	Cooperation	Reduction (%)	No cooperation	Cooperation	Reduction (%)
(1, 2, 3, 4, 5)	1	296,639	247,633	16.5%	428,141	592,500	-38.4%	388,699	1,974,990	8.27%
	2	371,762	306,889	17.5%				442,216		
	3	411,783	318,267	22.7%				494,986		
	4	289,112	225,657	21.9%				381,258		
	5	355,680	284,044	20.1%				445,957		
Total		1,724,975	1,382,490	19.85%				2.153.116		
(1, 3, 5)	1	296,639	263,929	11.0%	92,060	245,451	7.6%	388,699	1,165,120	12.37%
	3	411,783	350,730	14.8%	83,203			494,986		
	5	355,680	305,010	14.2%	90,277			445,957		
(2, 4)	2	371,762	363,826	2.1%	70,454	172,780	-6.3%	442,216	806,921	2.01%
	4	289,112	270,315	6.5%	92,146			381,258		
Total		1,724,975	1,553,810	9.9%	428,141	418,231	2.3%	2,153,116	1,972,041	8.41%

It must be noted that the perception of fairness for the allocation of gains of a collaboration by the parties involved often involves some subjective elements and may be quite dependent on the situation under analysis (e.g., on the distribution of power among parties) (Stadtler 2009).

A comprehensive sensitivity analysis revealed that the algorithm operates as expected. As an example, it is interesting to analyse the effect on the total cost of the possible GPOs (see Figure 5.8), and on the final cooperative solution (see Figure 5.9) of the changes experimented in two of the cooperation related variables – the fixed administrative costs of establishing a commercial relation (a_{ij}), and the quantity discounts offered by the suppliers (w_{glj}).

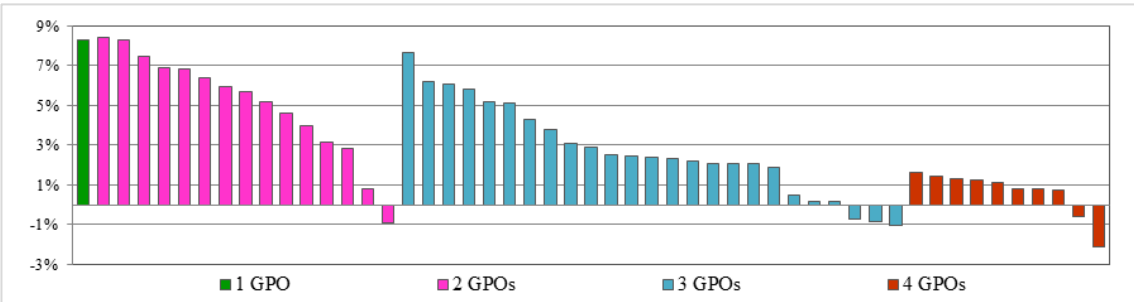

Figure 5.7 Total cost savings of various cooperative solutions vs. non-cooperative solution

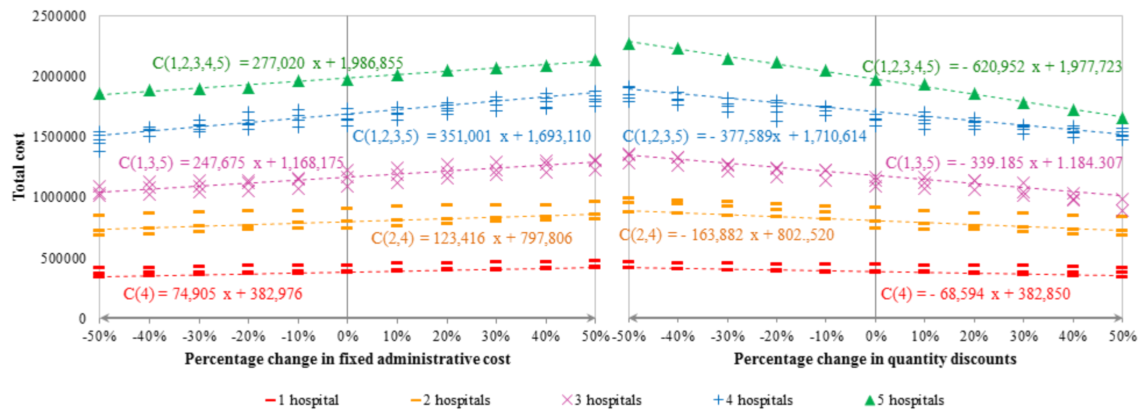

Figure 5.8 Sensitivity analysis: GPOs total cost

When the fixed administrative cost increases, the total cost of the various possible GPOs rises (see Figure 5.8), as expected. In this situation, there will be a higher incentive to cooperate, because joint solutions allow the GPO members to engage in less commercial relations. This was what happened in the GPO structure solution: when the fixed administrative cost is higher, the solution recommended by our approach corresponds to the *grand GPO* (see Figure 5.9).

	-50%	-40%	-30%	-20%	-10%		10%	20%	30%	40%	50%
Percentage change in fixed administrative cost											
Best solution	(2, 3, 4, 5), (1)	(1, 3, 5), (2, 4)		(1, 2, 5), (3, 4)		(1, 3, 5), (2, 4)				(1, 2, 3, 4, 5)	
2nd best	(1, 3, 5), (2, 4)	(1, 2, 5), (3, 4)		(1, 3, 5), (2, 4)		(1, 2, 5), (3, 4)		(1, 2, 3, 4, 5)		(1, 3, 5), (2, 4)	(1, 2, 5), (3, 4)
Savings relative to NO cooperation (%)	13.0%	10.8%	11.1%	11.1%	11.0%	8.4%	9.1%	9.4%	9.2%	8.5%	8.4%
Total cost change (%)	-10.8%	-7.5%	-6.1%	-4.8%	-3.8%		1.4%	2.6%	4.2%	6.1%	8.3%
Percentage change in quantity discount											
Best solution	(1, 3, 5), (2, 4)		(1, 4, 5), (2, 3)	(1, 3, 5), (2, 4)	(1, 2, 5), (3, 4)	(1, 3, 5), (2, 4)	(1, 2, 5), (3, 4)	(1, 2, 3, 4, 5)			
2nd best	(1, 4, 5), (2, 3)	(1, 2, 5), (3, 4)	(1, 3, 5), (2, 4)	(1, 4, 5), (2, 3)	(1, 3, 5), (2, 4)	(1, 2, 5), (3, 4)	(1, 2, 3, 4, 5)	(1, 2, 5), (3, 4)			
Savings relative to NO cooperation (%)	6.3%	5.8%	9.3%	7.4%	7.6%	8.4%	11.2%	11.2%	13.0%	14.2%	15.2%
Total cost change (%)	13.4%	11.3%	5.2%	5.7%	3.4%		-0.7%	-5.6%	-9.6%	-12.8%	-15.8%

Figure 5.9 Sensitivity analysis: GPO structure solution

When the quantity discounts increase, if the required item quantity volumes are attained, prices decrease and subsequent commercial margins and inventory costs do also decrease. As a consequence, as expected, the total cost of the various possible GPOs decreases (see Figure 5.8). We can observe that larger GPOs take a better advantage of this situation than small GPOs (e.g., on average, a rise of 10% in the quantity discounts decreases the *grand GPO* total cost by approximately 3%, while the total cost of a GPO formed by two hospitals will only decrease approximately 2%). Additionally, there will be a higher incentive to cooperate, since the consolidation of purchased volumes will enable GPOs to access prices that are lower than they were before, and only larger GPOs can purchase the quantity needed to reach the better prices. When the quantity discounts are higher, the solution recommended by our approach is, as expected, the *grand GPO* (see Figure 5.9).

We must recall that our work assumes that the involved GPOs are *informally structured programmes*, and consequently, in this illustrative example, larger GPOs are not hindered by rising GPO coordination costs associated with GPO size. The results obtained are, therefore, in accordance with the characteristics of the modelled situation. In other contexts, if much larger and formal GPOs were involved, we could have a different behaviour as the observed direct relation between higher fixed administrative costs and higher quantity discounts and cooperation could be counterbalanced by the impact of a rise on GPO coordination and operation costs. Our approach can, however, be easily adapted to analyse problems with different cost structures.

5.6 Conclusion

The approach proposed can be quite useful in supporting the design and evaluation of alternative cooperative purchasing strategies for health care supply chains. Given the combinatorial nature of the problem and the dimension of real life instances, we have designed a computational procedure based on metaheuristics. Moreover, the flexibility of the approach allows its application to purchasing groups with quite different characteristics, namely in order to perform experiences concerning the optimal size of purchasing groups under different operative and market circumstances, and involving supply chains with different topologies and atypical cost characteristics.

The approach can also be used to promote and facilitate the cooperation process, since it is easily applicable, and it makes the financial impact of the various cooperation alternatives transparent, opening way to negotiation processes concerning the allocation of the costs and gains of cooperation between the participating hospitals.

Preliminary computational experiments show the potential of the developed approach in solving quite different cooperative purchasing problems. These experiments have been designed for illustrative purposes, but we believe that the future incorporation of these tools in a Decision Support System can significantly contribute to an increase of health care supply chains efficiency and encourage the establishment of cooperative partnerships between their members.

6 Conclusion

6.1 Summary of the research work

In a first part of this work, we have made a synthesis of the literature on hospital materials supply chain segmentation, having analysed, reconciled and condensed the information related to the segmentation variables used, the resulting segments, and the recommended operational strategies for those segments. The results of this exercise were compared with qualitative information collected from two hospital systems. Points of agreement and also points of discrepancy have been recognised, and several interesting research or managerial gaps identified.

We then used Cluster Analysis to derive a classification scheme for the items flowing in a hospital supply chain. This scheme consists of a segmentation of those items, based on their characteristics that are relevant in terms of the required operational supply chain capabilities. In the course of this work, we have proposed a service related proxy for hospital item criticality. The identified segments were linked to the operational supply chain capabilities, processes and resources that have been recommended for their management.

The research work described in chapters 4 and 5 was directed towards one of the identified hospital supply chain segments: *high volume, frequent and generalised use* items, and involved the modelling of the associated supply chain.

In chapter 4, the analysis focused on the internal hospital supply chain, and involved the development of several System Dynamics simulation models, designed to analyse alternative supply chain operational processes. These processes involved: decentralised inventory control with no information sharing *versus* centralised inventory control and some information sharing; the possibility of emergency deliveries from the Distribution Centre (DC), in case of a stock-out at a ward, giving (or not) priority to the emergency room (ER) in the allocation of inventory when the inventory on hand at the DC is insufficient to meet all requests; and/or the existence of lateral transshipments from the other wards to the ER. Furthermore, the effects of some usual behavioural based hospital management practices, namely the "just-in-case" approach to inventory control, were analysed.

In chapter 5, the analysis considered both the hospital internal supply chain, and the cooperative opportunities involving neighbour hospitals. A flexible approach was developed to be used for recommending and evaluating the structure of Group Purchasing Organisations (GPO) (i.e., the number of GPOs to form, their size and composition) for a set of hospitals willing to cooperate, while minimising their shared supply chain costs. For this purpose, a VNS / Tabu Search based approach was designed, combining the recommendation of a GPO structure with the use of an optimisation procedure to determine the supply chain configuration of the resulting GPOs (i.e., where, when and in which quantities supplied items are stored and flow in the supply chain). This approach makes the financial impact of the various cooperation alternatives transparent, opening the way to negotiation processes on the allocation of the costs and gains of cooperation between the participating hospitals.

The results of this doctoral project answer the stated research questions:

- *How do the characteristics of the services provided or materials supplied influence the capabilities required from a hospital materials supply chain?*

This question is answered, in chapter 2, when, through literature review and interviews with materials supply chains managers of two hospital systems, we identify characteristics of the services or materials provided that are considered as affecting the capabilities required from a hospital materials supply chain (see details in section 2.5 and subsection 2.6.2), and when we list the identified *cost, service, time* and *space related* hospital materials supply chain capabilities and associate them to the type of materials segment they have been recommended for (see details in subsection 2.6.4).

The question is also answered in chapter 3, which links the three materials segments identified in the internal supply chain of a hospital system (*X: expensive, specific use items*, *V: high volume, frequent and generalised use items*, and *C: critical items*) to the materials supply chain operational capabilities they require from the supply chain (see details in section. 3.4).

- *How can the required hospital materials supply chain capabilities be achieved? (i.e., which processes and resources are needed to attain those capabilities?)*

In chapter 2, we answer this question by highlighting how, according to the literature and the interviewees, the identified *cost, service, time* and *space related* hospital materials supply chain capabilities can be linked to operational processes and/or resources (see details in subsection 2.6.4).

In chapter 3, we link the operational capabilities required by the identified materials segments (*X: expensive, specific use items*, *V: high volume, frequent and generalised use items*, and *C: critical items*) to the operational processes and resources that have been recommended to attain them (see details section 3.4).

In chapters 4 and 5, the developed models are directed at one of the materials supply chain segments identified in chapter 3 (*high volume, frequent and generalised use items*). In both chapters, we consider alternative decisions that constitute strategic operational processes (e.g., the level of centralisation of the chain inventory management decision making, in chapter 4, or the group of neighbour hospitals with which to cooperatively purchase a given material, in chapter 5). These alternatives are evaluated relatively to outcomes (inventory level and service level, in chapter 4, and various types of costs, in chapter 5) that can be linked to operational capabilities. The research described in chapter 4 goes further in the answer of the research question since the obtained results can be used as propositions to be tested in the future, because the performed simulations used data based on quantitative information collected from a real hospital system and System Dynamics models can provide insights about the analysed systems with minimal data inputs. In the case of chapter 5, the data were generated based on qualitative information, which implies that the results must be interpreted prudently.

- *How are good hospital supply chain operational strategies (for differentiated types of materials) defined in terms of operational capabilities, processes and/or resources?*

By answering the previous research question, chapter 2 does also contribute to answer this question. In chapter 3, we identify three hospital materials supply chain segments (*X: expensive, specific use items*, *V: high volume, frequent and generalised use items*, and *C: critical items*) and link them to recommended operational capabilities and to processes and/or resources to attain them (see section 3.4). For the reasons and with the limitations presented relatively to the previous research question, the developed models described in chapters 4 and 5 do also contribute to answer this question for *high volume, frequent and generalised use items*. For example, the results obtained in chapter 4 indicate that, when a high service level is required at a critical ward, reactive lateral transshipments from the ordinary ward with the lower probability of having a stock-out to the critical ward may result in a positive outcome in terms of service level at that critical ward, without harming the average inventory level at the whole hospital.

Thus, the work presented in chapters 2 and 3 contributes to achieve the following operational objectives of the research project: I.a) identify opportunities for hospital materials supply chain management enhancement through a better fit between operational strategies and services/items characteristics; I.b) explain how the capabilities required for the materials supply chain of a hospital are influenced by characteristics of the services provided or of the items that flow through the supply chain; and I.c) develop a scheme to simplify hospital materials supply chain management through the identification of a manageable number of groups (segments) of homogeneous items (in terms of the capabilities required from the supply chain), linking those groups with specific operational capabilities and the necessary processes and resources.

The work described in chapters 4 and 5 contributes to achieve operational objective II, namely, “taking the determined segments into account, develop (simulation or optimisation) models to assess different hospital materials supply chain operations strategies, at various levels of analysis (in the internal and/or external supply chain), while evaluating the impact of those strategies for different hospital supply chain players / stakeholders".

6.2 Main contributions

The full research and managerial contributions of the work developed in this doctoral project have been described in detail in the different chapters of the dissertation. At this point, we highlight the following points:

- We have made relevant contributions to the systematisation and integration of the literature on materials supply chain segmentation for hospitals. The comparison of information from the literature with qualitative information collected from two hospital systems led to the identification of a set of interesting research and managerial gaps. These results provide useful insights of otherwise disperse research content in an organised and comparative way.
- The developed empirical segmentation for the materials hospital supply chain has the following advantages over previous taxonomies or typologies: the determined segments are mutually exclusive and comprehensive; it highlights the relations between several item associated variables that are relevant for an operational supply chain strategy; and it incorporates knowledge both from the literature and from the hospital supply chain managers.
- The proposed service related proxy for item criticality in hospital contexts can be a useful starting point for the application of systematic criticality based differentiated supply chain policies.
- The System Dynamics based models developed to analyse various hospital supply chain relevant decision processes, and the simulation experiments performed using those models, have highlighted the impacts and interactions between those processes. These models have also provided some simple management guidelines that can be easily considered by hospital supply chain managers.
- The development of a model for the determination of the best GPO structure in a group of cooperating organisations (in our case, hospitals), integrated with the multi-period optimisation of the resulting GPO supply chains, computing the costs of all participants, and combining (for the first time, as far as we are aware of) the following characteristics: interrelated purchasing; distribution and inventory decisions; more than two echelons; multiple suppliers; multiple products; quantity discounts; fixed costs; path-dependent costs; and bundled storage and supply capacity constraints.

6.3 Future research

As mentioned above about the main contributions of the developed research work, some detailed paths for future research have been pointed out in each of the previous chapters.

The research work described in chapters 2 and 3 has explicitly incorporated the perspectives of some hospital supply chain managers. But some additional interesting insights may surely be gained if the views of health professionals working at wards with different characteristics are also taken into account. Additionally, a very relevant future development of the proposed classification scheme (i.e., segmentation) might be the study of the relation between hospital supply chain fit and performance.

The natural future developments of the work described in chapter 4 involve integrating the developed simulation models with optimisation procedures, as a way to optimise the management policy parameters used in the models, and to analyse the influence of these parameters on the different models. Furthermore, the developed models can be modified in order to analyse other strategic hospital supply chain issues (e.g., more echelons or more entities in the considered tiers, other network configurations, different inventory allocation rules, etc.). The developed models seem to be rather flexible, and could therefore be used and modified, refined and improved iteratively with the participation of hospital supply chain managers, for example, in the scope of an *action research* project.

Finally, in what concerns the work in chapter 5, there is plenty of room for improvement in the problem resolution methods, for example, in the development of algorithms to solve related problems for large (nationwide) GPOs. In general, we might expect that extensions and adaptions of these methods would be able to solve complex real cases, with a significant positive impact in the organisations.

Appendices

Appendix 2.1 – Supply chain segmentation: a detailed summary of relevant studies

The framework of analysis is explained in section 2.4. The underlying *element of exchange* of all the studies were the *materials* supplied.

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Fisher (1997) /conceptually based typology	• product innovation • demand predictability • product life cycle duration • make-to-order lead time • product variety • contribution margin $\left[= \frac{price - variable\ cost}{price}\right]$ • end-of-sale mark down	functional products[55] (predictable demand)	physically efficient process	low cost	manufacturing: maintain high average utilization rate inventory: generate high turns and minimize inventory throughout the chain lead-time: shorten lead time as long as it does not increase cost suppliers: select primarily for cost and quality product-design: maximize performance and minimize cost
		innovative products[56] (unpredictable demand)	market responsive process	quick response to demand to minimise stock-outs, forced markdowns, and obsolete inventory	manufacturing: deploy excess buffer capacity inventory: deploy significant buffer stocks of parts or finished goods lead-time : invest aggressively in ways to shorten lead time suppliers: select primarily for speed, flexibility and quality product-design: use modular design to postpone product differentiation for as long as possible
Naylor et al. (1999)[57] /PC supply chain case study	• demand volume stability • demand variety stability	stable demand (level schedule) volatile market place	lean manufacturing	reduced cost	A comparison of lean, agile and hybrid (*leagile*) strategies, aggregating insights of various researchers, can be seen in Table 2.2.
		fluctuating demand (in terms of volume and variety)	agile manufacturing	high service level	

[55] Long life cycle (> 2 years), low contribution margin (5 to 20%), low product variety, low (10%) average margin of error in the forecast at the time production is committed, low (1 to 2%) average stock-out rate, 0% average forced end-of-season markdown as percentage of full price, long (6 months to 1 year) lead-time required for made-to-order products.

[56] Short life cycle (3 months to 1 year), high contribution margin (> 20%), high product variety, 40 to 100% average margin of error in the forecast at the time production is committed, high (10 to 40%) average stock-out rate, 10 to 25% average forced end-of-season markdown as percentage of full price, short (1 day to 2 weeks) lead-time required for made-to-order products

[57] The authors recommend that lean and agile strategies are both used in a supply chain by carefully positioning the decoupling point.

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Mason-Jones et al. (2000)	• life cycle length • demand uncertainty • risk of stock-out and obsolescence	commodities (e.g., tinned soups) (long life cycle + low demand uncertainty)	cost reduction: lean supply chain	market winners: price market qualifiers: quality, lead time, service level	• reduce the material throughput time, i.e. compress all lead times. • link factories to customer demand via an integrated Distribution Requirements Planning (DRP) system • use the shortest planning period • reduce and synchronize `time buckets' throughout the chain • streamline and make highly visible all information flows
		fashion goods (e.g., trendy clothing) (short life cycle + high demand uncertainty)	improve match between supply and demand and respond faster to marketplace: agile or *leagile* (lean preceding agile) supply chain	market winners: service level market qualifiers: quality, price	• products pulled by current sales demand • behind the decoupling point, suppliers work to level schedules • accelerate the lean part of the supply chain
Lamming et al. (2000)	• innovation • uniqueness • physical complexity of the product	functional products + low complexity (e.g., canned soft drinks, beer cans, wheel cylinders, window wipers)	not explicitly named	cost (by high volume production), service	sharing of resources and information: generally unproblematic - may include cost and strategic knowledge - IT less critical
		functional products + high complexity (e.g., off-road car)	not explicitly named	cost reduction, quality sustainability, service	sharing of resources and information: large amounts of nonstrategic information enabled by IT - generally unproblematic: may include cost breakdowns and strategic knowledge
		innovative and unique products + low complexity (e.g., drugs, LED semi-conductor, communications technology)	not explicitly named	speed and flexibility, innovation, quality supremacy	sharing of resources and information: problematic exchange of sensitive information[58] and knowledge - IT less critical
		innovative and unique products + high complexity	not explicitly named	speed and flexibility, innovation, quality supremacy	sharing of resources and information: large amounts of nonstrategic information enabled by IT - problematic when involving sensitive information[58] and knowledge

[58] When sharing of cost information is problematic, implementation of lean supply chain strategy is also difficult.

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Christopher and Towill (2000)[59] (DWV^3 classification) /theoretically derived /retrospectively applied to a case study by Childerhouse et al. (2002) /application also described by Aitken et al. (2003)	• Duration of life cycle (D) • time Window for delivery (W) • Volume (V) • Variety (V) • Variability (V)	low volume	MRP (Materials Requirement Planning)	order winners: service level (i.e., maximise availability) market qualifiers: cost, quality, lead service	• make-to-order approach via MRP control • common raw material stocks and shared manufacturing resources
		high volume + low variety	kanban	order winners: cost market qualifiers: quality, service level, lead time	• two-bin system operated across the supplier interface, with kanban control • lean supply channel • make-to-stock policy (deliveries to customer orders in very short lead times)
		high volume + high variety	packing centre	order winners: cost market qualifiers: quality, lead time, variant availability	• (production) postponement (- in the case described, the decoupling point had been placed at the subassembly level) • *leagile strategy:* lean production behind the decoupling point (as in the previous segment); downstream of the decoupling point in the final packing centre specific customer orders are assembled and dispatched, offering multiple variants cost effectively and with very short order cycle times
		short product life cycle product life cycle stage: infant	design and build	order winners: design capacity market qualifiers: quality, cost, design, lead time	• agile supply chain

[59] When disconnected from some practical framing, the DWV^3 *a priori* classification scheme proposed by Christopher and Towill (2000) has the disadvantage of leading to a large number of theoretical supply chain strategies.

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Lee (2002)	• demand uncertainty (functional x innovative products) − demand variability, product variety, − product selling life duration, − inventory cost, − profit margin, − volume per SKU, − stock-out costs, − obsolescence risk • supply uncertainty (stable x evolving process) − breakdown risk, − yield volume and stability, − risk of quality problems, − number of supply sources, − suppliers reliability, − number of process changes, − capacity constraints, − flexibility, − lead time stability	low[60] demand uncertainty + low[61] supply uncertainty e.g., grocery, basic apparel, food, oil and gas	efficient supply chain (demand uncertainty reduction, if a bullwhip effect is observed)	cost efficiency	• eliminate non-value added activities, pursue scale economies, optimise capacity utilisation, establish information linkages to ensure efficient, accurate and cost effective transmission of information • share demand information and synchronise planning across the supply chain • collaborative joint replenishment potentiated by internet (once demand, inventory and capacity information is transparent)
		low[60] demand uncertainty + high[62] supply uncertainty e.g., hydro-electric power; some food.	risk-hedging supply chain (supply uncertainty reduction)	share supply disruption risk	• sharing and pooling resources • more than one supply source • increase safety stocks of key components • sharing safety stock of key components with other companies (or keeping them upstream in the SC) • internet communication to provide information transparency between SC members sharing inventory • free exchanges of information, starting at the product development stage and continuing at the mature and end-of-life phases
		high[63] demand uncertainty + low[61] supply uncertainty e.g., fashion apparel, computers, and pop music.	responsive supply chain (demand uncertainty reduction)	responsiveness and flexibility (to changing and diverse needs of customers)	• postponement: built-to-order and mass customisation • order accuracy relatively to customer requirements • internet communication (to transfer orders fast and accurately)
		high[63] demand uncertainty + high supply uncertainty e.g., telecom, high-end computers, semiconductor	agile supply chain (demand uncertainty reduction + supply uncertainty reduction)	responsiveness and flexibility (to customers' needs) while hedging supply or shortages risks	• pooling inventory or other capacity resources • implement strategies that combine *hedge* and *responsive* SCs • improve internet-based communication among multiple tiers of suppliers

[60] Functional products - Demand characteristics: low uncertainties, more predictable, stable, long product life, low inventory cost, low profit margins, low product variety, higher volume per SKU, low stock-out costs, low obsolescence.

[61] Stable process - Supply characteristics: less breakdowns, stable and higher yields, less quality problems, more supply sources, reliable suppliers, less process changes, less capacity constraints, easier to change, flexible, dependable lead time.

[62] Evolving process - Supply characteristics: vulnerable to breakdowns, variable and lower yields, potential quality problems, limited supply sources, unreliable suppliers, more process changes, potential capacity constraints, difficult to change, inflexible, variable lead time.

[63] Innovative products - Demand characteristics: high uncertainties, difficult to predict, variable, short selling season, high inventory cost, high profit margins, high product variety, low volumes per SKU, high stock-out costs, high obsolescence.

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Olhager (2003)	• delivery lead-time requirements • demand volatility • demand volume • product range and customisation requirements • customer order size and frequency • demand seasonality • product modularity • product customisation opportunities • material profile • product structure • production lead time • number of planning points • flexibility of the production process • production process bottleneck	standard product, commodity + predetermined, narrow product range + high volume, predictable demand	pre-OPP (Order Penetration Point) operations	order winners: price market qualifiers: design, quality, on-time delivery	• line, high-volume batch process • lag/track capacity • product focus facilities • vertical integration: supplier relationships, OPP buffer/post-OPP operations • process quality focus • centralised organisation • production planning and control: level Sales & Operations Planning (S&OP) strategy; order promising based on stock availability; rate-based material planning; pull-type execution • performance measurement: cost, productivity
		special product + wide product range + low volume, volatile demand	post-OPP operations	order winners: design, flexibility, delivery speed market qualifiers: price, quality, on-time delivery	• job shop, low-volume batch • lead/track capacity • process focus facilities • vertical integration: customer relationships, OPP buffer/pre-OPP operations • product quality focus • decentralised organisation (focussing on delivering a customised product on time) • production planning and control: chase S&OP strategy; order promising based on lead time agreement, and material and capacity availability; time-phased material planning; push-type execution • performance measurement: flexibility, delivery lead times

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
Yang et al. (2004a, 2004b)	• uncertainty (e.g., customer needs, technological or regulatory standards changes) • modularity (in the production development or cycle), i.e., processes can be divided into non-interdependent sub-processes	low uncertainty + low modularity	logistics (i.e., time[64] and space[65]) postponement	reduce obsolete inventories, improve responsiveness	• if the cost of shipping the product is low, ship it from one source directly to all customers • more relevant when products are more sensitive to inventory costs than transport costs (e.g., high value added products with large product variety) • eventually, distribution centres based on cross-docking and automatic identification techniques
		low uncertainty + high modularity	production postponement (i.e., manufacturing, assembly, packaging, or labelling)[66]	reduce the need to stock inventory of all product variations (and, consequently, inventory holding costs)[67]	• produce the generic semi-finished products and retain this status as long as possible in the production process • a key decision is where to implement postponement: it may lead to a downstream positioning of production activities from a manufacturer to the distributor, retailer or even the end customer • postponed activities should be designed to be easily carried out (by the distributors/retailers) immediately before shipment • base products or generic modules produced more efficiently (e.g. via centralised production plants)
		high uncertainty + low modularity	purchasing postponement	minimise component and raw material inventories, reduce risk and uncertainty costs	• purchasing components (namely, expensive and fragile raw materials and components that come in many different sizes and shapes) as close to the point of manufacture as possible • high level of collaboration between manufacturers and suppliers • from a supply chain wide perspective, postponement shifts the risk of ownership of goods to the most appropriate supply chain partner in order to minimize overall channel costs; but, the dominant manufacturer may postpone its purchase decisions until the latest possible time to diminish its own risk and uncertainty costs

[64] Delaying the forward movement of inventories.
[65] Maintaining inventories in centralised locations.
[66] The level of production postponement will depend on the degree of modularity.
[67] Success depends on the balance between the potential sacrifice that customers make (e.g. how much delay will they tolerate, how much will they pay for higher production customisation), and the company's ability to produce individualised products within an acceptable time and cost frame.

Authors / Method	Segmentation variables	Segments	Strategies	Operational capabilities	Processes / Resources
		high uncertainty + high modularity	product development postponement	development lead time reduction, reduction of costly redesigns	• information on customer requirements and on the available technology drives all the development process • customer-relationship management; cross-functional teams (marketing, R&D, manufacturing, suppliers and customers) • make specification decisions that are more likely to remain stable; certain decisions are deferred until late in the development process when better information is available • structuring design tasks: the product development process is typically partitioned into smaller tasks
Lovell et al. (2005) / case study: global electronics company (Sony broadcast and professional Europe)	• throughput (demand level) volume • demand variability/ service (product availability) factor • product value density (value/ weight or size)	high throughput + low demand variability/ service (availability) factor	decentralised[68] inventory holding + slower transport options	controlled inventory holding costs	transportation mode: sea freight
		low demand variability/ service (availability) factor + low product value density			
		high throughput + low product value density			
		high throughput + low product value density			
		low throughput + high demand variability/ service (availability) factor	centralised[69] inventory holding + faster[70] transport options	controlled inventory holding costs + fast transport	transportation mode: air freight
		high demand variability/ service (availability) factor + high product value density			
		low throughput + high product value density			

[68] Increasing throughput levels provide opportunities from economies of scale, therefore a more decentralised approach to inventory holding is possible.
[69] To take advantage of risk pooling, reducing safety stocks.
[70] To compensate longer lead times due to distance from the inventory holding points and mitigate their impact on holding stocks.

Appendix 2.2 – Guide of the interviews with Supply Chain and Pharmacy managers

Initial issues:

- Presentation;
- Explanation of the scope and objectives of the research study;
- Information about voluntary participation and guaranties of confidentiality and anonymity;
- Information about expected interview duration;
- Ask the interviewee to raise questions or concerns whenever necessary;
- Explain the meaning of the word *logística* (logistics) throughout the interview[71];
- Ask permission to record the interview;
- Turn the audio recorder on.

Questions / Themes to be addressed

Biographic information

- Function;
- Year of birth;
- Entry in the Hospital System (year);
- Years of experience in the health care sector;
- Previous professional experience.

Strengths and weaknesses of hospital supply chain management

- *Quais são os principais pontos fortes da gestão logística do hospital?* (What are the main strengths of the hospital system supply chain management?)
- *E quais são os principais pontos fracos ou obstáculos a uma logística optimizada?* (And what are the main weaknesses or obstacles to an optimised supply chain?)
- *Como é que a logística do hospital poderia ser melhorada? Porquê*? (How could the supply chain management of the hospital system be improved? Why?)

Change

- *Das várias mudanças nos processos logísticos que têm sido feitas no hospital, quais foram as que correram melhor? Porquê*? (From the various changes in the logistics and supply chain processes that the hospital system has implemented, which ones were the most successful? Why?)
- *E as que correram pior? Porquê?* (And the least successful? Why?)

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[71] In Portuguese, *logística* (logistics) frequently has a broad meaning, corresponding to Supply Chain Management; since the professional activity of the interviewees is related to the supply of materials in the hospital system network, it was implicit that the term had a materials (as opposed to services) focus.

- *Como é que se tem gerido a mudança de forma a garantir que as decisões tomadas são efectivamente implementadas?* (How has change been managed in order to assure that the decisions taken are implemented?)
- *Que tipos de resistência à mudança têm surgido?*(What kinds of change resistance sources have been observed?)
- *O que é poderá contribuir para que uma mudança seja mais fácil e bem sucedida?* (What can be done so that change is easier and more successful?)

Services/ Items

- *Os vários serviços do hospital têm as mesmas necessidades e exigências em termos de gestão logística?* (Do the various services provided by the hospital system have the same needs and requirements in terms of supply chain management?)

  No caso de resposta negativa, pedir para tipificar os vários serviços do hospital em termos dessas necessidades e exigências; ou seja, pedir para explicar como é que se distinguem em termos dessas necessidades/exigências (In case of a negative answer, ask to typify services in terms of their needs and requirements; that is, ask to explain how they differ in terms of those needs/requirements),
- *Os vários medicamentos/artigos de material clínico têm as mesmas exigências em termos de gestão logística?* (Do the various pharmaceuticals/ clinical materials have the same requirements in terms of supply chain management?)

  No caso de resposta negativa, pedir para tipificar famílias medicamentos/artigos de material clínico em termos dessas exigências; ou seja, pedir para explicar como é que se distinguem em termos dessas necessidades/exigências (In case of a negative answer, ask to typify pharmaceuticals/ clinical materials in terms of their requirements; that is, ask to explain how they differ in terms of those needs/requirements),

Suppliers

- *Como se caracterizam os fornecedores de medicamentos/ artigos de material clínico?* (How are the suppliers of pharmaceuticals and medical devices characterised?)

  Questionar sobre (ask about):

  - *localização* (localisation)
  - *capacidade de resposta* (agility)
  - *prazo de entrega* (delivery time)
  - *capacidades de gestão* (managerial skills)
  - *volume de vendas* (sales volume)
  - *poder negocial face ao hospital* (negotiating power in the relation with the hospital system)

- *Quais têm sido as principais dificuldades que têm sentido na gestão da relação com os fornecedores?* (What have been the main difficulties in the management of the relation with the suppliers?)

Partnerships/ Integration/ Cooperation

- *Existem parcerias ao nível da logística com entidades ou empresas externas? Quais?* (Does the hospital system have partnerships in the supply chain scope with external companies or organizations?)
- *Haveria vantagens em criar ou aprofundar essas parcerias? Como? Porquê?* (Would it be beneficial for the hospital system to build or deepen those partnerships? How? Why?)
- *A gestão logística poderia ser melhorada através de uma maior cooperação ou integração com outros hospitais? Como?* (Could the supply chain management be improved though a deepen cooperation or integration with other hospital systems?)
- *E com centros de saúde vizinhos? Como?* (And with neighbour primary care Units? How?)

Outsourcing

- *Que tipos de actividades logísticas poderiam ser externalizadas?* (What kind of logistical/ supply chain activities could be outsourced?)
- *E quais as que não deveriam sê-lo?* (And what kind of activities shouldn't be outsourced?)
- *Quais seriam as vantagens da externalização?* (What would the advantages of outsourcing be?)
- *E os riscos?* (And the risks?)

Future

- *Quais são as principais oportunidades para a gestão logística do hospital num futuro próximo?* (What are the main opportunities to the supply chain management of the hospital system in the near future?)
- *E os principais riscos?* (And the main risks?)
- *Como será a logística do hospital daqui a 10 anos?* (How will the supply chain management of the hospital system be in 10 years?)

Appendix 2.3 – Item characteristics that affect hospital materials supply chain management according to the respondents

In the following table we present the respondents original statements, in Portuguese, and the corresponding English translations concerning the item characteristics that they considered as influencing hospital supply chain management. The respondents' quotations are identified using the codes in Table 2.6.

Item characteristics	Interview transcriptions
Unit cost	*É muito diferente eu estar a gerir compressas, que têm cêntimos de preço unitário, ou produtos que valem mil euros ou quinze mil euros, um, uma unidade* [...] (It is very different to manage compresses, which have unit costs of cents, or items that are worth one thousand euros or fifteen thousand euros each unit [...]) (SCD, HS1) *Nos produtos farmacêuticos, lembro-me do paracetamol, que saiem aos quilos que custam uma ninharia, ou temos os medicamentos de HIV que são caríssimos, saiem em ambulatório. Portanto, é uma gestão logística completamente diferente, não tem nada a ver.* (In the pharmaceuticals, paracetamol is highly consumed and costs a pittance, or we have the very expensive HIV medicines, which go out in outpatient care. Therefore, their supply chain management is totally different, there are no similarities.) (SCD, HS1) [...] *temos, por exemplo, um armazém,* [...] *que é pequeno, mas onde temos esses materiais* [...] *que têm também um valor unitário, em termos de custo, elevado e que estão ali mais confinados a uma determinada área. Tudo aquilo que são... eh... produtos que, pelo seu valor unitário,* [...] *Estou-me a lembrar, por exemplo, de neuro-estimuladores para cirurgia de Parkinson.* (We have, for example, a small warehouse [...] where we have those materials [...] that have a unit value that is high in terms of cost and that are there confined to a given space. Everything that is... eh... items that, given their unit value, [...] for example, the neuro-stimulators to Parkinson surgeries.) (SCD, HS2) [...] *no internamento numa medicina têm muito material barato e é muito de volume* [...] *Agora se me for falar numa hemodinâmica, em cardiologia, no bloco central, em que eu apanho assim uns 70% do valor do stock* [...] ([...] at the medicine inpatient care they have lots of materials that are cheap and the volume is high [...] But, if you ask me about hemodynamics, cardiac surgery, the central OR, where we have approximately 70% of the inventory value [...]) (SCM, HS2)
Demand volume	*Nos produtos farmacêuticos, lembro-me do paracetamol, que saiem aos quilos* […] (In the pharmaceuticals, there is the paracetamol that is highly consumed […]) (SCD, HS1) [...] *temos artigos que são solicitados a pedido... a pedido dos interessados, ou para determinados doentes, para determinada cirurgia que vou fazer* [...] *Porque às tantas os consumos são tão pontuais e esporádicos que não faz sentido estarmos a alocar um espaço para ter esse produto.* ([...] we have items that are ordered by request... by request of whoever needs them, or to specific patients, to a given surgery that will be

Item characteristics	Interview transcriptions
	performed […] Because, in some situations, the consumptions are so occasional and rare that it wouldn't make sense to allocate a space to store that item.) (SCD, HS2)
Shelf life/ Expiry date	*Depois tem o prazo de validade: há produtos com o prazo de validade mais curto do que outros* […] (Then, we have the shelf-life: some items have a shorter shelf life than others […]) [included in a list of various item characteristics that the respondent mentioned when asked if all the materials had the same requirements from the supply chain] (SCD, HS1) [...] *as coisas têm melhorado significativamente... mas* [num passado recente] *ainda havia muito material a ultrapassar prazos de validade. E coisas que, muitas delas nem chegam ao nosso conhecimento, não é? Porque se o material já estiver no Serviço, provavelmente o que o enfermeiro faz, embora tenham sido já alertados para não o fazer e para comunicarem para nós abatermos o material por ultrapassagem de prazo de validade, é, às tantas, simplesmente deitam-no para o lixo* [...] *nós também temos as nossas limitações no próprio armazém e às vezes também temos materiais que expiram o prazo de validade. É uma situação que se tem vindo a minimizar nos últimos tempos, mas, de vez em quando, acontece.* (Things have improved significantly... but [in a recent past] there were still lots of materials that overcame their expiry date. And things that frequently are not known by us, isn't it? Because, if the materials are already on the wards, probably the nurse will simply dispose them, even though they have already been warned not to do it, and to communicate that the expiry date has been exceeded, so that we can write the material off. [...] we do also have our limitations in the warehouse and sometimes we have materials that exceed their expiry date. It's a situation that has recently been minimised, but that does still happen.) (SCD, HS2)
Demand variability	*E temos pela sua variabilidade* [...] (and their variability[...]) [included in a list of various item characteristics that the respondent mentioned when asked if all the materials had the same requirements from the supply chain] (SCD, HS1)
Demand dispersion/ material specificity (use in a specific care unit vs. use in the whole hospital)	[…] *e as fraldas também temos que ver que há em todos os lados de um hospital. Portanto, é preciso os serviços terem cada vez mais uma cultura de rotação de stocks entre os próprios serviços, entre eles, em vez de irem ao aprovisionamento, vão ao lado. O que sempre foi clássico* […] *foi não olhar para o lado, mas sim olhar logo para baixo, para o Serviço de Aprovisionamento ou para a Logística. E o que é certo é que eu tenho stock ao lado, mesmo ao meu lado.* ([…] the diapers, it must be seen that they are used and stored everywhere in a hospital. Therefore, the wards should have a culture that favours the exchange of inventory among the wards, instead of recurring to the central distribution centre. What is classic is not to look to the side, and to immediately look down[72], to the central distribution departments. And what is true is that there is inventory nearby, right at their side.) (SCM, HS2) [...] *as Técnicas de Gastro, Técnicas de Cardiologia e Hemodinâmica, por exemplo, gastam material muito específico* [...] (Gastric, cardiologic and hemodynamics' procedures, for example, use very specific materials [...]) (SCD, HS1) [...] *tudo o que são, por exemplo, próteses* [...] *ou* [dispositivos] *que são sempre para um*

[72] The central warehouse is located in the basement of the hospital.

Item characteristics	Interview transcriptions
	determinado doente, são pedidos caso a caso. Estou-me a lembrar, por exemplo, de neuro-estimuladores para cirúrgia de Parkinson. Pois isso tem de ser articulado, normalmente... naturalmente, com os Serviços. O Serviço sabe quando tem prevista e agendada uma cirúrgia de Parkinson, para implantação de um neuro-estimulador, pede, com a devida antecedência, a aquisição desse neuro-estimulador para aquele doente e fica registado aquele neuro-estimulador àquele doente [...] ([…] for example, prostheses [...] or [devices] that are for a given patient. For example, the neuro-stimulators for Parkinson surgeries. This is something that has to be articulated, normally… naturally, with the Services. The Service knows when a Parkinson surgery, during which a neuro-stimulator will be implanted, is expected, when it was scheduled, and asks, in due time before, for that neuro-stimulator to that patient to be acquired, and the neuro-stimulator is registered for that patient.) (SCD, HS2) *O que é de blocos* [...] *portanto, muito material, especialmente de ortopedia,* [...] *vem directamente para o serviço, directamente para aquela cirurgia* [...] (The operating rooms […] Many of the materials, mainly orthopaedics' materials [...] come directly from the supplier to the service and go directly to a specific surgery.) (SCM, HS2)
Existence of substitutes	[...] *ou porque o produto não tem substituto, ou porque tem* [...] ([...] or because the item doesn't have or has a substitute [...]) [included in a list of various item characteristics that the respondent mentioned when asked if all the materials had the same requirements from the supply chain] (SCD, HS1)
Criticality, urgency	*Um medicamento de urgência não tem o mesmo tratamento que um medicamento não urgente, não é? Como aquele penso, uma pomada não é tão urgente como um injectável ou adrenalina. Uma pomada pode ficar para o dia seguinte, não é urgente.* (An urgent medicine isn't treated the same way as a medicine that isn't urgent, isn't it? Like that bandage or an ointment - it is not so urgent as an injectable or adrenaline. An ointment can wait for the next day, it isn't urgent.) (PHD, HS1) [After having characterised material logistical requirements at the ERs, EORs, ICUs and ORs] *O resto dos materiais são materiais... banais, materiais de protecção, materiais de feridas, materiais de drenagem, aqueles materiais típicos dos cuidados médicos que se prestam no internamento, tipo fraldas, vestuário... estamos a falar de coisas mais... enfim, é escusado ter preocupações tão...* (The remaining materials are... ordinary, protection materials, materials for wounds, drainage, the materials that are typical of the medical care provided at inpatient care, such as diapers, clothes… These materials do not need the same worries.) (SCM, HS2)
Variety	[...] *stents com dispositivos para... Quando uma artéria não está em condições para manter a passagem do sangue, eles são implantados e, só depois de estar o doente deitado é que o médico sabe qual é o tamanho que vai meter, se é com fármaco ou se é sem fármaco... E isso exigia, por parte do hospital, face à multiplicidade de tamanhos e de soluções e de empresas que oferecem o stent... ter um stock brutal para o movimento de uma semana, por exemplo.* [...] *porque há ... de um modelo de um stent eu sou capaz de ter uma lista para aí com vinte ou vinte e cinco diferentes. Porque depois tenho 2,5/10, 2,5/11, 2,5/12, depois 3/10, 3/11..., não é? E isto multiplica consideravelmente e, se pensarmos na Hemodinâmica e que isto é apenas um produto e há vários com este*

Item characteristics	Interview transcriptions
	tipo de situações. ([...] stents with devices to... When an artery isn't in the right conditions to maintain blood flow, they are implanted and, the surgeon only knows which size he will use, and if the stent will have a pharmaceutical or not, after the patient is laid… And that requires that, given the multiplicity of sizes and solutions and firms that offer stents… the hospital holds a huge inventory stock to face the movement of one week, for example. [...] because there are... for one stent model, I can have a list of approximately twenty or twenty-five different possibilities. Because then I have 2.5/10, 2.5/11, 2.5/12, then 3/10, 3/11..., isn't it? And this multiplies considerably and, if we think in the hemodynamics, and this is only one item, there are several with this type of situation.) (SCD, HS2)
Physical size	No *transporte de fraldas, por exemplo,* [...]*: O meu carro é finito e bem finito, portanto não posso ter grandes volumes de fraldas sobre os assentos* ([...] for example, in the transportation of diapers, my car has a finite capacity, I cannot put large volumes of diapers on the car seats…) (SCM, HS2)
Storage conditions	[...] *nós também temos algum cuidado e fazemos alguma diferenciação em tudo o que são, por exemplo, próteses, não só pelo seu custo, mas também pelas suas condições de armazenagem, porque são materiais que... vão para o bloco... e não podem estar armazenados de qualquer maneira e em qualquer condição, porque tudo o que se conseguir evitar de pós e ter em boas condições de armazenagem são factores que devem ser tidos em conta.* ([...] we do also take some care and make some differentiation in all the, for example, prostheses, not only because of their cost, but also for their storage conditions, because these are material that… go to the operating room… and they can't be stored any way, because all the dust that we can avoid and the good storage conditions are factors that must be taken into account.) (SCD, HS2) *Quase a totalidade dos medicamentos têm que estar a uma temperatura controlada entre 2 e 8 graus. Depois, temos os de frio. Quer nos de frio, quer nos da temperatura ambiente, há medicamentos que não podem sofrer... que têm que ser protegidos da luz, porque senão alteram-se. E nos ultracongelados, que requerem -20/-30 graus, mas estes são meia dúzia de produtos, não são mais do que isso. Essencialmente, os mais complicados são a protecção da luz e o frio. O medicamento não é um produto fácil, não é uma mercadoria.* (Almost all medicines have to be preserved at a controlled temperature between 2 and 8 degrees centigrade. Then, we have the cold medicines. Both in the cold and in the ambient temperature medicines, there are medicines that cannot suffer… that have to be protected from light, otherwise they will be damaged. And the ultra-frozen that require temperatures between -20 and -30 degrees centigrade, but these are only half a dozen, not more. Essentially, the more complicated features are light protection and cold. A medicine isn't an easy product, it isn't a commodity.) (PHD, HS1)

Appendix 2.4 – Service characteristics that affect hospital materials supply chain management according to the respondents

In the following table we present the respondents original statements, in Portuguese, and the corresponding English translations concerning the service characteristics that they considered as influencing hospital supply chain management. The respondents' quotations are identified using the codes in Table 2.6.

Service characteristics		Interview transcriptions
Demand volume	**high**	*O fluxo da área médica, da Medicina: são doentes com processos terapêuticos mais complicados*[73]*, maior número, principalmente idosos, exige uma reposição maior de produtos.* (The flow of medicine inpatient care: these are patients with difficult[73] therapeutic processes, in large number, and mostly elderly people, so there is a need for higher item replenishment.) (PHD, HS2) [...] *no internamento numa medicina têm muito material barato e é muito de volume* ([...] at the medicine inpatient care they have lots of materials that are cheap and the volume is high [...]) (SCM, HS2) [...] *Internamentos de Medicina: são doentes muito acamados, doentes com recurso a muita medicação e muito material clínico.* [...] *são doentes que ficam muito tempo internados, muitos dias, o tipo de produto é mais ou menos o mesmo para todos, mas consomem muita quantidade* [...] *muita medicação em dose unitária* [...] ([Medicine inpatient care: the patients are mainly confined to their beds and use lots of medicines and clinical materials. [...] the patients stay in the hospital for a long time, several days, and the type of product is more or less the same for all of them, but they consume a high quantity [...] a lot of unit dose medication [...]) (SCD, HS1) *Depois temos os Internamentos de Cirurgia* [...]*: tem um elevado consumo, idêntico à Medicina, em termos de materiais e de farmácia.* (Then, at the surgery inpatient care [...]: the consumption is high, identical to that of medicine inpatient care, in terms of materials and pharmaceuticals.) (SCD, HS1) [...] *temos blocos* [...] *de oftalmologia, de cirurgia de ambulatório, que são cirurgias curtas e muitas cirurgias por dia, portanto, o volume de produtos é grande, em termos de produtos pequenos - são cirurgias muito curtas, de meia hora/ uma hora,* [...] *portanto, o ritmo de utilização do produto é muito grande.* ([...] the ophthalmology and ambulatory surgery operating rooms; these are short surgeries and lots of surgeries a day, so, the volume of materials is high, in terms of small items – these are very short surgeries that last half an hour/ one hour, therefore, the rhythm of product use is very high.) (SCD, HS1)

[73] The therapeutic processes are *difficult* more due to the patients' conditions than to the technical complexity of the treatments.

Service characteristics		Interview transcriptions
	low	[...] *uma Consulta Externa gasta pouquíssimos materiais, produtos farmacêuticos praticamente nada, e portanto, praticamente não exige nada de nós, ou exige muito pouco de nós.* ([...] outpatient care consumes very few materials and therefore it doesn't demand much from us, or demands only a little.) (SCD, HS1)
Demand variability	**high**	[...] *uma Urgência obriga... tem uma variabilidade de consumo muito grande e obriga-nos a ter mais stock e obriga-nos a ter entregas mais frequentes, com uma frequência maior.* (An emergency room forces us to... has a very big variability of consumption and forces us to have higher inventory and more frequent replenishments, with higher frequency.) (SCD, HS1) *Começando* [...] *pela Urgência e face ao tipo de serviço que tem, que não é previsível, pelo menos não é tão previsível quanto qualquer outro serviço.* [...] *pode haver picos de procura e não basta a reposição directa diária para... para garantir e ter essa margem de segurança. Se formos ver ao longo dos tempos, em termos de número de episódios, às tantas achamos que até não é assim tão desproporcionado quanto isso e que aquilo tem uma estabilidade em termos de produção, mas, no dia a dia, de um dia para o outro, pode haver aqui picos e que nós temos que garantir... e penso que essa é a maior especificidade:* [...] *não podem faltar os materiais de que eles necessitam* [...] (Starting by the emergency room and considering the type of service provided there, which is not predictable, or at least is not as predictable as any other service.[…] there can be demand peaks and daily replenishment is not enough to…guarantee and have the necessary safety margin. If we observe it as time goes by, in terms of number of episodes, we may think that the unbalance is not so big and that there is some stability in terms of production, but, on a day to day basis, peaks may occur and we have to assure… and I think that is the main specificity: […] the materials that they need cannot be missing […]) (SCD, HS2)
	low	*No outro extremo* [relatively to the Emergency Room, described has having high variability], *uma Consulta Externa gasta pouquíssimos materiais, produtos farmacêuticos praticamente nada, e portanto, praticamente não exige nada de nós, ou exige muito pouco de nós.* (On the other extreme [relatively to the emergency room, which is described as having a high variability], outpatient care consumes very few materials and therefore it doesn't demand much from us, or demands only a little.) (SCD, HS1)
Criticality, urgency	**high**	*Pelo tipo de doentes: críticos, complicados, quer a Urgência, quer as UCIs* [Unidades de Cuidados Intensivos] *e blocos, obrigam a uma rotação maior de entregas, pelo tipo de produtos, e maiores quantidades, porque são críticos.* (Because of the type of patients: critical, complex, both the emergency rooms and the ICUs [Intensive Care Units] and operating rooms, force us to increase the replenishment turnovers, due to the type of products, and higher quantities, because they are critical.) (PHD, HS2) *Por exemplo, uma Unidade de Cuidados Intensivos* [...] *Tem necessidade às vezes de medicamentos com uma certa urgência de entrega* [...] (For example, an intensive care unit [...] It sometimes needs medicines with a certain replenishment

Service characteristics		Interview transcriptions
		urgency [...]) (PHD, HS1) *Aí, uma falha, no Serviço de internamento, não deve acontecer, como é natural, mas não tem o mesmo peso que tem uma rotura ou uma falha de entrega num Serviço de Urgência ou numa Unidade de Cuidados Intensivos. Tem uma carga diferente.* (There, a stock-out, in the inpatient care, shouldn't happen, naturally, but it doesn't have the same importance as a stock-out or a replenishing problem in an emergency room or in an intensive care unit. The seriousness is different.) (SCD, HS2) *Nos Cuidados Intensivos, dado que os doentes estão com suporte ventilatório permanente, não é? Essa é a principal característica de uma Unidade* [de Cuidados Intensivos]. *Há materiais que* [...], *quer pelo seu valor, quer pela..., e valor não só comercial, em termos de custo, mas também daquilo que representa para o doente, porque tudo o que seja afecto a suporte ventilatório para o doente tem que estar disponível e tem que estar lá.* (In the intensive care units, since the patients are on permanent ventilation support, isn't it? That is the main characteristic of a[n intensive care] unit. There are materials that […], because of their value and because of… and value is not only commercial value, in terms of cost, but also what it represents to the patient, because everything that is related with ventilation support to the patient has to be available and has to be there.) (SCD, HS2) [...] *em tudo o que é urgente, incluo aqui o Bloco de Urgência e a Urgência,* [...] *aqui interligados os UCIs* [...] *Uma coisa que as Urgências e UCIs têm é que tem de ser tudo rápido, especialmente na Urgência e UCIs.* ([…] in all that is urgent, I include here the Emergency Operating Room, the Emergency Room, and the ICUs […] one characteristic that these emergency departments and ICUs have is that everything has to be fast, especially in the emergency room and the ICUs.) (SCM, HS2)
	low	[uma unidade de cuidados intensivos] *é diferente de uma consulta externa, não é? [...] numa consulta externa, se não for hoje pode ser entregue amanhã, a não ser um caso de emergência [...]* ([...] [an intensive care unit] is different from outpatient care, isn't it? […] in the outpatient care, if it isn't today, it can be delivered tomorrow, unless there is an emergency […]) (PHD, HS1) *Aí, uma falha, no Serviço de internamento, não deve acontecer, como é natural, mas não tem o mesmo peso que tem uma rotura ou uma falha de entrega num Serviço de Urgência ou numa Unidade de Cuidados Intensivos. Tem uma carga diferente.* (a stock-out in the inpatient care shouldn't happen, naturally, but it doesn't have the same importance has a stock-out or a replenishing problem in an emergency room or in an intensive care unit. The seriousness is different.) (SCD, HS2) *O resto dos materiais são materiais... banais, materiais de protecção, materiais de feridas, materiais de drenagem, aqueles materiais típicos dos cuidados médicos que se prestam no internamento, tipo fraldas, vestuário... estamos a falar de coisas mais... enfim, é escusado ter preocupações tão.* ([After having characterised

Service characteristics	Interview transcriptions
	material logistical requirements at the ERs, EORs, ICUs and ORs] The remaining materials are... ordinary, protection materials, materials for wounds, drainage, the materials that are typical of the medical care provided at inpatient care, such as diapers, clothes… These materials do not need the same worries.) (SCM, HS2)
Unit cost (of the consumed materials)	[...] *uma Ortopedia ou uma Neurocirurgia que usa muito material pesado, caro e pesado, e duram 4 ou 5 horas ou 8 horas uma cirurgia* [...] (Orthopaedics or neurosurgery use very heavy materials, expensive and heavy, and a surgery lasts 4 or 5 or 8 hours [...]) (SCD, HS1) [...] *medicamento que é fornecido em ambulatório* [...] *É um medicamento muito caro, preço unitário, e basta que mude a prescrição ou que saia um medicamento novo que seja mais eficaz do que o antigo para que o perfil de consumo se altere drasticamente*. ([...] the medicines that are provided by ambulatory care [...] These are very expensive medicines, in terms of unit cost, and a prescription change or the advent of a new, more effective medicine is enough for the consumption profile to change dramatically.) (SCD, HS1) [...] *no internamento numa medicina têm muito material barato e é muito de volume* [...] *Agora se me for falar numa hemodinâmica, em cardiologia, no bloco central, em que eu apanho assim uns 70% do valor do stock* [...] ([...] at the medicine inpatient care they have lots of materials that are cheap and the volume is high [...] But, if you ask me about hemodynamics, cardiac surgery, the central OR, where we have approximately 70% of the inventory value [...]) (SCM, HS2)
Use of (patient) specific materials	[...] *as Técnicas de Gastro, Técnicas de Cardiologia e Hemodinâmica, por exemplo, gastam material muito específico* [...] (Gastric, cardiologic and hemodynamics' procedures, for example, use very specific materials [...]) (SCD, HS1) [...] *a Hemodinâmica, que coloca stents com dispositivos para... Quando uma artéria não está em condições para manter a passagem do sangue, eles são implantados e, só depois de estar o doente deitado é que o médico sabe qual é o tamanho que vai meter, se é com fármaco ou se é sem fármaco... E isso exigia, por parte do hospital, face à multiplicidade de tamanhos e de soluções e de empresas que oferecem o stent... ter um stock brutal para o movimento de uma semana, por exemplo.* [...] *porque há ... de um modelo de um stent eu sou capaz de ter uma lista para aí com vinte ou vinte e cinco diferentes. Porque depois tenho 2,5/10, 2,5/11, 2,5/12, depois 3/10, 3/11..., não é? E isto multiplica consideravelmente e, se pensarmos na Hemodinâmica e que isto é apenas um produto e há vários com este tipo de situações.* ([...] hemodynamics that places stents with devices to... When an artery isn't in the right conditions to maintain blood flow, they are implanted and, the surgeon only knows which size he will use, and if the stent will have a pharmaceutical or not, after the patient is laid… And that requires that, given the multiplicity of sizes and solutions and firms that offer stents… the hospital holds a huge inventory stock to face the movement of one week, for example. [...] because there are... for one stent model, I can have a list of approximately twenty or twenty-five different possibilities. Because then I have 2.5/10, 2.5/11, 2.5/12, then 3/10,

Service characteristics	Interview transcriptions
	3/11..., isn't it? And this multiplies considerably and, if we think in the hemodynamics, and this is only one item, there are several with this type of situation.) (SCD, HS2) [...] *nós também temos algum cuidado e fazemos alguma diferenciação em tudo o que são, por exemplo, próteses* [...] *ou [dispositivos] que são sempre para um determinado doente, são pedidos caso a caso. Estou-me a lembrar, por exemplo, de neuro-estimuladores para cirúrgia de Parkinson. Pois isso tem de ser articulado, normalmente... naturalmente, com os Serviços. O Serviço sabe quando tem prevista e agendada uma cirúrgia de Parkinson, para implantação de um neuro-estimulador, pede, com a devida antecedência, a aquisição desse neuro-estimulador para aquele doente e fica registado aquele neuro-estimulador àquele doente* [...] ([...] we do also take some care and make some differentiation in all the, for example, <u>prostheses [...] or [devices] that are for a given patient</u>. For example, the <u>neuro-stimulators for Parkinson surgeries</u>. This is something that has to be articulated, normally… naturally, with the Services. The Service knows when a Parkinson surgery, during which a neuro-stimulator will be implanted, is expected, when it was scheduled, and asks, in due time before, for that neuro-stimulator to that patient to be acquired, and the neuro-stimulator is registered for that patient.) (SCD, HS2) *O que é de blocos* [...] *portanto, muito material, especialmente de ortopedia,* [...] *vem directamente para o serviço, directamente para aquela cirurgia* [...] (The <u>operating room</u> […] Many of the materials, mainly <u>orthopaedics</u>' materials [...] come directly from the supplier to the service and go directly to a specific surgery.) (SCM, HS2)
Variety (of the consumed materials)	[...] *a Hemodinâmica, que coloca stents com dispositivos para... Quando uma artéria não está em condições para manter a passagem do sangue, eles são implantados e, só depois de estar o doente deitado é que o médico sabe qual é o tamanho que vai meter, se é com fármaco ou se é sem fármaco... E isso exigia, por parte do hospital, face à multiplicidade de tamanhos e de soluções e de empresas que oferecem o stent... ter um stock brutal para o movimento de uma semana, por exemplo.* [...] *porque há ... de um modelo de um stent eu sou capaz de ter uma lista para aí com vinte ou vinte e cinco diferentes. Porque depois tenho 2,5/10, 2,5/11, 2,5/12, depois 3/10, 3/11..., não é? E isto multiplica consideravelmente e, se pensarmos na Hemodinâmica e que isto é apenas um produto e há vários com este tipo de situações.* ([...] <u>hemodynamics</u> that places stents with devices to... When an artery isn't in the right conditions to maintain blood flow, they are implanted and, the surgeon only knows which size he will use, and if the stent will have a pharmaceutical or not, after the patient is laid… And that requires that, given the multiplicity of sizes and solutions and firms that offer stents… the hospital holds a huge inventory stock to face the movement of one week, for example. [...] because there are... for one stent model, I can have a list of approximately twenty or twenty-five different possibilities. Because then I have 2.5/10, 2.5/11, 2.5/12, then 3/10, 3/11..., isn't it? And this multiplies considerably and, if we think in the hemodynamics, and this is only one item, there are several with this type of

Service characteristics	**Interview transcriptions**
	situation.) (SCD, HS2)
Innovation (of the services or of the involved materials)	[...] *temos Serviços que querem inovar todos os dias e, portanto, todos os dias há introdução de produtos novos, há retirada de produtos, há entrada de produtos novos, depois não temos histórico e temos de trabalhar muito com o Serviço, portanto, passamos a vida no Serviço.* [...] *aqui no hospital* [...] *somos muito fortes em Cardiologia:* [...] *gasta muito material e tem um grau de inovação muito grande* [...]*temos um Director de Serviço* [...] *que faz todo o tipo de cirurgias topo de gama* [...], *portanto, qualquer intervenção nova que se possa fazer* [...], *ele já teve formação, é dos primeiros no país, e portanto aparecem os materiais todos novos,* [...] *em termos do material clínico.* ([...] we have Services that want to innovate every day and, therefore, there are introductions of new items, there are withdrawals of items, there are entries of new items every day, so we do not have historical data and have to work very closely with the Service, and consequently, we are always in the Service. [...] At this hospital, we are very good in cardiovascular surgery, which consumes high quantities of materials and has a very high degree of innovation [...] we have a surgeon [...] that performs all kind of over the top surgeries [...], so, he has already had training in every new procedure that may have been developed, he is one of the first of our country, and, consequently, we deal with all the new materials [...] as far as clinical devices are concerned.) (SCD, HS1) [...] *medicamento que é fornecido em ambulatório* [...] *É um medicamento muito caro, preço unitário, e basta que mude a prescrição ou que saia um medicamento novo que seja mais eficaz do que o antigo para que o perfil de consumo se altere drasticamente*. ([...] the medicines that are provided by ambulatory care [...] These are very expensive medicines, in terms of unit cost, and a prescription change or the advent of a new, more effective medicine is enough for the consumption profile to change dramatically.) (SCD, HS1)
Physical size and/or weight (of the involved materials)	*Temos blocos* [...] *de oftalmologia, de cirurgia de ambulatório,* [...], *portanto, o volume de produtos é grande, em termos de produtos pequenos* [...]. ([...] we have ophthalmology and ambulatory surgery operating rooms; [...], so, the volume of materials is high, in terms of small items [...]) (SCD, HS1) [...] *uma Ortopedia ou uma Neurocirurgia que usa muito material pesado, caro e pesado, e duram 4 ou 5 horas ou 8 horas uma cirurgia* [...] ([...] Orthopaedics or neurosurgery use very heavy materials, expensive and heavy, and a surgery lasts 4 or 5 or 8 hours [...]) (SCD, HS1)
Traceability requirements (of the involved materials)	[...] *há serviços que já estão diferenciados, porque, por exemplo, tiveram um processo de certificação e portanto têm que ter todos os materiais rastreados, e exigiram-nos um processo de rastreabilidade, quer para materiais de consumo clínico, quer para reagentes, quer para fármacos.* [...] *Para estes Serviços em particular, tenho que ter todos os materiais devidamente rastreados, independentemente de valerem um cêntimo ou de valerem mil euros* [...]. ([...] some services are already differentiated, because, for example, they went through a certification process, and thus, they have to all materials tracked, and they required

Service characteristics	Interview transcriptions
	a traceability process from us, involving clinical materials, reagents and pharmaceuticals. [...] For these services, I have to track all materials, regardless of the fact that they are worth one cent or a thousand euros [...]) (PUD, HS1) [...] *nós também temos algum cuidado e fazemos alguma diferenciação em tudo o que são, por exemplo, próteses* [...] *ou* [dispositivos] *que são sempre para um determinado doente, são pedidos caso a caso. Estou-me a lembrar, por exemplo, de neuro-estimuladores para cirúrgia de Parkinson. Pois isso tem de ser articulado, normalmente... naturalmente, com os Serviços. O Serviço sabe quando tem prevista e agendada uma cirúrgia de Parkinson, para implantação de um neuro-estimulador, pede, com a devida antecedência, a aquisição desse neuro-estimulador para aquele doente e fica registado aquele neuro-estimulador àquele doente* [...] ([...] we do also take some care and make some differentiation in all the, for example, <u>prostheses</u> [...] or <u>[devices] that are for a given patient</u>. For example, the <u>neuro-stimulators for Parkinson surgeries</u>. This is something that has to be articulated, normally… naturally, with the Services. The Service knows when a Parkinson surgery, during which a neuro-stimulator will be implanted, is expected, when it was scheduled, and asks, in due time before, for that neuro-stimulator to that patient to be acquired, and the neuro-stimulator is registered for that patient.) (SCD, HS2)

Appendix 2.5 – Supply chain operational processes used to deal with the requirements of some services/items in terms of materials supply chain capabilities according to the respondents

In the following table we present the respondents original statements, in Portuguese, and the corresponding English translations suggesting processes or resources for dealing with the specificities of referred items or services. The respondents' quotations are identified using the codes in Table 2.6.

Item/ service	Interview transcriptions
Emergency Room (ER), **Emergency Operating Room (EOR)** **and/or** **Intensive Care Unit (ICU)**	Higher inventory levels and more frequent deliveries: *A Urgência* [...] *tem uma variabilidade de consumo muito grande e obriga-nos a ter mais stock e obriga-nos a ter entregas mais frequentes, com uma frequência maior.* (At the ER, [...] the consumption variability is high and this forces us to have more inventory and more frequent deliveries.) (SCD, HS1) Inventory pooling and visibility involving the ERs, EORs and ICUs: [...] *em tudo o que é urgente, incluo aqui o Bloco de Urgência e a Urgência,* [...] *aqui interligados os UCIs, ou seja, quando aqui digo interligados* [...] *é partilharem... é os stocks poderem ser vistos de um lado e de outro, é poderem, de uma forma rápida, uma Urgência, se precisar de um cateter, poder ter o stock online, haver armazéns avançados em todos os UCIs, partilhar os stocks e vê-los. Isso promove eficiências incríveis de tempo e de stock.* . ([...] in all that is urgent in the hospital, and I include here the Emergency Operating Room and the Emergency Room, also linked the ICUs (Intensive Care Units), when I say linked, I mean sharing inventories, having [inventory] visibility from both sides [...] in a fast way. If a catheter is needed in the ER, there is online inventory visibility and the *advanced warehouses*[74] of all ICUs can be searched, inventory is shared and visible. That promotes incredible efficiencies in terms of time and inventory.) (SCM, HS2) *Uma coisa que as Urgências e UCIs têm é que tem de ser tudo rápido, especialmente na Urgência e UCIs. Portanto, aqui têm que se encontrar sistemas de reposição um bocadinho diferentes: tem que se conseguir ver os stocks, registar, de preferência ao doente, mas, por outro lado, também não se pode dar mais trabalho ao pessoal de saúde, porque ele não tem tempo, está sob pressão, aqui não é razoável pedir ao pessoal de saúde que tenha um PDA* [para registar saídas de stock], *olhe o episódio, o pulso do doente... Pelo menos em algumas situações não é razoável que se peça isso, não é? Mas também há dogmas que facilmente caiem por terra, não é? Nem tudo é assim tão urgente como parece, numa módica percentagem tem que se agir de forma diferente* (One of the characteristics of the ERs and ICUs is that everything has to be fast, particularly in the ERs and ICUs. Therefore, we have to find replenishing systems

[74] *Advanced warehouses* are storage rooms located near the clinical services. The materials consumed from these warehouses are registered to the patient. The hospital system has also storage rooms located at the wards (different ones) that are managed using a two-bin kanban replenishing system.

Item/ service	Interview transcriptions
	that are a little different. It has to exist inventory visibility, the patient has to have the priority, but, on the other side, we cannot give more work to the clinical staff, because they haven't got time, they are under pressure. In these services it is not reasonable to ask the health professionals to use a PDA [to update inventory records], look at the episode, at the patient's pulsation... At least in some situations, it is not reasonable to ask this, isn't it? But, there are also dogmas that are easily overturn, isn't it? The patient is not as urgent as it seems, in a small percentage there is the need to act in a different way.) (SCM, HS2) Storage of specific materials only at the services and daily replenishment: [...] *a Urgência gasta o mesmo material que os internamentos e que as UCIs, no fundo. E as exigências logísticas, como disse, têm mais a ver com os serviços e nós cá só temos que garantir uma boa frequência de reposição diária e depois temos que permitir, e acho que aí é que está o segredo, é que as coisas rodem muito mais entre eles, ou seja, eles vêm os seus stocks - as UCIs e urgências funcionam 24 sobre 24 horas e então interessa-me que o stock, por exemplo, os cateteres de monitorização intracraniana, esteja todo no serviço, que é lá que ele se usa e não se usa fora de lá, portanto mais vale estar lá, porque cá em baixo não está a fazer nada e interessa-me que eles a meio da noite consigam ver onde é que está. Portanto, aí interessa-me mais pôr os stocks lá no serviço do que pô-los em* [armazéns] *avançados*[75]*, porque me interessa mais promover a rotação dos stocks entre eles.* ([...] in general terms, the emergency room consumes the same materials an inpatient care unit or an ICU does. The logistical requirements have more to do with the services, and we only have to assure a good frequency of daily replenishments, and then we have to let – and I think this is the secret – things to roll out more between them [i.e., emergency rooms and ICUs]. This is, they see their inventory - and ICUs and ERs work round-the-clock, and therefore it is useful that all the inventory of, for example, intra-cranial monitoring catheters, is stored in the services, because it is consumed there and not in other locations. Consequently, it is better to have it there, because it is not doing anything down here and I want them to be able to see where it is in the middle of the night. Therefore, in that situation, it is more useful to store the inventory at the services [...], because we want to promote the exchanges of inventory between them.) (SCM, HS2)

[75] In HS2, the *advanced warehouses* were located in the ICUs (and not at the emergency rooms).

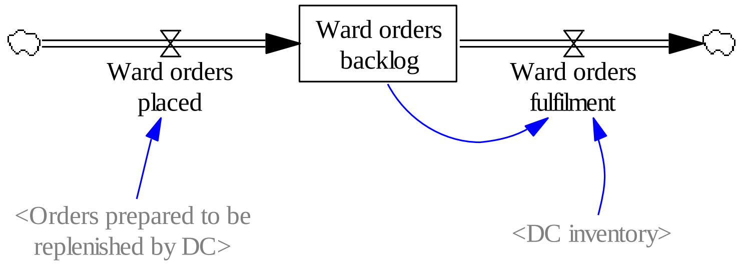
Item/ service	Interview transcriptions
Operating room	Cross-docking and reliable lead times (following the purchasing order)*: O que é de blocos... têm exigências muitas vezes muito cross-docking, portanto, muito material, especialmente de ortopedia,* […] *vem directamente* [do fornecedor] *para o serviço, directamente para aquela cirurgia* […] *Portanto, aí* […] *o stock pode estar cá em baixo* [localização dos armazéns centrais] *ou lá em cima* [nos serviços], *é indiferente, o que é importante é que ele tenha um cross-docking muito eficiente. Porquê? Porque é material que não existe cá no hospital, por isso o que me interessa é que, quando ele seja encomendado, ele tenha um bom lead time, todo* [o *lead time*], *desde a nota de encomenda até estar no serviço. A mim interessa-me que ele chegue aqui e tenha uma central de distribuição que garanta duas horas até estar lá em cima.* (The operating rooms… have frequently *cross-docking* requirements. Many of the materials, mainly orthopaedics' materials [...] come directly from the supplier to the service and go directly to a specific surgery. Therefore, in this case […], the inventory can be down here [at the central warehouse location] or up there [at the OR], it is indifferent, what is important is that it has a very efficient *cross-docking*, because it is material that we do not store in the hospital. Therefore, what is important is that, once a purchasing order is placed, a good lead time is assured, the whole lead time, from the moment the purchasing order is issued until the material is at the OR. I want to assure that, when the material arrives, there is a distribution service that places the material in the OR within two hours.) (SCM, HS2) Registration of consumption to the patient: *se me for falar numa hemodinâmica, em cardiologia, no bloco central, em que eu apanho assim uns 70% do valor do stock, se eu conseguir que este serviço tenha um registo ao doente* [which, at HS2, is achieved when the wards have *advanced warehouses*], *eu acho que tenho o sistema perfeito. Tenho um sistema híbrido.* [Other wards, e.g., inpatient care, have kanban systems] (But, if you ask me about hemodynamics, cardiac surgery, the central OR, where we have approximately 70% of the inventory value, if I can implement a registration of the consumption to the patient [which, at HS2, is achieved when the wards have *advanced warehouses*], the system will be perfect. We have a hybrid system.) [Other wards, e.g., inpatient care, have kanban systems] (SCM, HS2)
Hemodynamics (stents) – ward that consumes high unit cost, high variety materials	Consignment: *A solução que encontrámos foi solicitar às empresas com quem tínhamos fechado os concursos... a possibilidade de colocar esses materiais à consignação e o médico depois utilizaria aquele que mais se adequasse.* [...] *só temos o gasto e a despesa quando efectivamente ele é consumido.* (The solution that we adopted was to ask the companies with each we had closed contracts… the possibility of consigning those materials and afterwards the surgeon would use the most adequate stent. […] we only have the cost and the expenditure when it is actually consumed.) (SCD, HS2) Demand information sharing with the supplier and Vendor Managed Inventory (VMI): *– e, depois, também permite-nos passar para o fornecedor a responsabilidade da gestão do stock, porque temos uma ferramenta que nos permite comunicar, a partir do momento em que o Serviço faz o registo da utilização, o fornecedor é alertado com a indicação daquele consumo, através de e-mail, e sabe que tem que o repor, e, com esta informação que vai passando, liberta-nos um bocadinho para a gestão de stocks desses materiais que são críticos para o Serviço.* (- and, moreover, we transfer the

Item/ service	Interview transcriptions
	responsibility of inventory control to the supplier, since we have a tool to communicate: at the moment the service reports the consumption, the supplier receives an email alert that indicates that consumption, and knows that he has to replenish that material, and, this information exchanges save the hospital central services from part of the inventory control effort when these materials that are so important to the clinical services are involved.) (SCD, HS2) Two alternative suppliers*: Ou seja, temos uma dupla mais valia: transferimos totalmente a responsabilidade da gestão dos stocks para o fundo de tesouraria do fornecedor, que está muito atento, porque o facto de ter o dispositivo cá disponível é um factor de motivação para a facturação, não é? Nessa área temos dois fornecedores alternativos. Se o médico não tiver de um vai utilizar o outro... Por isso eles têm todo o interesse em ter o controlo de stocks bem apertado. E, por outro lado, o hospital não investe em stock nessa área e não corre riscos de ultrapassar os prazos de validade.* (This is, we obtain two types of advantages: we transfer all the responsibility of inventory control to the cash flow of the supplier, which is very aware, because the fact that the material is available here induces sales, isn't it? In that area, we have two alternative suppliers. If the surgeon does not have the product of one of them available, he will use the other… That is why they have an incentive to have a tight inventory control. And, on the other hand, the hospital does not need to make inventory investments in this area and it does not run the risk of exceeding the expiry date of the materials.) (SCD, HS2) Registration of consumption to the patient: *se me for falar numa hemodinâmica, em cardiologia, no bloco central, em que eu apanho assim uns 70% do valor do stock, se eu conseguir que este serviço tenha um registo ao doente, eu acho que tenho o sistema perfeito, tenho um sistema híbrido.* [Other wards, e.g., inpatient care, have kanban systems] (But, if you ask me about hemodynamics, cardiac surgery, the central OR, where we have approximately 70% of the inventory value, if I can implement a registration of the consumption to the patient [which, at HS2, is achieved when the wards have *advanced warehouses*], the system will be perfect. We have a hybrid system. [Other wards, e.g., inpatient care, have kanban systems]) (SCM, HS2)
Medicine inpatient care	Kanban two bin system: [...] *no internamento numa medicina têm muito material barato e é muito de volume e eu ponho lá o Kanban, é o que interessa a um serviço muito grande que tem muitos enfermeiros. O que me interessa ali é que os enfermeiros percam pouco tempo com registos de compressas e sacos de urina e resguardos ao doente, não estou muito interessado...* [...] ([...] at medicine inpatient care they have lots of materials that are cheap and the volume is high, therefore I put there a kanban warehouse, since it is suitable for a big department with many nurses. What I want is that the nurses spend little time registering compresses, urine bags and mattress protections to the patient.) (SCM, HS2)
High unit cost medicines provided at ambulatory care	Demand information sharing with the supplier, VMI and RFID: [...] *é uma área que tem um acompanhamento muito grande e onde estamos também, neste momento, a implementar um sistema logístico diferente. Por um lado, é onde nós temos mais comunicação com os fornecedores em termos de consumos, para eles fazerem a reposição, para também termos o mínimo stock possível, por causa do valor, e onde*

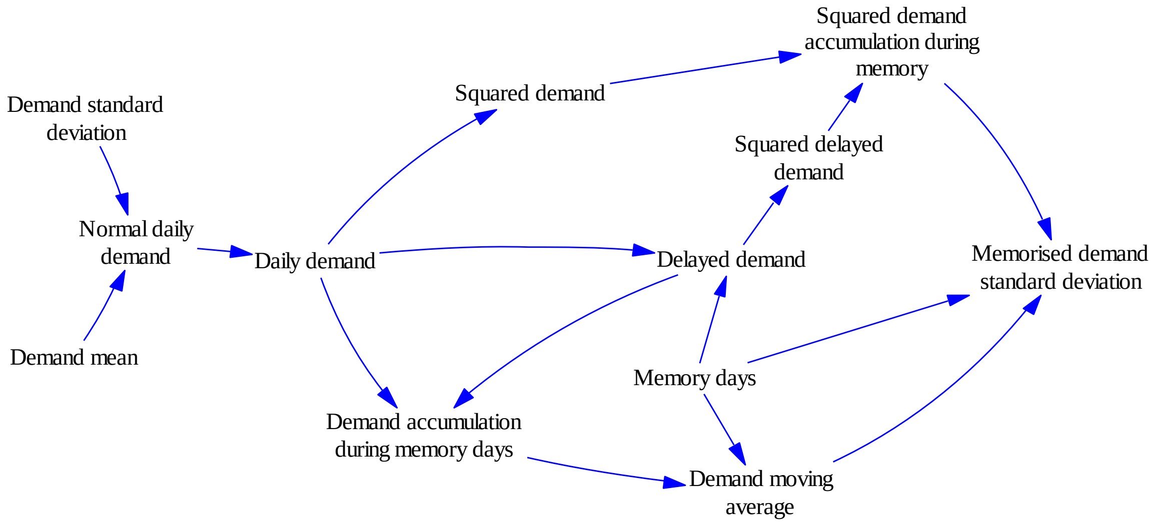
Item/ service	Interview transcriptions
	vamos implementar RFID para [seguir] todos os movimentos do medicamento. (This is an area where there is a tight control and where we are also, at this moment, implementing a new logistics system. On one hand, is the area where we have more communication with the suppliers in terms of the consumptions, so that they can replenish, and that we can have the minimum possible inventory level, because of the value involved, and where we are going to implement RFID to [follow] all movements of the medicine.) (SCD, HS1) Consumption aggregation (in case of medicines with limited life after their package is opened): [...] *a situação de à segunda vir um doente, à terça vir outro, a quarta vir outro... tenta-se que esses quatro ou cinco doentes venham todos no mesmo dia, porque assim com um, dois ou três frascos trata-se os doentes todos. [Nota: depois de aberta a embalagem, o medicamento tem validade de algumas horas]. É melhor que estar a utilizar uma porção dum frasco, outra doutro... Ao fim de um ano o desperdício é muito grande, isto é... cada frasco anda à volta de 1000 e tal euros, por isso ganha-se muito. Fracciona-se, adapta-se a toma para aquele doente, na dose certa e evita-se o desperdício*. ([...] instead of having one patient coming on Monday, another on Thursday, even another on Wednesday... we try that those four or five patients come in the same day, because this way we can treat all of them with one, two or three bottles. [Note: after the bottle is opened, the medicine has a limited life of a few hours] It is better than using part of one bottle and part of another… In a year, the waste would be huge, since… each bottle costs more than 1000 euros, therefore the savings are significant. We fraction, adapt the quantity taken by each patient to the correct dose and we avoid wastes.) (PHD, HS2)

Appendix 4.1 – Model of a traditional SC with one DC and one ward: diagrams of auxiliary parts

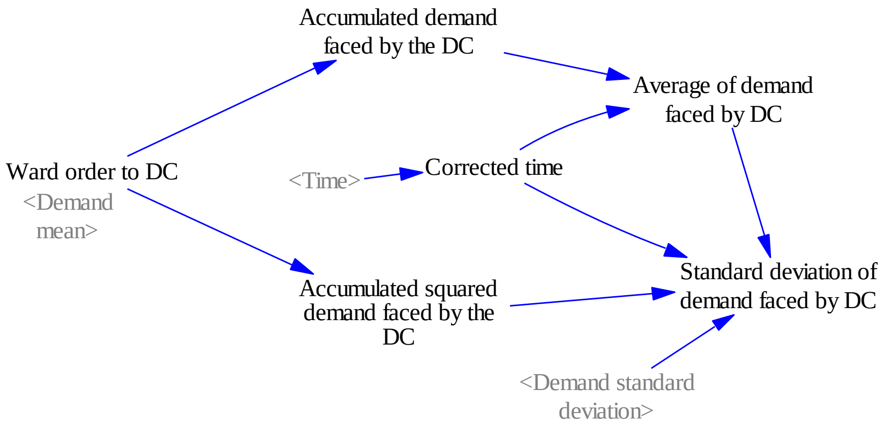
Ward orders backlog:



Daily demand, Demand moving average and Memorised demand standard deviation:

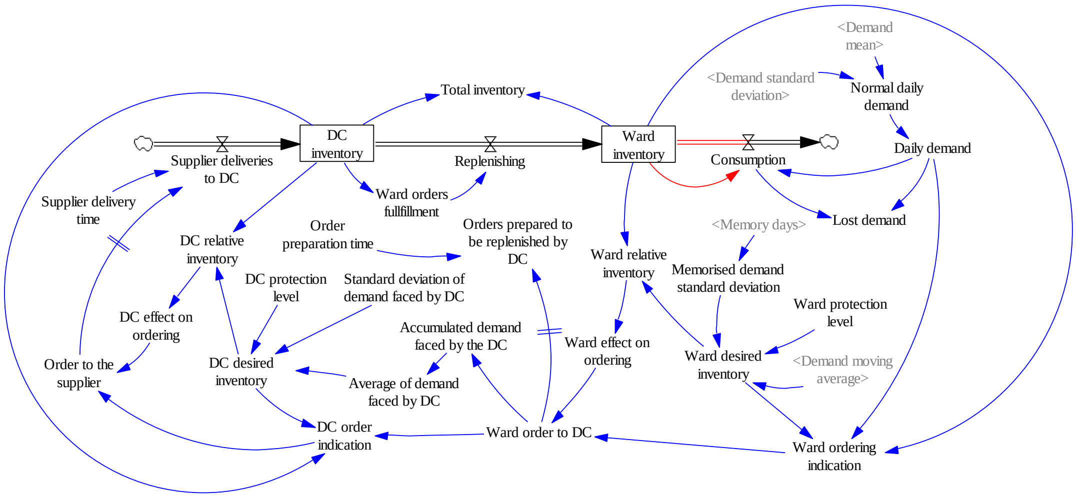


Average and standard deviation of the demand faced by the DC:



Appendix 4.2 – Traditional SC with one DC and one ward: feedback loops involving ward inventory, DC inventory or lost demand

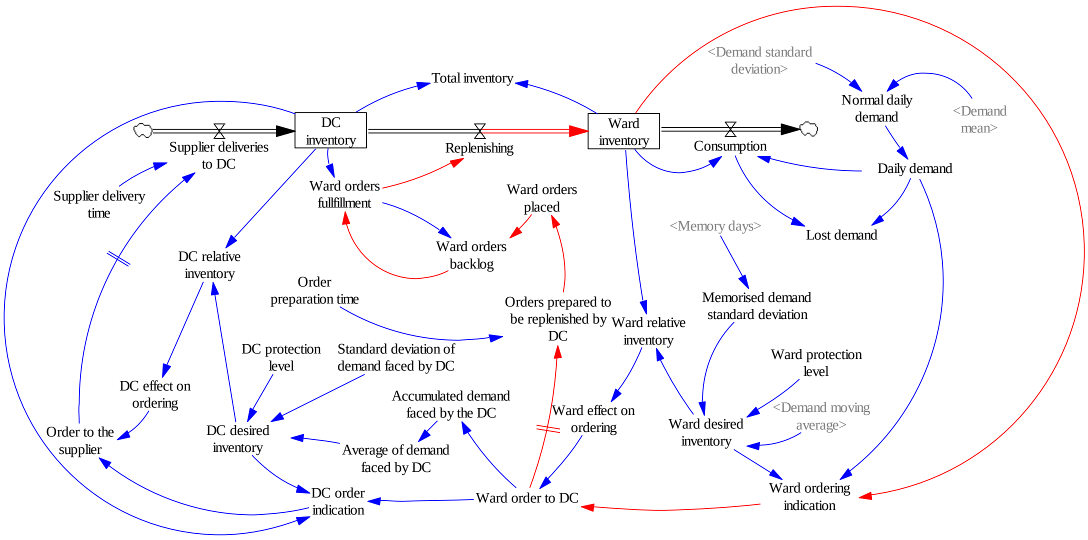
Loop 1: *Ward inventory – Consumption* dependence



→ Ward inventory → Consumption → Ward inventory

Consumption is limited by *Ward inventory*, and decreases it

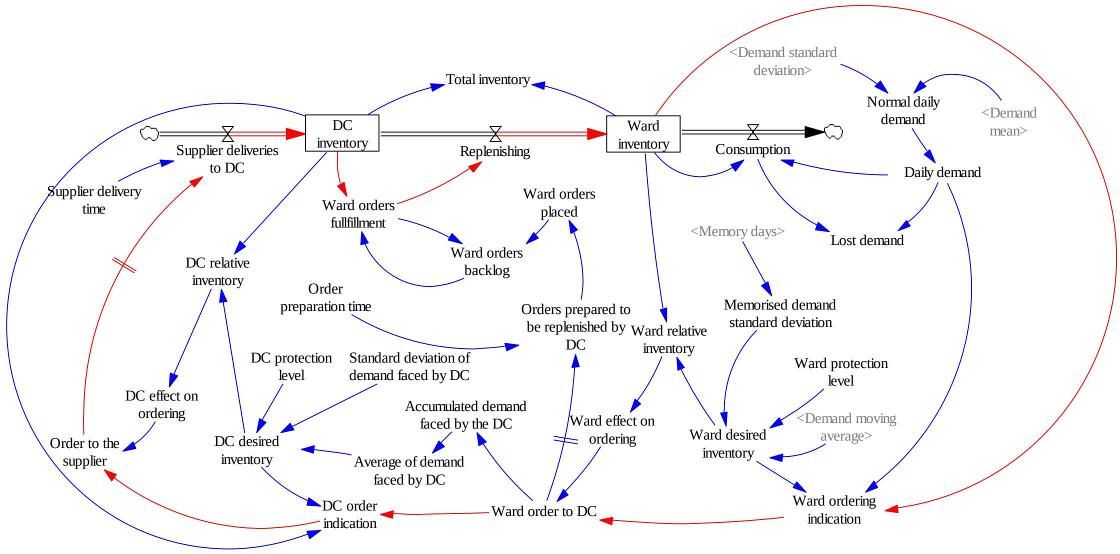
Loop 2: Ward inventory replacement cycle



→ Ward inventory → Ward ordering indication → Ward order to DC → Orders prepared to be replenished by DC → Ward orders placed → Ward orders backlog → Ward orders fulfilment → Replenishing → Ward inventory

When the ward inventory is low, the order indication is higher, increasing the order placed to DC, the replenishing quantities and ultimately the ward inventory level, and vice-versa. There is a time delay between the placement of the order and consequent replenishment.

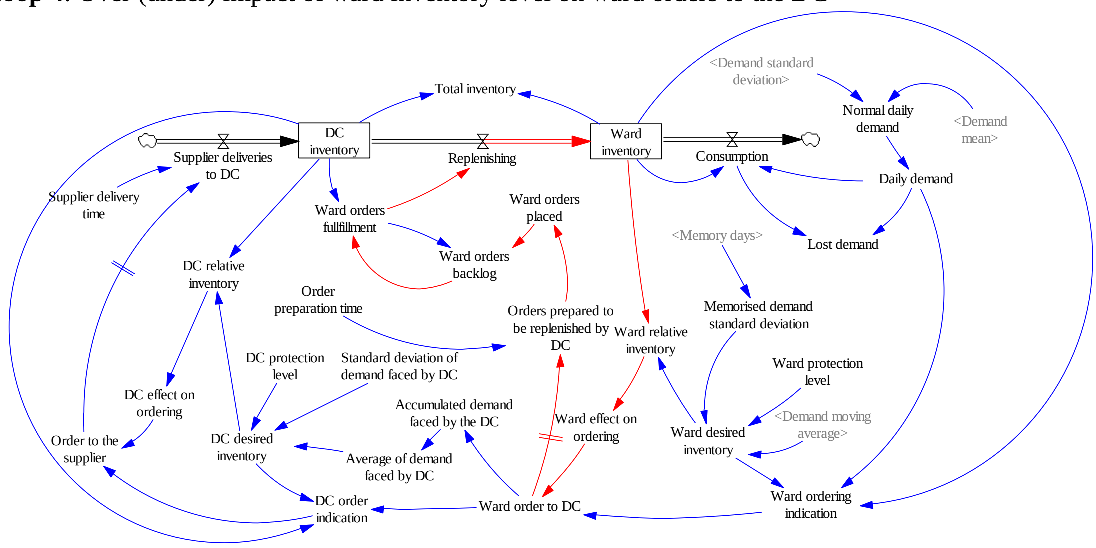
Loop 3: Inventory replacement cycle



→ Ward inventory → Ward ordering indication → Ward order to DC → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

From *Ward orders fulfilment* to *Ward order to DC* (on the right-hand side of the scheme), this loop is identical to Loop 2 (see description above). When the order placed to DC by the ward increases, the DC order indication increases, increasing the order placed to the supplier, then (with a delay) the quantity delivered by the supplier, the DC inventory level, the replenishing of the ward, and ultimately the ward inventory increase too.

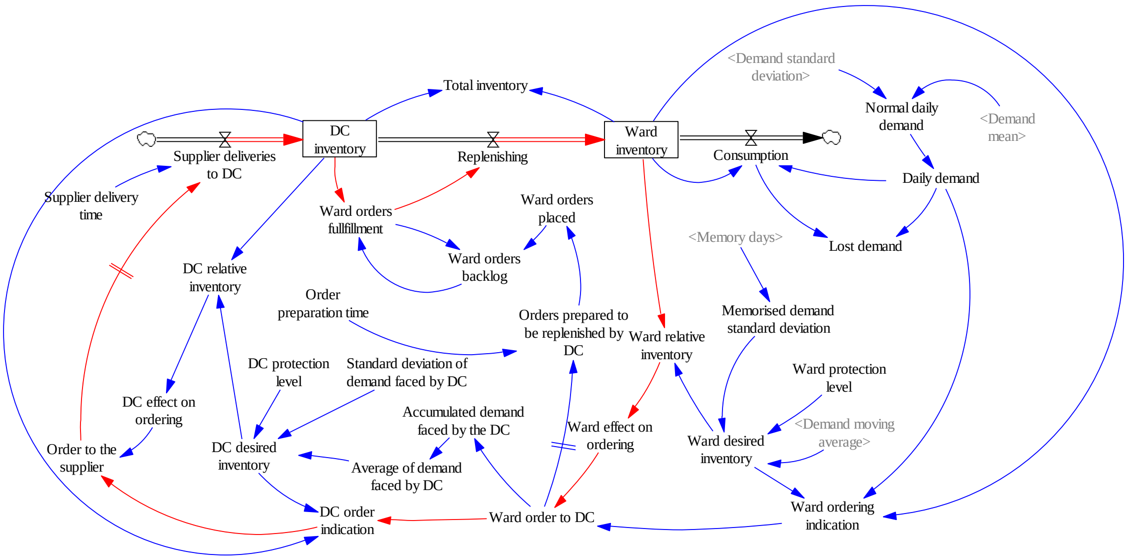
Loop 4: Over (under) impact of ward inventory level on ward orders to the DC



→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Orders prepared to be replenished by DC → Ward orders placed → Ward orders backlog → Ward orders fulfilment → Replenishing → Ward inventory

When the ward inventory is low, the ward relative inventory is lower. This may have an impact on the ward effect on ordering if, when the ward relative inventory falls below a given level, there is an over-ordering (hoarding) effect. In this case, the order placed by the ward is amplified, and, with a time delay, the consequent replenishment rises. The ordering effect considered can also be neutral, and, in this case, the order placed by the ward will not be affected, or we can consider a smoothing (under-ordering) effect, to apply in the case the ward relative inventory rises above a certain limit, in which case the order placed by the ward will be decreased.

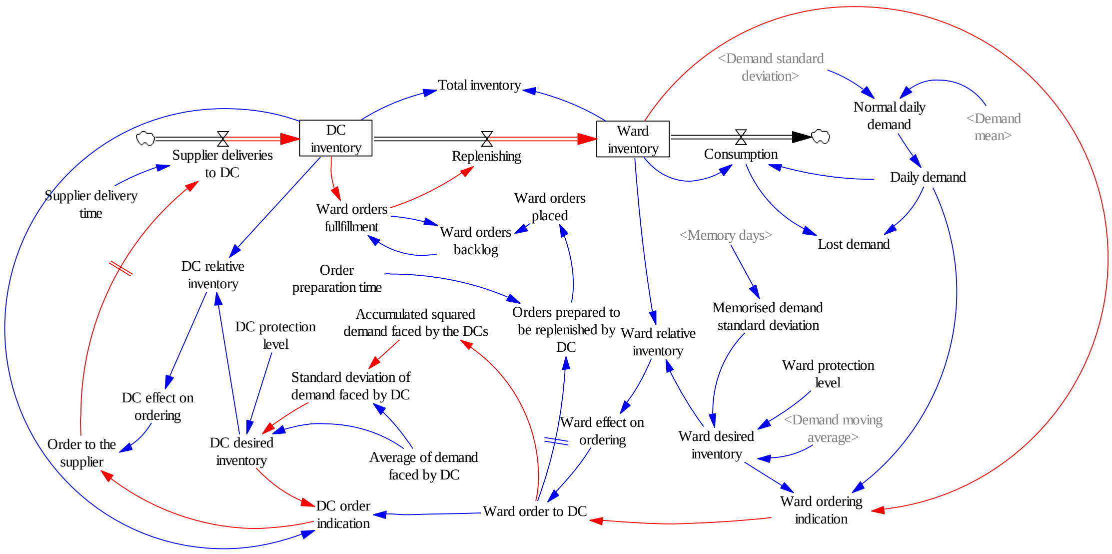
Loop 5: Over (under) impact of ward inventory level on replenishing by the DC



→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

From *Ward inventory* to *Ward order to DC*, this loop is identical to Loop 4, and from *Ward order to DC* to *Ward inventory*, i.e., on the left-hand side of the scheme, this loop is identical to Loop 3 (see loops descriptions above).

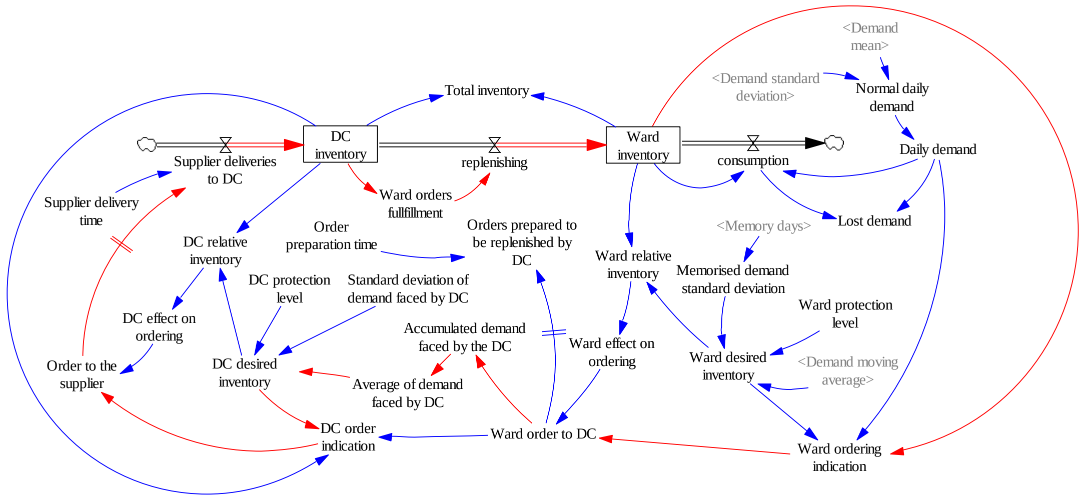
Loop 6: Effect of the variability of the demand faced by the DC



→ Ward inventory → Ward ordering indication → Ward order to DC → Accumulated squared demand faced by the DC → Standard deviation of demand faced by DC → DC desired inventory → DC order indication → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

From *Ward orders fulfilment* to *Ward order to DC* (on the right-hand side of the scheme), this loop is identical to Loop 2, and from *DC order indication* to *Ward inventory* (on the left-hand side of the scheme) this loop is identical to Loop 3 (see loops descriptions above). The part of the loop that has not been described yet, from *Ward order to DC* to *DC order indication*, incorporates the effect of the variability of the demand faced by the DC, measured by the standard deviation of this demand, on the quantity ordered by the DC: when demand variability is higher, the DC desired inventory is higher, and thus, the DC order indication is higher, and vice-versa.

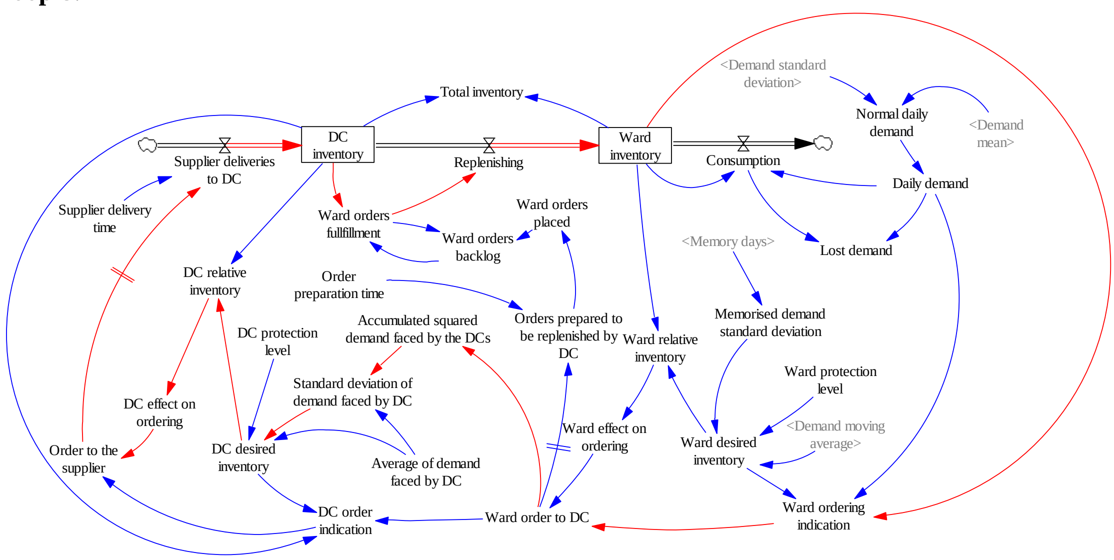
Loop 7: Effect of the level of demand faced by the DC



→ Ward inventory → Ward ordering indication → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → DC desired inventory → DC order indication → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

From *Ward orders fulfilment* to *Ward order to DC* (on the right-hand side of the scheme), this loop is identical to Loop 2, and from *DC order indication* to *Ward inventory* (on the left-hand side of the scheme) this loop is identical to Loop 3 (see loops descriptions above). The part of the loop that has not been described yet, from *Ward order to DC* to *DC order indication*, incorporates the effect of the demand level faced by the DC, measured using this demand average, on the quantity ordered by the DC: when demand level is higher, the DC desired inventory is higher, and thus, the DC order indication is higher, and vice-versa.

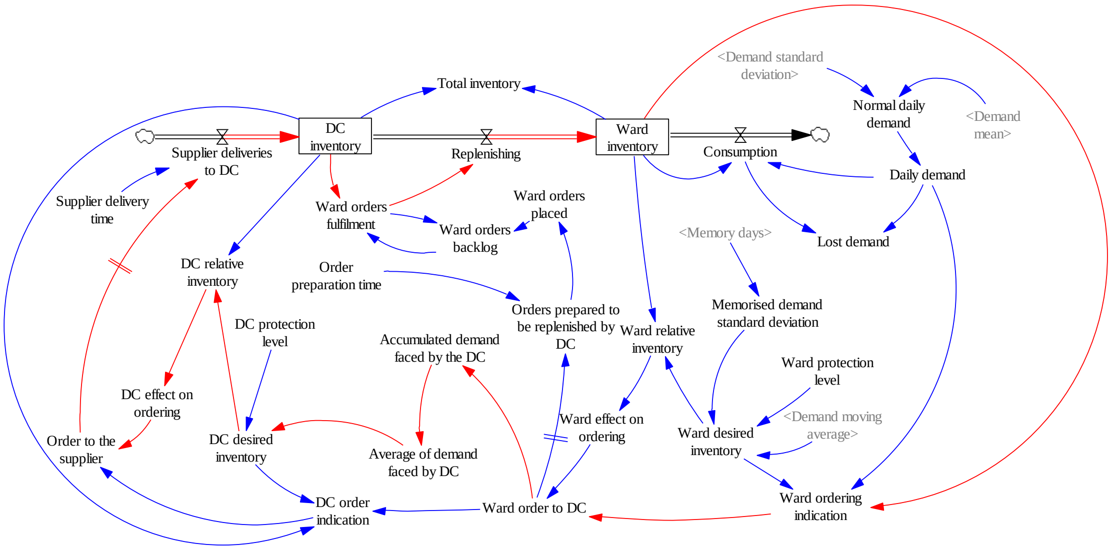
Loop 8:



→ Ward inventory → Ward ordering indication → Ward order to DC → Accumulated squared demand faced by the DCs → Standard deviation of demand faced by DC → DC desired inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

This loop is identical to Loop 6 (see above), except from *DC desired inventory* to *Order to the supplier*. In this part of the loop, the higher the DC desired inventory, the lower the DC relative inventory. This may have an impact on the quantity ordered to the supplier, if the DC effect on ordering is not neutral (i.e., is different from 1) – an identical effect concerning the ward was described on Loop 4.

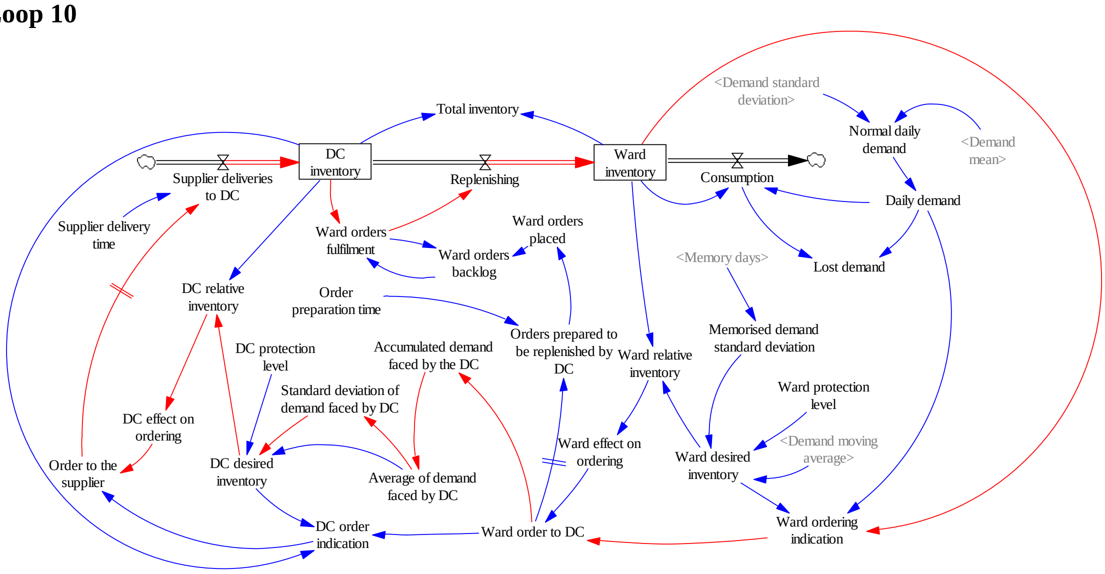
Loop 9



→ Ward inventory → Ward ordering indication → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → DC desired inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

This loop is identical to Loop 7 (see above), except from *DC desired inventory* to *Order to the supplier*. In this part of the loop, the higher the DC desired inventory, the lower the DC relative inventory. This may have an impact on the quantity ordered to the supplier, if the DC effect on ordering is not neutral (i.e., is different from 1) – an identical effect concerning the ward was described on Loop 4.

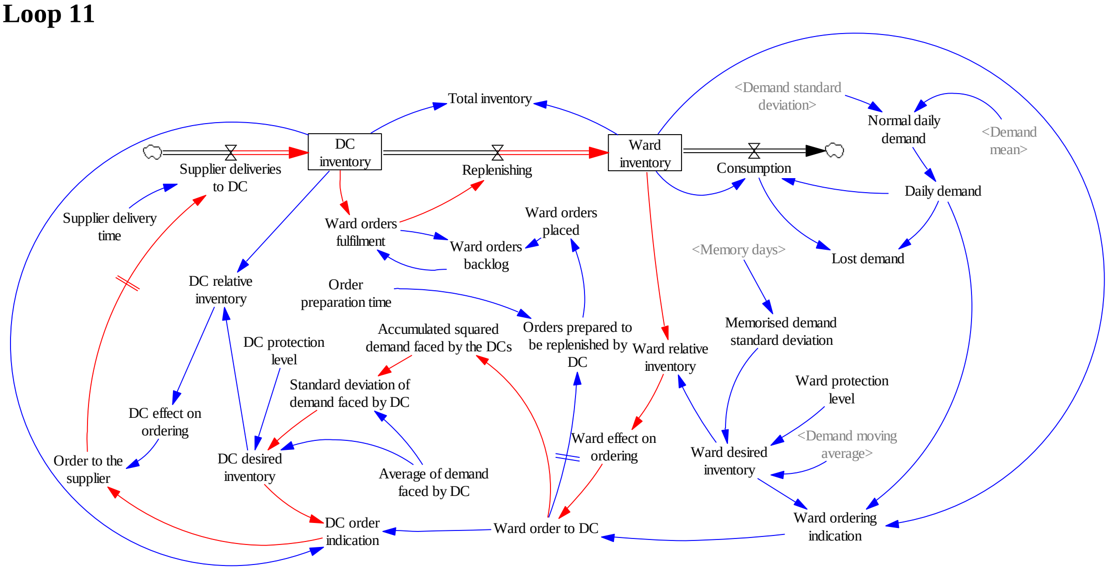
Loop 10



→ Ward inventory → Ward ordering indication → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → Standard deviation of demand faced by DC → DC desired inventory → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

This loop is similar to Loop 8 (see above) – the only difference is that it highlights the fact that the *Average of demand faced by DC* is used to calculate the *Standard deviation of demand faced by DC.*

Loop 11



→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Accumulated squared demand faced by the DCs → Standard deviation of demand faced by DC → DC desired inventory → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → replenishing → Ward inventory

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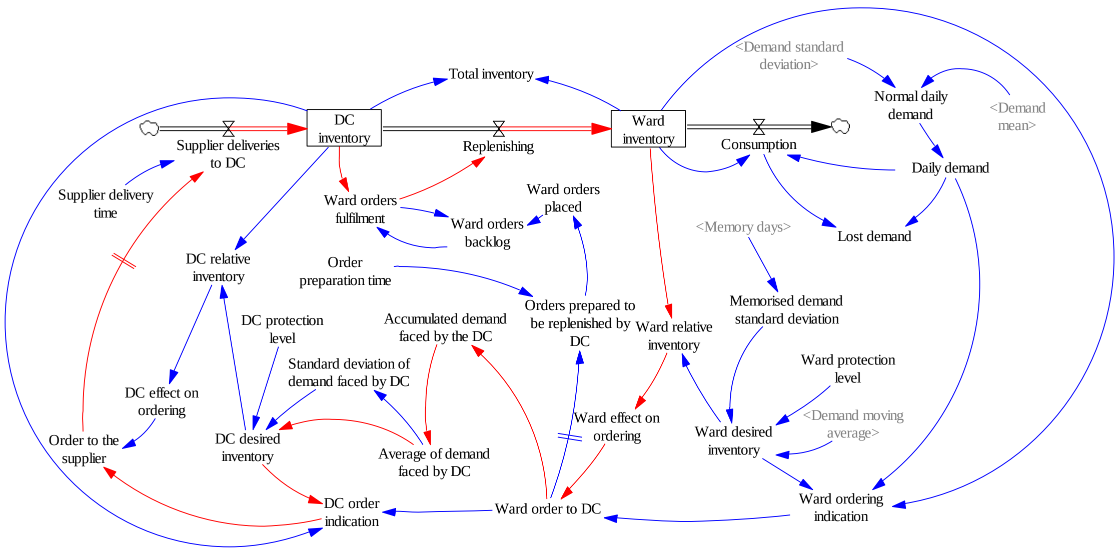
Loop 12



→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → DC desired inventory → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

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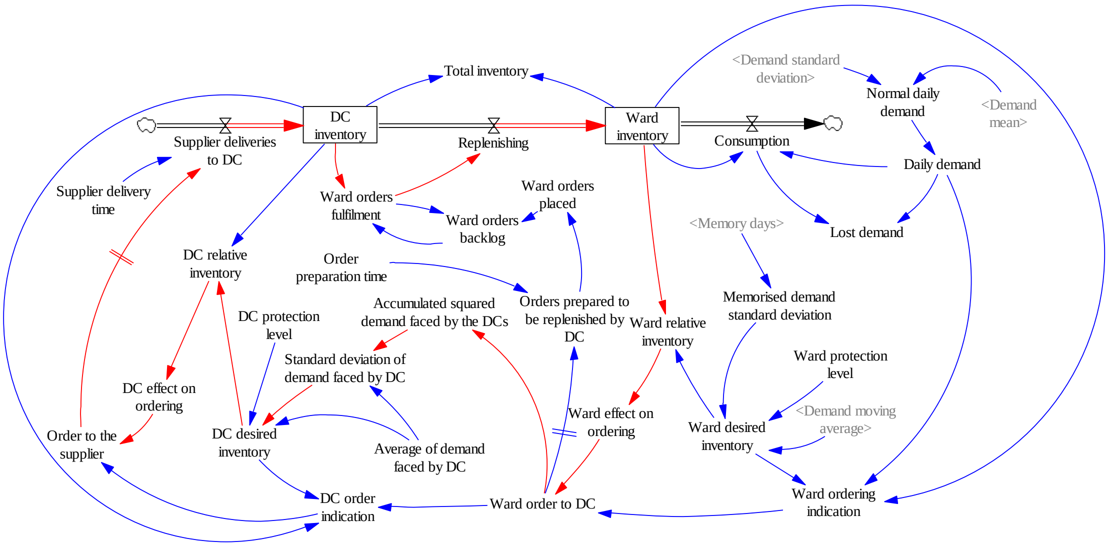
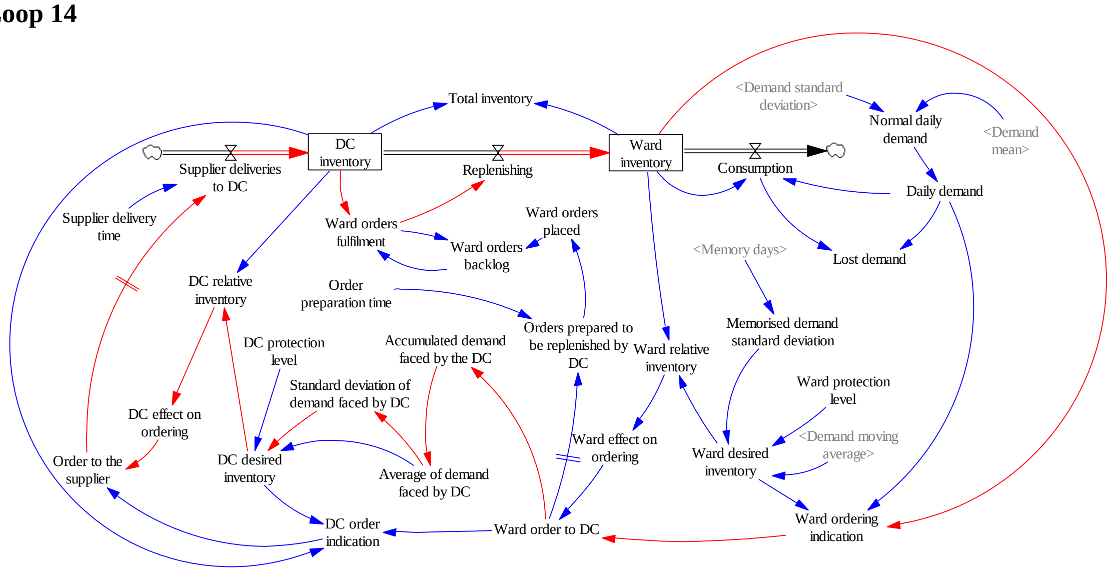
Loop 13



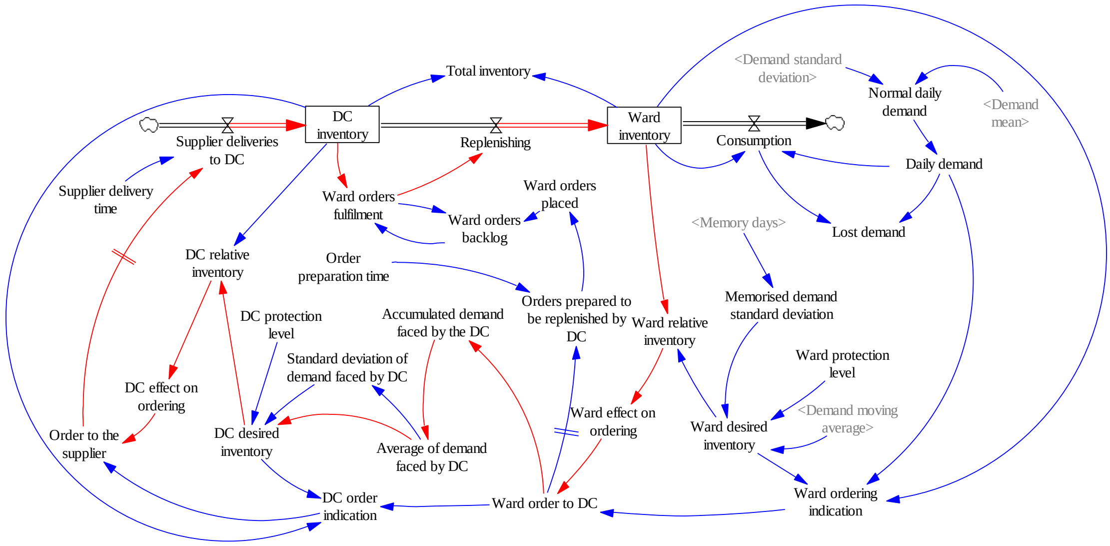
→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Accumulated squared demand faced by the DCs → Standard deviation of demand faced by DC → DC desired inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

Loop 14



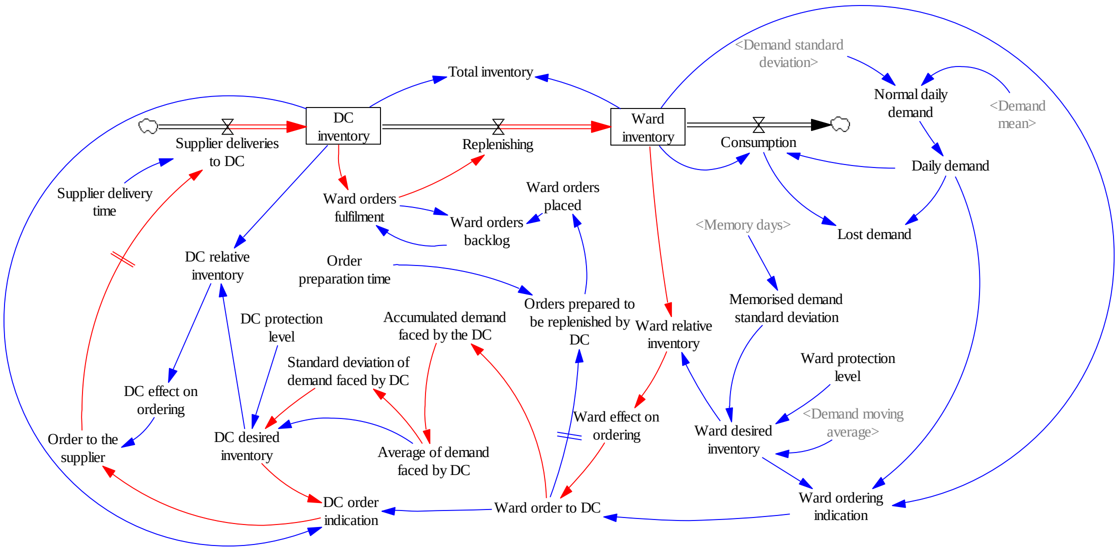
→ Ward inventory → Ward ordering indication → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → Standard deviation of demand faced by DC → DC desired inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

Loop 15



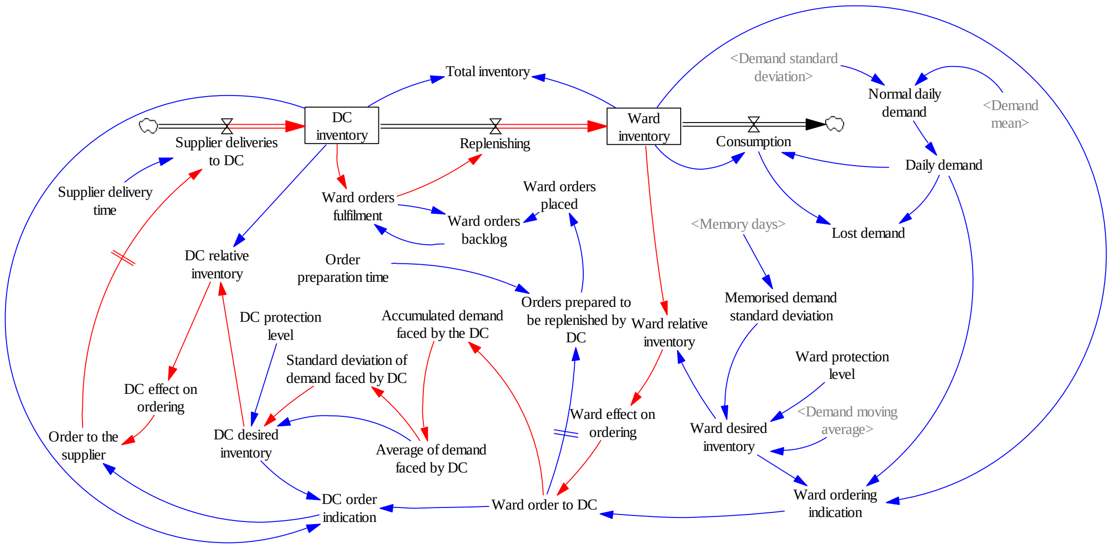
→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → DC desired inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

Loop 16



→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → Standard deviation of demand faced by DC → DC desired inventory → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

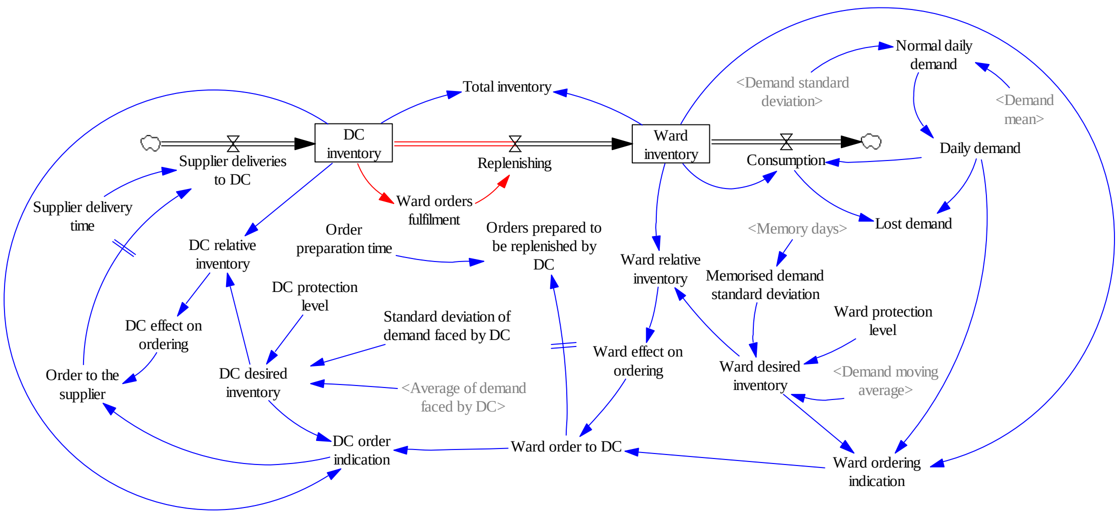
Loop 17



→ Ward inventory → Ward relative inventory → Ward effect on ordering → Ward order to DC → Accumulated demand faced by the DC → Average of demand faced by DC → Standard deviation of demand faced by DC → DC desired inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory → Ward orders fulfilment → Replenishing → Ward inventory

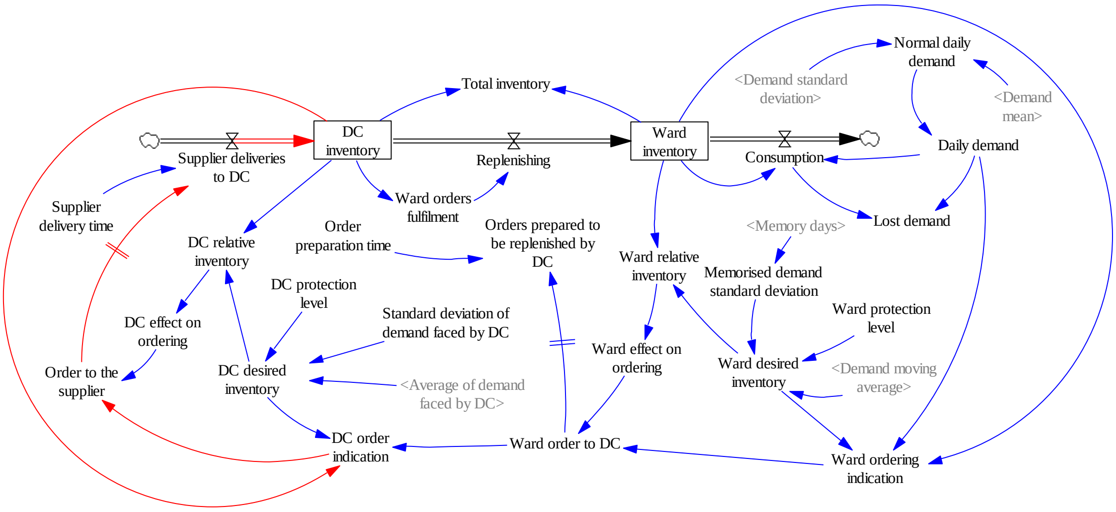
This loop is similar to Loop 15 (see above) – the only difference is that it highlights the fact that the *Average of demand faced by DC* is used to calculate the *Standard deviation of demand faced by DC.*

Loop 18



→ DC inventory → Ward orders fulfilment → Replenishing → DC inventory

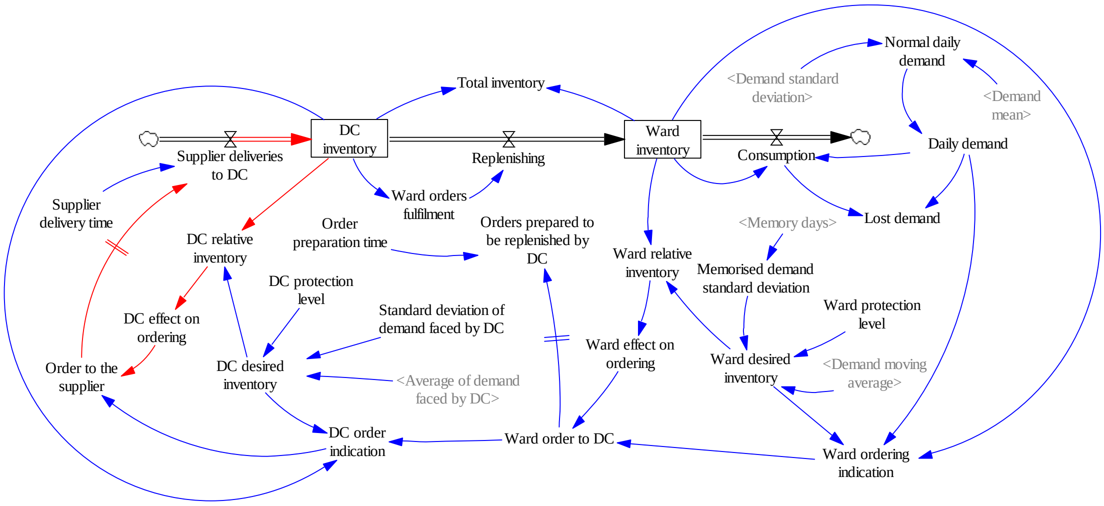
Loop 19: DC inventory replacement cycle



→ DC inventory → DC order indication → Order to the supplier → Supplier deliveries to DC → DC inventory

When the DC inventory is low, the order indication is higher, increasing the order placed by the DC, then (with a delay) the quantity delivered by the suppliers and ultimately the DC inventory level, and vice-versa.

Loop 20: Impact of *DC effect on ordering* on *DC inventory*



→ DC inventory → DC relative inventory → DC effect on ordering → Order to the supplier → Supplier deliveries to DC → DC inventory

When *DC inventory* is high, *DC relative inventory* rises. Consequently, if a smoothing behaviour is considered when the *DC relative inventory* rises above a given limit, the order placed by the DC is decreased, and consequently, the (delayed) *Suppliers deliveries to DC* decreases and *DC inventory* decreases too. The ordering effect considered can be neutral, and, in this case, the order placed by the DC will not be affected, or we can consider an over-ordering effect, in which case, the order placed by the DC would be amplified if relative inventory fell below a certain limit.

Appendix 4.3 – Traditional SC with one DC and one ward: modifications to generate considered daily demand distributions

Process 2: *Daily demand* = *Demand size* × *Day with occurrence of demand* (1=yes; 0=no), where *Demand size* is generated from a Normal distribution with mean 147 units and standard deviation 85 units, and *Day with occurrence of demand* from a Bernoulli distribution with success proportion of 0.71

Constants, stocks and auxiliary variables		Units
Demand mean	= 147	Units/Day [0, ?]
Demand standard deviation	= 85	Units/Day [0, ?]
Proportion of days with demand	= 0.71	Dimensionless [0, 1]
Daily demand	= Demand size*Occurrence of demand	Units/Day [0, ?]
Random number	= RANDOM 0 1()	Dimensionless [0, 1]
Ocurrence of demand	= IF THEN ELSE(Random number<= Proportion of days with demand, 1, 0)	Dimensionless [0, 1]
Demand size	= INTEGER(RANDOM NORMAL(0, M , Demand mean, Demand standard deviation , 2))	Units/Day [0, M]

Process 3: *Daily demand* = *Inventory exit size* × *Number of inventory exits per day*, where *Inventory exit size* is generated from a Normal distribution with mean 120 units and standard deviation 82, and *Number of inventory exits per day* is generated from a Poisson distribution with mean 1 exit;

Constants, stocks and auxiliary variables		Units
Exit mean	= 120	Units/Day [0, ?]
Exit standard deviation	= 82	Units/Day [0, ?]
Mean no. of inventory exits per day	= 1	Exits/Day [0, ?]
Daily demand	= Inventory exit*Number of inventory exits	Units/Day [0, ?]
Number of inventory exits per day	= RANDOM POISSON(0, M, Mean no of inventory exits per day, 0, 1, 0)	Exits/Day [0, ?]

Constants, stocks and auxiliary variables		Units
Inventory exit	= INTEGER(RANDOM NORMAL(0, M , Exit mean, Exit standard deviation , 2))	Units/Day [0, M]

Process 4: *Daily demand* = *Inventory exit size* × *Number of inventory exits per day*, where *Inventory exit size* is generated from a Normal distribution with mean 120 units/exit and standard deviation 82 units/exit, and *Number of inventory exits per day* is generated from a Binomial distribution with N = 4 and proportion 0.23.

Constants, stocks and auxiliary variables		Units
Exit mean	= 120	Units/Day [0, ?]
Exit standard deviation	= 82	Units/Day [0, ?]
Max number of exits day	= 4	Exits/Day [0, ?]
Probability that each possible exit occurs	= 0.23	Dimensionless [0, 1]
Daily demand	= Inventory exit*Number of inventory exits	Units/Day [0, ?]
Number of inventory exits per day	= RANDOM BINOMIAL(0, M , Binomial proportion , N , 0 , 1 , 0)	Exits/Day [0, ?]
Inventory exit	= INTEGER(RANDOM NORMAL(0, M , Exit mean, Exit standard deviation , 2))	Units/Day [0, M]

Appendix 4.4 – Traditional SC with one DC and one ward: modifications so that urgent direct deliveries from the DC are considered

	Stocks and auxiliary variables	Units
Missing units	= IF THEN ELSE(Daily demand>Consumption, Daily demand-Consumption, 0) Positive differences between *Daily demand* and *Consumption*, i.e., situations when demand exceeds the item quantity that can be consumed, due to inventory insufficiency.	Units/Day [0, ?]
Emergency delivery	= MIN((DC inventory-Replenishing), Missing units) If there are enough units at the DC, the missing units are fulfilled.	Units/Day [0, ?]
DC inventory	= INTEG(Supplier deliveries to DC-(Replenishing+Emergency delivery), INTEGER(Demand mean)*Corrected time) DC inventory declines also with *Emergency delivery*.	Units [0, ?]
Lost demand	= Missing units-Emergency delivery Registers demand that could not be fulfilled due to inventory insufficiency both at the ward and at the DC; when the needed units are not available, the treatment of patients cannot be postponed for the following day and some alternative item has to be used.	Units/Day [0, ?]

Appendix 4.5 – Modelling of a traditional SC with one distribution centre (DC) and N identical wards: formulation

This model is conceptually similar to the model of a traditional, simple serial supply chain with one DC and one ward with emergency deliveries (described in section 4.3.3). The used constants and lookup functions are also similar, and identical for the various wards, with the only exception that different seeds are used to generate the wards' demands.

	Subscripts	Units
w:	Ward1, Ward2, …, WardN W= (Ward1, Ward2, …, WardN)	Dimensionless

	Stocks and auxiliary variables	Units
Daily demand[w]	= IF THEN ELSE(Normal daily demand[w]>=0, INTEGER(Normal daily demand[w]) , 0)	Units/Day [0, ?]
Normal daily demand[Ward1]	= INTEGER(RANDOM NORMAL(-M, M, Demand mean[Ward1], Demand standard deviation[Ward1], 0))	Units/Day [-M, M]
Normal daily demand[Ward2]	= INTEGER(RANDOM NORMAL(-M, M, Demand mean[Ward2], Demand standard deviation[Ward2], 1))	
…	…	
Normal daily demand[WardN]	= INTEGER(RANDOM NORMAL(-M, M, Demand mean[WardN], Demand standard deviation[WardN], N-1))	
DC inventory	= INTEG (Supplier deliveries to DC-(Replenishing+ Sum of emergency deliveries to wards), INTEGER(Sum of demand means of the wards)*Corrected time)	Units [0, ?]
Ward inventory[w]	= INTEG (Ward orders fulfilment[w]-Consumption[w], INTEGER(Demand mean[w])*Corrected time)	Units [0, ?]
Consumption[*w*]	= MIN(Daily demand[w],Ward inventory[w])	Units/Day [0, ?]
Missing units[w]	= IF THEN ELSE(Daily demand[w]>Consumption[w], Daily demand[w]-Consumption[w], 0)	Units/Day [0, ?]
Emergency delivery[w]	= IF THEN ELSE(Missing units[w]>0, IF THEN ELSE(SUM(Missing units[w!])>(DC inventory-Replenishing), INTEGER((Missing units[w]/ SUM(Missing units[w!]))*(DC inventory-Replenishing)), Missing units[w]), 0) If there are missing units at the wards (i.e., daily demand exceeds the available inventory at the ward) and there is available inventory at the DC, emergency deliveries are made; in case the units at the DC are not enough to fulfil all demand, the available units are distributed by the wards with missing units proportionally to the required quantity (*Missing units*).	Units/Day [0, ?]

	Stocks and auxiliary variables	Units
Sum of emergency deliveries to wards	= SUM(Emergency delivery[w!])	Units/Day [0, ?]
Lost demand[w]	= Missing units[w]-Emergency delivery[w]	Units/Day [0, ?]
Ward desired inventory[w]	= ACTIVE INITIAL (Demand moving average[w]+Ward protection level[w]*Memorised demand standard deviation[w], INTEGER(Demand mean[w])*Corrected time)	Units [0, ?]
Demand moving average[w]	= Demand accumulation during memory days[w]/Memory days	Units/Day [0, ?]
Memorised demand standard deviation[w]	= SQRT((Squared demand accumulation during memory[w]/ Memory days)-(Demand moving average[w]* Demand moving average[w]))	Units/Day [0, ?]
Ward ordering indication[w]	= ACTIVE INITIAL (IF THEN ELSE((Daily demand[w]+Ward desired inventory[w]-Ward inventory[w])>0, (Daily demand[w]+ Ward desired inventory[w]-Ward inventory[w]), 0), INTEGER(Demand mean[w]))	Units/Day [0, ?]
Ward relative inventory[w]	= IF THEN ELSE(Ward desired inventory[w]>0, Ward inventory[w]/Ward desired inventory[w], Ward inventory[w]/1)	Dimensionless [0, ?]
Ward order to DC[w]	= ACTIVE INITIAL (INTEGER(Ward ordering indication[w]* Ward effect on ordering[w]), INTEGER(Demand mean[w]))	Units/Day [0, ?]
Sum of ward orders to DC	= SUM(Ward order to DC[w!])	Units/Day [0, ?]
Orders prepared to be replenished by DC[w]	DELAY FIXED (Ward order to DC[w], Order preparation time[w], INTEGER(Demand mean[w]))	Units/Day [0, ?]
Ward orders placed[w]	= Orders prepared to be replenished by DC[w]	Units/Day [0, ?]
Ward orders backlog[w]	= INTEG (Ward orders placed[w]-Ward orders fulfilment[w], INTEGER(Demand mean[w])*Corrected time)	Units [0, ?]
Ward orders fulfilment[w]	= IF THEN ELSE(Ward orders backlog[w]>0, IF THEN ELSE(SUM(Ward orders backlog[w!])>DC inventory, INTEGER(DC inventory*(Ward orders backlog[w]/ SUM(Ward orders backlog[w!]))) , Ward orders backlog[w]), 0) If there is not enough inventory at the DC to fulfil the order backlogs of all the wards, the available inventory is distributed between the wards proportionally to their orders backlog.	Units/day [0, ?]
Replenishing	= SUM(Ward orders fulfilment[w!])	Units/Day [0, ?]
DC desired inventory	= ACTIVE INITIAL (Average of demand faced by DC+DC protection level*Standard deviation of demand faced by DC, INTEGER(Sum of demand means of the wards)*Corrected time)	Units [0, ?]

	Stocks and auxiliary variables	Units
Average of demand faced by DC	= Accumulated demand faced by the DC/Corrected time	Units/Day [0, ?]
Standard deviation of demand faced by DC	= IF THEN ELSE(((Accumulated squared demand faced by the DC/ Corrected time)-(Average of demand faced by DC* Average of demand faced by DC))>=0, SQRT((Accumulated squared demand faced by the DC/ Corrected time)-(Average of demand faced by DC* Average of demand faced by DC)), Sum of demand standard deviations)	Units/Day [0, ?]
DC ordering indication	= ACTIVE INITIAL (IF THEN ELSE((DC desired inventory+ Sum of ward orders to DC-DC inventory)>0, (DC desired inventory+Sum of ward orders to DC-DC inventory), 0), INTEGER(Sum of demand means of the wards))	Units/day [0, ?]
DC relative inventory	IF THEN ELSE(DC desired inventory>0, DC inventory/ DC desired inventory, DC inventory/1)	Dimensionless [0, ?]
Order to the supplier	ACTIVE INITIAL (INTEGER(DC order indication* DC effect on ordering), INTEGER(Sum of demand means of the wards)	Units/day [0, ?]
Supplier deliveries to DC	DELAY FIXED (Order to the supplier, Supplier delivery time, INTEGER(Sum of demand means of the wards)	Units/day [0, ?]
Sum of demand means of the wards	= SUM(Demand mean[w!])	Units/Day [0, ?]
Sum of demand standard deviations	= SUM(Demand standard deviation[w!])	Units/Day [0, ?]
Delayed demand[w]	= DELAY FIXED (Daily demand[w], Memory days, INTEGER(Demand mean[w]))	Units/Day [0, ?]
Demand accumulation during memory days[w]	INTEG (Daily demand[w]-Delayed demand[w], Demand mean[w]*Memory days)	Units [0, ?]
Squared delayed demand[w]	= Delayed demand[w]*Delayed demand[w]	(units/Day)* (units/Day) [0, ?]
Squared demand[w]	= Daily demand[w]*Daily demand[w]	(units/Day)* (units/Day) [0, ?]
Squared demand accumulation during memory[w]	= INTEG (Squared demand[w]-Squared delayed demand[w], (Demand mean[w]*Demand mean[w])*Memory days)	(Units*Units) /Day [0, ?]

	Stocks and auxiliary variables	Units
Accumulated demand faced by the DC	= INTEG (Sum of ward orders to DC, Sum of demand means of the wards*Time)	Units [0, ?]
Accumulated squared demand faced by the DC	INTEG (Sum of ward orders to DC * Sum of ward orders to DC, (Sum of demand means of the wards* Sum of demand means of the wards)*Time)	(Units*Units) /Day [0, ?]
Corrected time	= IF THEN ELSE(Time>0, Time, 1)	Days [1, ?]

Appendix 4.6 – Modelling of a traditional SC with one distribution centre (DC) and N identical wards, one of which is an ER having priority in inventory allocation: formulation changes relatively to previous models

	Subscripts	Units
w:	Ward1, Ward2, …, WardN, ER W=(Ward1, Ward2, …, WardN, ER)	Dimensionless

	Stocks and auxiliary variables	Units
Ward orders fulfilment[ER]	= IF THEN ELSE(Ward orders backlog[ER]>0, MIN(Ward orders backlog[ER], DC inventory), 0) All ER orders backlog will be fulfilled or, if the DC inventory is not enough to fulfil them, all DC inventory will be fulfilled to the ER.	Units/day [0, ?]
Ward orders fulfilment[WardN]	= IF THEN ELSE(Ward orders backlog[WardN]>0, IF THEN ELSE((Ward orders backlog[Ward1]+ Ward orders backlog[Ward2]+…+ Ward orders backlog[WardN])> (DC inventory-Ward orders fulfilment[ER]), INTEGER((DC inventory-Ward orders fulfilment[ER])*(Ward orders backlog[WardN]/ (Ward orders backlog[Ward1]+ Ward orders backlog[Ward2]+…+ Ward orders backlog[WardN]))), Ward orders backlog[WardN]), 0) If, after fulfilling the ER, there is not enough inventory at the DC to fulfil the order backlogs of all the other wards, the available inventory is distributed between these other wards proportionally to their orders backlog.	Units/day [0, ?]
Emergency delivery[ER]	= IF THEN ELSE(Missing units[ER]>0, MIN(Missing units[ER], (DC inventory-Replenishing), 0) If there are missing units at the wards (i.e., daily demand exceeds the available inventory at the ward) and there is available inventory at the DC, a quantity that equals the missing units is used to fulfil demand at the ER. If the inventory available is lower than the missing units at the ER, all available inventory at the DC is used to fulfil ER demand.	Units/Day [0, ?]
Emergency delivery[WardN]	= IF THEN ELSE(Missing units[WardN]>0, IF THEN ELSE((Missing units[Ward1]+ Missing units[Ward2]+…+ Missing units[WardN])> (DC inventory-Replenishing-Emergency delivery[ER]), INTEGER((Missing units[WardN]/ (Missing units[Ward1]+ Missing units[Ward2]+…+ Missing units[WardN]))*(DC inventory-Replenishing-Emergency delivery[ER])), Missing units[WardN]), 0) If there are missing units at wards N and there is available inventory at the DC (after replenishing all the wards and fulfilling ER missing units), emergency deliveries are made; in case the units still available at the DC are not enough to fulfil all demand, the available units are distributed by the wards (except the ER) with unfulfilled demand proportionally to the required quantity (in case of Ward N, *Missing units [WardN]*).	Units/Day [0, ?]

Appendix 4.7 – Modelling of a centralised inventory control SC (with some inventory visibility), with one DC and one ward: variable changes and additions relatively to the model of a traditional SC for the same SC topology

The table presents the model formulation changes relatively to the model described in subsection 4.3.3.

	Stocks and auxiliary variables	Units
Ward order to DC	=ACTIVE INITIAL(INTEGER(Daily demand[76]), INTEGER(Demand mean)) A quantity equal to the demand of the day is ordered daily by the ward to the DC.	Units/Day [0, ?]
DC desired inventory	=ACTIVE INITIAL (Average of demand faced by the hospital+ DC protection level* Standard deviation of demand faced by the hospital, INTEGER(Demand mean)*Corrected time) The *DC desired inventory* is now determined based on the final demand faced by the hospital (instead on the demand faced by the DC); the *DC protection level* is thus relative to the whole hospital.	Units [0, ?]
DC relative inventory	= IF THEN ELSE(DC desired inventory<>0, (DC inventory+Ward inventory)/DC desired inventory, (DC inventory+Ward inventory)/1) The *DC relative inventory* takes into account the inventory available in the whole hospital (this change only has effects when ordering effects at the DC are modelled).	Dimensionless [0, ?]

Observation: The following variables are not used in this model: *Accumulated demand faced by the DC, Accumulated squared demand faced by the DC, Average of demand faced by DC, Delayed demand, Demand accumulation during memory days, Demand moving average, Memorised demand standard deviation, Memory days, Squared delayed demand, Squared demand, Squared demand accumulation during memory, Standard deviation of demand faced by DC, Ward desired inventory, Ward effect on ordering, Ward ordering indication, Ward protection level, Ward relative inventory*

Besides the variables included in the table, the average and standard deviation of the hospital daily demand are determined using auxiliary variables similar to those used to calculate the average and standard deviation of the demand faced by the DC in model of a traditional supply chain.

[76] If the hospital supply chain under analysis has various wards, the sum of the daily demands of the wards is considered.

Appendix 4.8 – Modelling of traditional quasi-arborescent supply chain with lateral transshipments: variable additions and changes relatively to the model of a traditional supply chain with the possibility of urgent direct deliveries from the DC

	Subscripts	Units
w:	Ward1, Ward2, ER W=(Ward1, Ward2, ER)	Dimensionless

	Stocks and auxiliary variables	Units
Lost demand[w]	= Still missing units[w]-Emergency delivery[w] *Missing units[w]* in the model with no lateral transshipments was replaced by *Still missing units[w]*.	Units/Day [0, ?]
Still missing units[Ward1]	= Missing units[Ward1]	Units/Day [0, ?]
Still missing units[Ward2]	= Missing units[Ward2]	
Still missing units[ER]	= Missing units[ER]- SUM(Lateral transshipments to the ER[w!]) At the ER the *Still missing units* are equal to the Missing units minus the *Lateral transshipments* from other wards to the ER	
Emergency delivery[w]	= IF THEN ELSE(Still missing units[w]>0, IF THEN ELSE(SUM(Still missing units[w!])> (DC inventory-Replenishing), INTEGER((Still missing units[w]/ SUM(Still missing units[w!]))*(DC inventory-Replenishing)), Still missing units[w]), 0) If there are *Still missing units* at ward *w* and if the total *Still missing units* at all wards exceeds the available inventory at the DC (i.e., the DC inventory minus the quantities replenished to the various wards, the available inventory at the DC is distributed by the wards proportionally to the weight of their *Still Missing units* on total *Still Missing Unit;* otherwise, all the *Still Missing Units* of the ward are delivered.	Units/Day [0, ?]
Ward inventory[w]	= INTEG(Ward orders fulfilment[w]-(Consumption[w]+ Lateral transshipments[w]), INTEGER(Demand mean[w])*Corrected time) The ward *w* inventory also declines with the Lateral transshipments from ward *w*.	Units [0, ?]

	Stocks and auxiliary variables	**Units**
Ward ordering indication[Ward1]	= ACTIVE INITIAL(IF THEN ELSE((Daily demand[Ward1]+ Lateral transshipments[Ward1]+Ward desired inventory[Ward1]- Ward inventory[Ward1])>0, (Daily demand[Ward1]+ Lateral transshipments[Ward1] +Ward desired inventory[Ward1]- Ward inventory[Ward1]), 0), INTEGER(Demand mean[Ward1]))	Units/Day [0, ?]
Ward ordering indication[Ward2]	= ACTIVE INITIAL(IF THEN ELSE((Daily demand[Ward2]+ Lateral transshipments[Ward2]+Ward desired inventory[Ward2]- Ward inventory[Ward2])>0, (Daily demand[Ward2]+ Lateral transshipments[Ward2] +Ward desired inventory[Ward2]- Ward inventory[Ward2]), 0), INTEGER(Demand mean[Ward2]))	
Ward ordering indication[ER]	= ACTIVE INITIAL(IF THEN ELSE((Daily demand[ER]+ Lateral transshipments[ER]+Ward desired inventory[ER]- (Ward inventory[ER])+ SUM(Lateral transshipments to the ER[w!]))>0, (Daily demand[ER]+Lateral transshipments[ER]+ Ward desired inventory[ER]-(Ward inventory[ER]+ SUM(Lateral transshipments to the ER[w!]))), 0), INTEGER(Demand mean[ER])) When determining the quantity to be ordered, each ward takes into account not only the demand it faced, but also the quantity it provided to the ER; the ER takes into account the quantities received from the other wards by decreasing the quantity ordered (in the simulated version of the model *Lateral transshipments[ER] =0* since the ER does not provide the item to other wards).	
Lateral transshipments to the ER[Ward1]	= IF THEN ELSE(Missing units[ER]>0, IF THEN ELSE(Standardised available inventory[Ward1]> Standardised available inventory[Ward2], IF THEN ELSE((Ward inventory[Ward1]-Consumption[Ward1])>0, MIN(Missing units[ER], (Ward inventory[Ward1]- Consumption[Ward1])), 0), 0),0)	Units/Day [0, ?]
Lateral transshipments to the ER[Ward2]	= IF THEN ELSE(Missing units[ER]>0, IF THEN ELSE(Standardised available inventory[Ward2]>= Standardised available inventory[Ward1], IF THEN ELSE((Ward inventory[Ward2]-Consumption[Ward2])>0, MIN(Missing units[ER], (Ward inventory[Ward2]- Consumption[Ward2])), 0), 0),0)	
Lateral transshipments to the ER[ER]	= 0 The ward chosen to provide the transshipment to the ER is the one with lower *Standardised available inventory*.	
Lateral transshipments[w]	= Lateral transshipments to the ER[w] In the simulated version of the model, only transshipments to the ER were modelled. If transshipments to other wards were included, we would need to sum them to determine the Lateral transshipments[w].	Units/Day [0, ?]

	Stocks and auxiliary variables	Units
Standardised available inventory[w]	= IF THEN ELSE(Standard deviation of ward demand[w]>0, ((Ward inventory[w]-Consumption[w])- Average of ward demand[w])/ Standard deviation of ward demand[w], 0) The standardised inventory on hand at ward *w* - i.e., the difference between the observed inventory on hand and the historical (i.e., calculated using the data since the beginning of the simulation) daily demand average divided by the daily demand historical standard deviation – is used as an indicator of the probability of fulfilling all the daily demand at ward *w*.	Dimensionless [?, ?]

Observation: Apart from the variables presented, some auxiliary variables used to determine the Average of ward demand[w] and the Standard deviation of ward demand[w] were also used. The formulations used are similar to those used on previous models to determine the average and standard deviation of the demand faced by the DC.

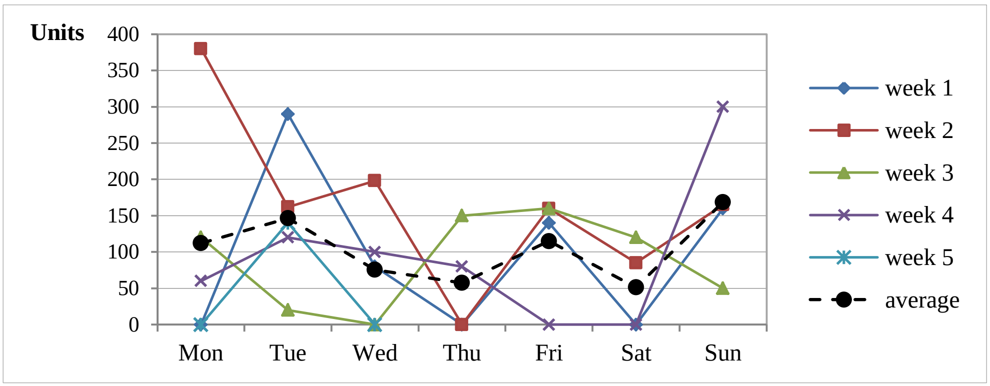
To model centralised models, some adaptations of these changes were performed.

Appendix 4.9 – Analysis of a hospital high volume, frequent and generalised use item demand

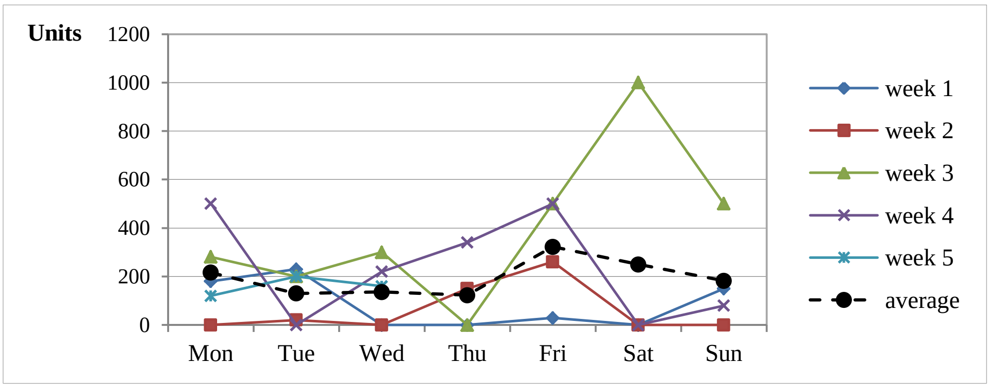
We analysed the daily demand of the considered type of compresses in three different unit care units, including one of the emergency rooms (ER) of the hospital system. The main objective of this analysis was to identify patterns in the daily demand behaviour to be incorporated in the simulations performed. Although some guidelines about the demand behaviour were seek, we did not aspire to obtain precise results – indeed, given the size of the available samples, such an aim would be unrealistic - since one of the objectives of the developed work was to analyse the robustness of the conclusions drawn from the simulations under different, although plausible, demand characteristics.

We could not observe any apparent seasonality pattern in the available samples, as can be observed in the following graphs.

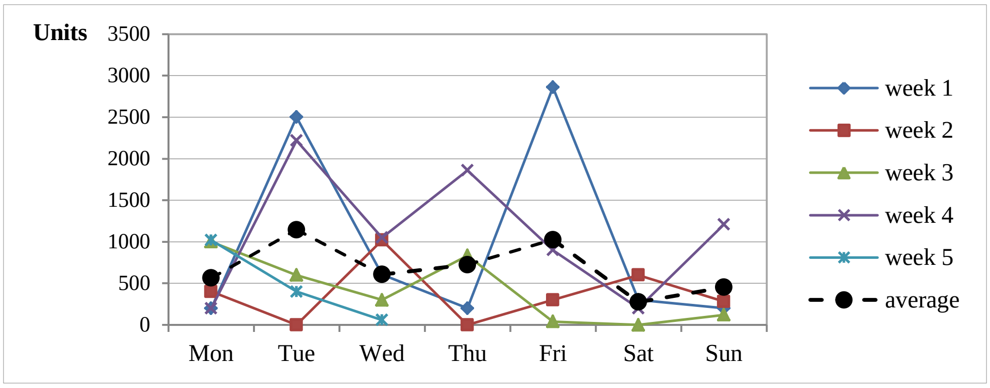
Daily demand at ward 1:



Daily demand at ward 2:

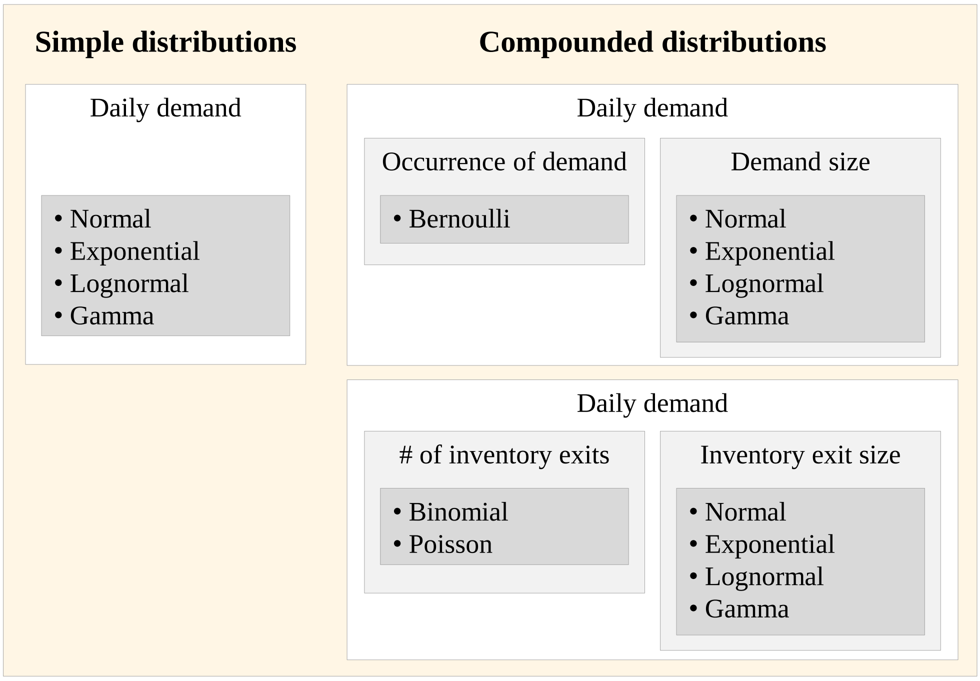


Daily demand at ward 3:



Some days with no demand were observed, mainly on ward 1 and ward 2, therefore we decided to consider the modelling of daily demand both directly, using a single statistical distribution, and using a combination of two phenomena (i.e., the occurrence of demand in each day and the size of the demand on that day, or the number of inventory exits per day and the size of those exits), as summarised in the figure that follows.

Tested statistical distributions to generate daily demand:



Anderson-Darling (A-D), Kolmogorov-Smirnov (K-S) and Chi-square (C-S) goodness of fit tests for continuous distributions were performed using Easyfit Professional 5.5 by Mathwave Technologies (http://www.mathwave.com). The corresponding results are summarised in the tables bellow.

Results of the goodness of fit tests to daily demand of the three wards:

Distribution	**Ward 1** (n=31)	**Ward 2** (n=31)	**ER** (n=31)
Normal	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\mu = 104.52$; $\sigma = 98.449$	Do not reject H_0: A-D, K-S: $\alpha = 0.1$ C-S: $\alpha = 0.2$ Parameters: $\mu = 190.97$; $\sigma = 225.68$	Do not reject H_0: A-D: $\alpha = 0.05$, K-S: $\alpha = 0.1$, C-S: $\alpha = 0.2$ Parameters: $\mu = 692.9$; $\sigma = 754.1$
Exponential	Do not reject H_0: C-S: $\alpha = 0.05$ A-D, K-S: Reject H_0 Parameters: Irrelevant	Reject H_0 A-D, K-S, C-S Parameters: Irrelevant	Do not reject H_0: K-S, C-S: $\alpha = 0.2$ A-D: Reject H_0 Parameters: $\lambda = 0.00144$
Lognormal	Reject H_0 A-D, K-S, C-S Parameters: Irrelevant	Reject H_0 A-D, K-S, C-S Parameters: Irrelevant	Do not reject H_0: K-S, C-S: $\alpha = 0.2$ A-D: Reject H_0 Parameters: $\mu = 6.1558$; $\sigma = 1.0577$; $\gamma = 0$
Gamma	Do not reject H_0: C-S: $\alpha = 0.05$ A-D, K-S: Reject H_0 Parameters: Irrelevant	Reject H_0 A-D, K-S, C-S Parameters: Irrelevant	Do not reject H_0: K-S, C-S: $\alpha = 0.2$ A-D: Reject H_0 Parameters: $\alpha = 0.84428$; $\beta = 820.7$; $\gamma = 0$

Legend: A-D: Arderson-Darling, K-S: Kolmogorov-Smirnov; C-H: Chi-square
If the test statistic < 0.05, H_0 (i.e., the hypothesis that the sample was extracted from a population with the stated distribution) is rejected; the tested significant levels in the acceptance region were 0.2 and 0.1; for each test, the higher of these levels with a no rejection decision is presented.

Results of the goodness of fit tests to demand size per day (when demand occurs) of the three wards:

Distribution	**Ward 1** (n=22)	**Ward 2** (n=21)	**ER** (n=28)
Normal	Do not reject H_0: A-D, C-S: $\alpha = 0.2$ K-S: $\alpha = 0.1$ Parameters: $\mu = 147.27$; $\sigma = 85.143$	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\mu = 281.9$; $\sigma = 222.44$	Do not reject H_0: A-D, C-S: $\alpha = 0.1$ K-S: $\alpha = 0.2$ Parameters: $\mu = 767.14$; $\sigma = 756.83$
Exponential	Do not reject H_0: A-D: $\alpha = 0.05$, C-S: $\alpha = 0.1$ K-S: Reject H_0 Parameter: $\lambda = 0.00833$	Do not reject H_0: A-D, K-S: $\alpha = 0.2$ C-S: $\alpha = 0.1$ Parameters: $\lambda = 0.00355$	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\lambda = 0.0013$
Lognormal	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\mu = 5.2652$; $\sigma = 0.38312$; $\gamma = -61.001$	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\mu = 5.7273$; $\sigma = 0.56543$; $\gamma = -77.995$	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\mu = 6.1998$; $\sigma = 1.011$; $\gamma = -12.205$
Gamma	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\alpha = 2.9919$; $\beta = 49.223$; $\gamma = 0$	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\alpha = 1.6061$; $\beta = 175.52$; $\gamma = 0$	Do not reject H_0: A-D, K-S, C-S: $\alpha = 0.2$ Parameters: $\alpha = 1.0274$; $\beta = 746.66$; $\gamma = 0$

Legend: A-D: Arderson-Darling, K-S: Kolmogorov-Smirnov; C-H: Chi-square
If the test statistic < 0.05, H_0 is rejected; the tested significant levels in the acceptance region were 0.2 and 0.1; for each test, the higher of these levels with a no rejection decision is presented.

Results of the goodness of fit tests to inventory exits size of the three wards:

Distribution	**Ward 1** (n=27)	**Ward 2** (n=25)	**ER** (n=60)
Normal	Do not reject H_0: A-D, K-S, C-S: α = 0.2 Parameters: μ = 120; σ = 81.561	Do not reject H_0: A-D, K-S: α = 0.1 C-S: Reject H_0 Parameters: μ = 236.8; σ = 202.06	Reject H_0 A-D, K-S, C-S Parameters: Irrelevant
Exponential	Do not reject H_0: A-D: α = 0.1, C-S: α = 0.05 K-S, Reject H_0 Parameter: λ = 0.00833	Do not reject H_0: A-D, C-S: α = 0.2 K-S: Reject H_0 Parameters: λ = 0.00422	Do not reject H_0: A-D: α = 0.05 K-S, C-S: Reject H_0 Parameters: λ = 0.00279
Lognormal	Do not reject H_0: A-D: α = 0.1, K-S: α = 0.05, C-S: α = 0.2 Parameters: μ = 5.232; σ = 0.37858; γ = -81.135	Do not reject H_0: A-D, K-S, C-S: α = 0.2 Parameters: μ = 5.4285; σ = 0.61596; γ = -39.915	Do not reject H_0: A-D: α = 0.1, C-S: α = 0.2 K-S: Reject H_0 Parameters: μ = 5.4251; σ = 0.9973; γ = -14.804
Gamma	Do not reject H_0: A-D, K-S, C-S: α = 0.2 Parameters: α = 2.1647; β = 55.435; γ = 0	Do not reject H_0: A-D, K-S, C-S: α = 0.2 Parameters: α = 1.3735; β = 172.41; γ = 0	Reject H_0 A-D, K-S, C-S Parameters: Irrelevant

Legend: A-D: Arderson-Darling, K-S: Kolmogorov-Smirnov; C-H: Chi-square
If the test statistic < 0.05, H_0 is rejected; the tested significant levels in the acceptance region were 0.2 and 0.1; for each test, the higher of these levels with a no rejection decision is presented.

The choice of the distributions to test was guided by two types of reasons: first, the chosen distributions are frequently used in inventory control settings; and second, they can be easily modelled with the Vensim version we used to perform the model simulations. We did not attempt to model the time between successive days with demand because the available time series are not long enough to obtain a sample that could be studied.

The daily demand at each of the care units can be considered normal, which is consistent with the characteristics of the item (high volume, frequent demand). This is also true for the demand size (in the days demand occurs), and the size of inventory exits, except for the emergency room. Other tested distributions are also compatible with the characteristics of the samples, as can be observed in the tables.

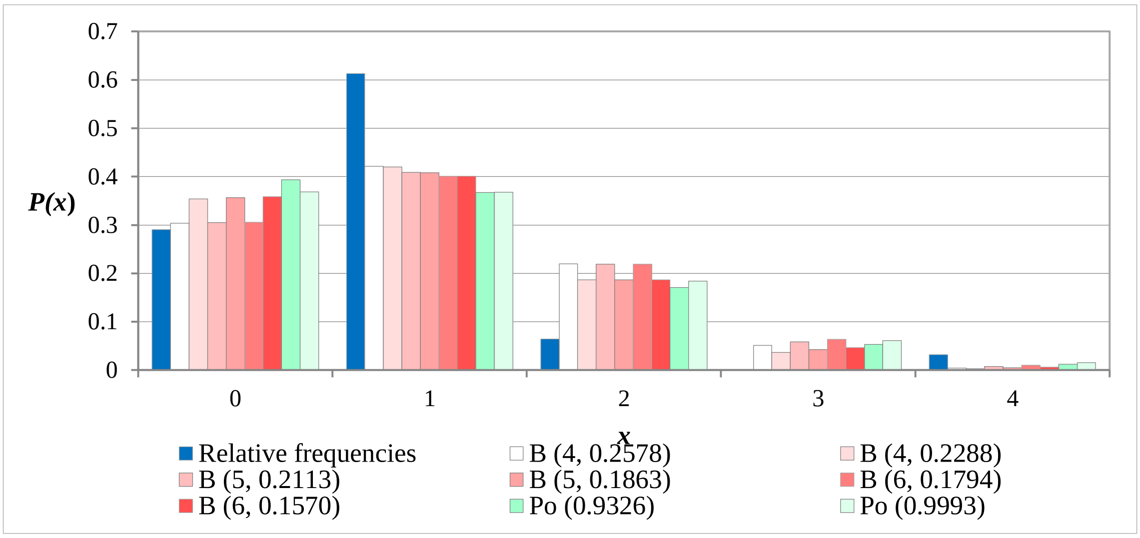
To model the occurrence of demand in each day, defined as a binary variable (that is 1, for a day with demand; and is 0, for a day with no demand), we used a Bernoulli distribution with probability of success equal to the proportion of days with demand in each ward (i.e., 0.7097 in ward 1, 0.6774 in ward 2, and 0.9032 in the ER).

Relatively to the number of inventory exits per day, we used MS Excel Solver to determine the Binomial proportion and Poisson average that minimised the sum of absolute or square differences between the samples relative frequencies and the theoretical probability functions. The resulting distribution parameters and mean absolute and square differences for ward 1, ward 2 and the emergency room are presented on the following tables. We do also present figures with comparisons between the samples relative frequencies and the probabilities of the considered theoretical distributions.

Binomial and Poisson distributions for ward 1 number of inventory exits per day:

	Binomial						Poisson	
Parameters	N = 4, p = 0.2578	N = 4, p = 0.2288	N = 5, p = 0.2113	N = 5, p = 0.1863	N = 6, p = 0.1794	N = 6, p = 0.1570	λ= 0.9325	λ= 0.9993
Mean sum of absolute errors	0.0877	0.0891	0.0914	0.0928	0.0937	0.0951	0.1014	0.1018
Mean sum of square errors	0.0128	0.0117	0.0140	0.0128	0.0147	0.0135	0.0171	0.0169

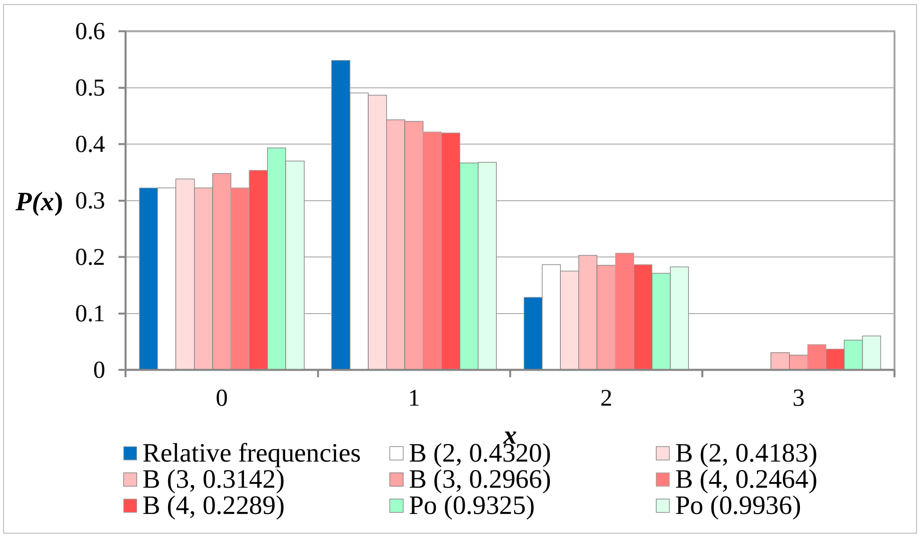
Comparison of sample relative frequencies of ward 1 number of inventory exits per day with theoretical distributions probabilities:



Binomial and Poisson distributions for ward 2 number of inventory exits per day:

	Binomial						Poisson	
Parameters	N = 2, p = 0.4320	N = 2, p = 0.4183	N = 3, p = 0.3142	N = 3, p = 0.2966	N = 4, p = 0.2464	N = 4, p = 0.2289	λ= 0.9325	λ= 0.9936
Mean sum of absolute errors	0.0288	0.0309	0.0525	0.0541	0.0633	0.0643	0.0945	0.0949
Mean sum of square errors	0.0017	0.0015	0.0044	0.0041	0.0060	0.0056	0.0107	0.0104

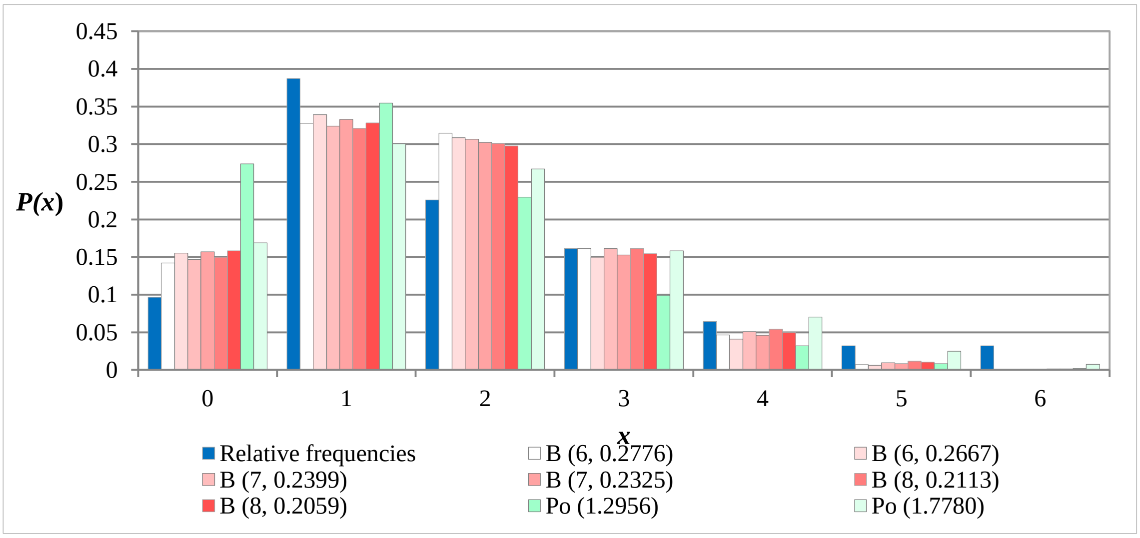
Comparison of sample relative frequencies of ward 2 number of inventory exits per day with theoretical distributions probabilities:



Binomial and Poisson distributions for emergency room number of inventory exits per day:

	Binomial						Poisson	
Parameters	N = 6, p = 0.2776	N = 6, p = 0.2667	N = 7, p = 0.2399	N = 7, p = 0.2325	N = 8, p = 0.2113	N = 8, p = 0.2059	λ= 1.2956	λ= 1.7780
Mean sum of absolute errors	0.0384	0.0404	0.0373	0.0390	0.0366	0.0381	0.0331	0.0406
Mean sum of square errors	0.0022	0.0021	0.0021	0.0021	0.0020	0.0020	0.0055	0.0022

Comparison of sample relative frequencies of emergency room number of inventory exits per day with theoretical distributions probabilities:



All the presented distributions seem plausible, although for ward 1 the mean errors are relatively high (i.e., mean absolute errors of 8-10%). For our simulation experiments, we selected the following parameters:

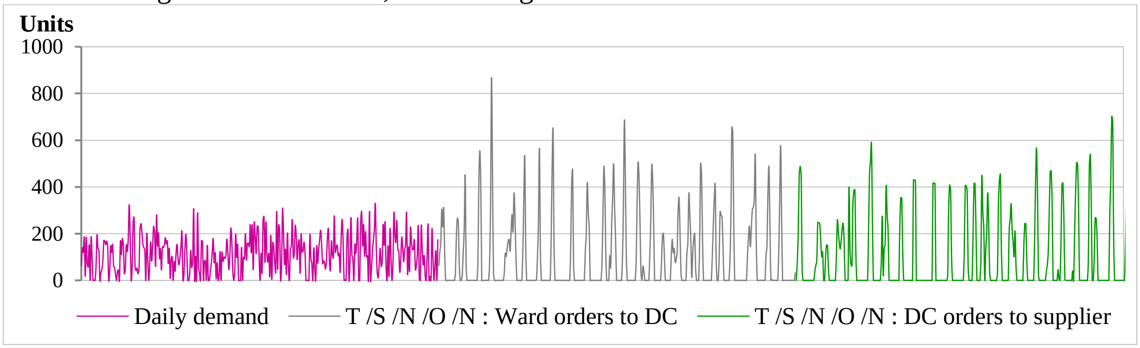
- Ward 1: Binomial distribution with N=4 and p around 0.2288; Poisson distribution with λ around 0.9993;
- Ward 2: Binomial distribution with N=3 and p around 0.2966; Poisson distribution with λ around 0.9936;
- ER: Binomial distribution with N=8 and p around 0.2113; Poisson distribution with λ around 1.7780.

Appendix 4.10 – Traditional SC with one DC and one ward: simulation of over and under-ordering effects at the ward - demand amplification in the supply chain

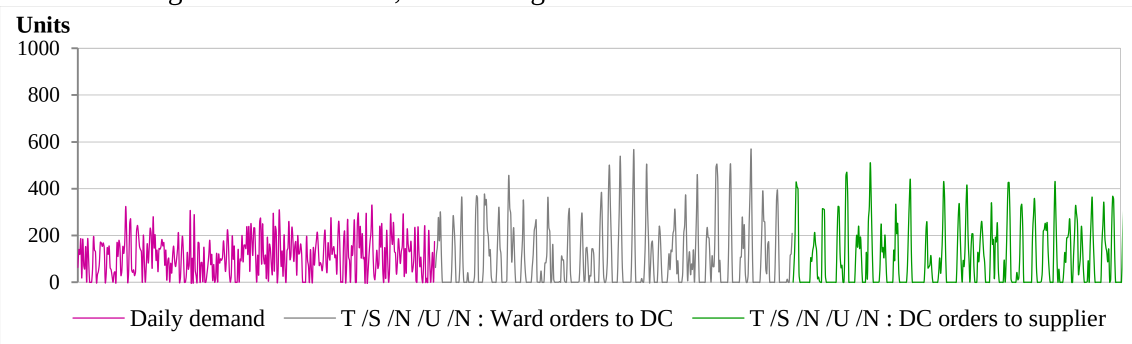
Comparison of the demand faced at the various SC echelons (Observation: The comparison of graphs obtained from the simulations of models using different generated demands must be cautious, since the corresponding scales can be different.)

<u>Generated demand 1</u>

Over-ordering effect at the ward, no ordering effects at the DC:

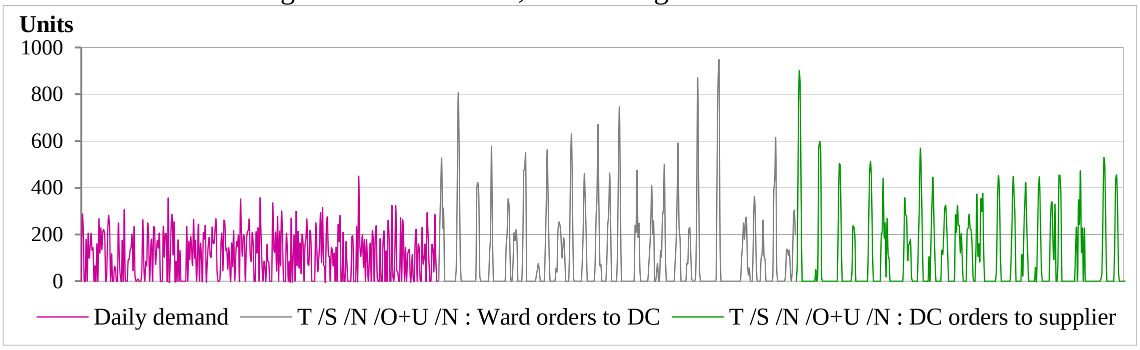


Under-ordering effect at the ward, no ordering effects at the DC:

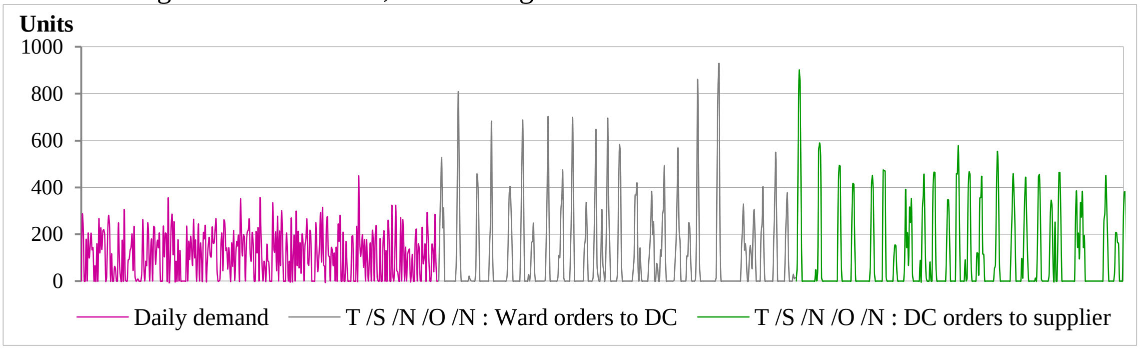


Generated demand 2

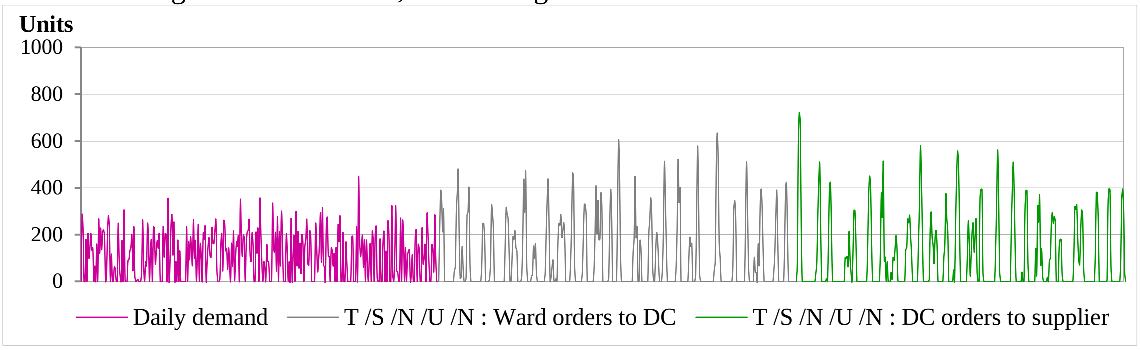
Over and under-ordering effects at the ward, no ordering effects at the DC:



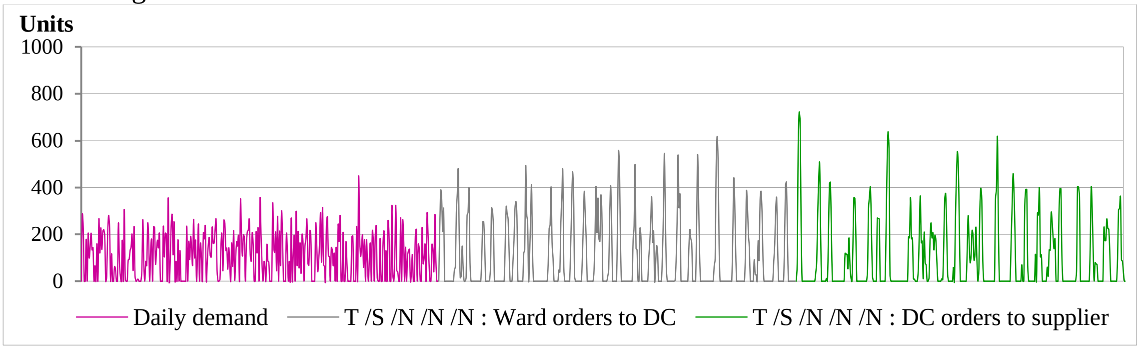
Over-ordering effect at the ward, no ordering effects at the DC:



Under-ordering effect at the ward, no ordering effects at the DC:

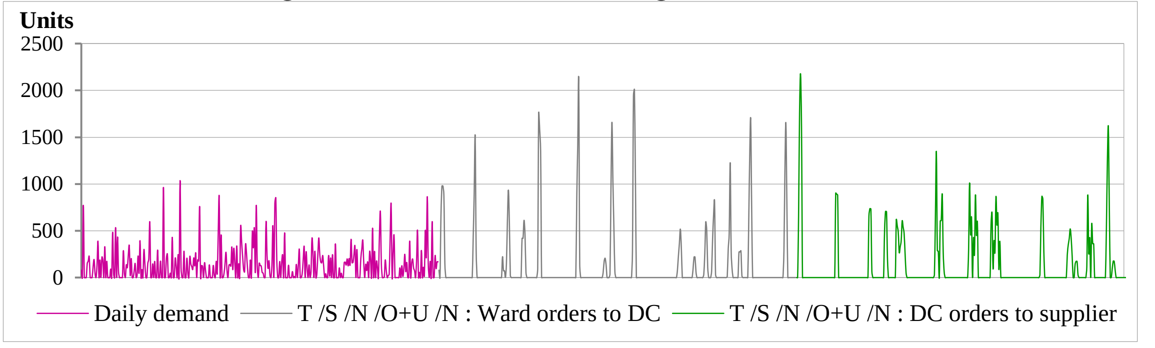


No ordering effects at the ward or at the DC:

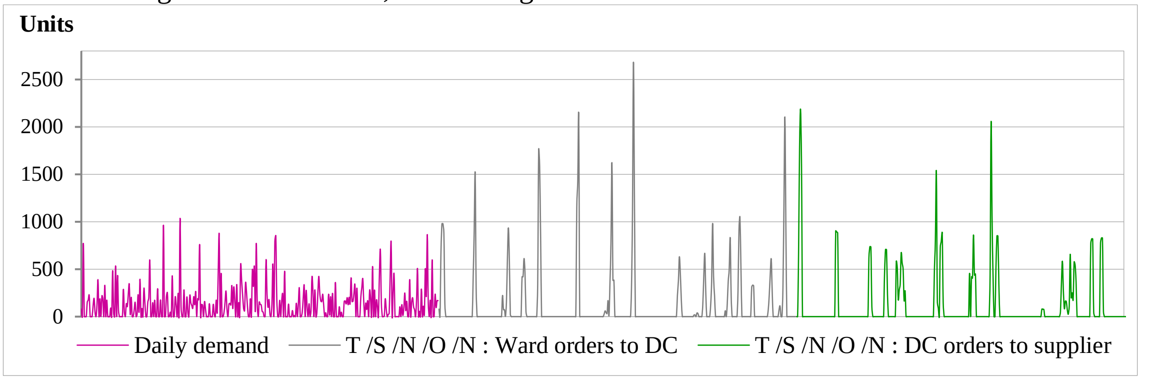


Generated demand 3

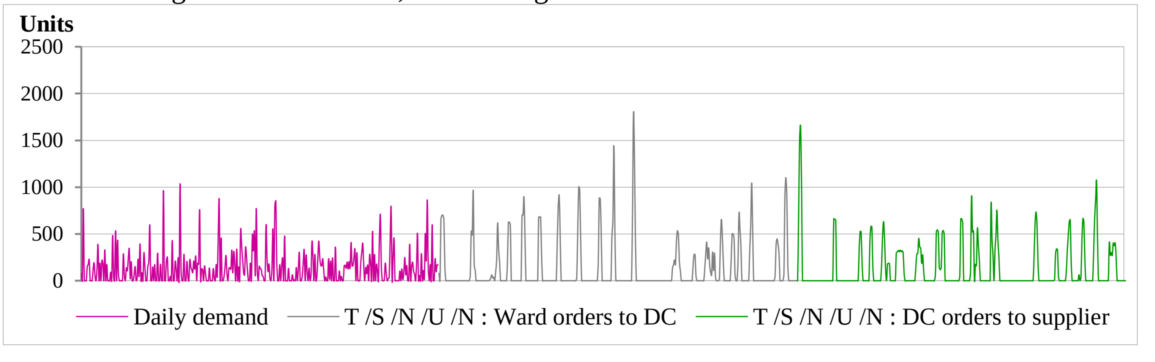
Over and under-ordering effects at the ward, no ordering effects at the DC:



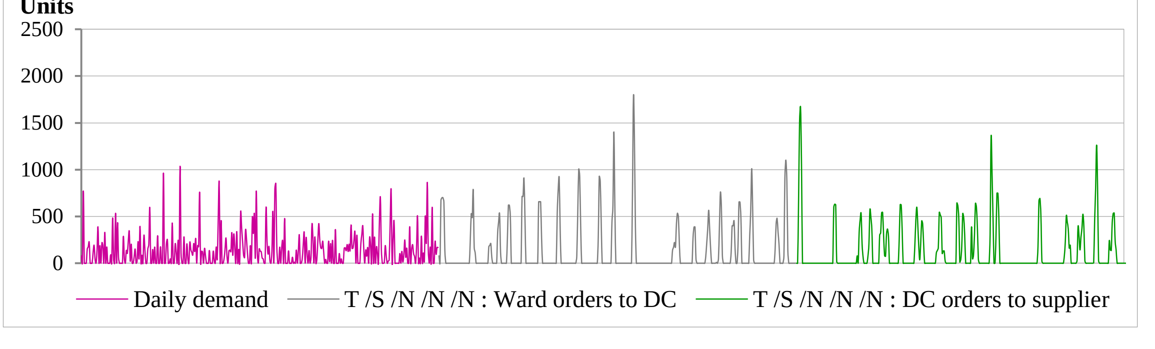
Over-ordering effect at the ward, no ordering effects at the DC:



Under-ordering effect at the ward, no ordering effects at the DC:

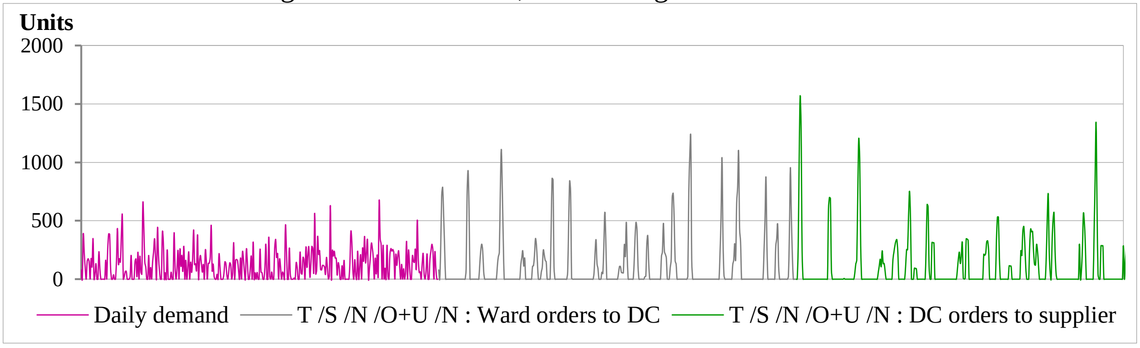


No ordering effects at the ward or at the DC:

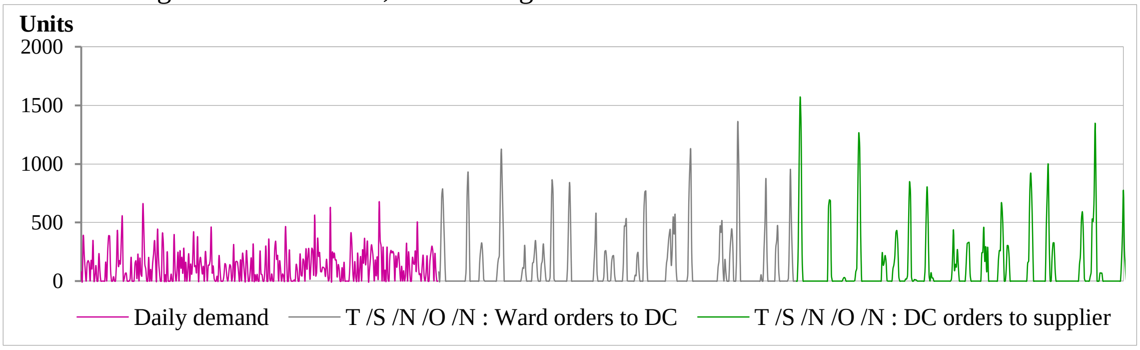


Generated demand 4

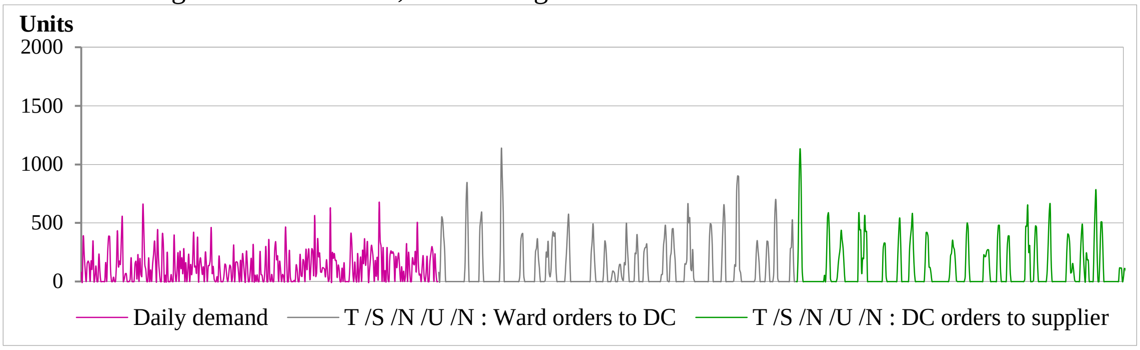
Over and under-ordering effects at the ward, no ordering effects at the DC:



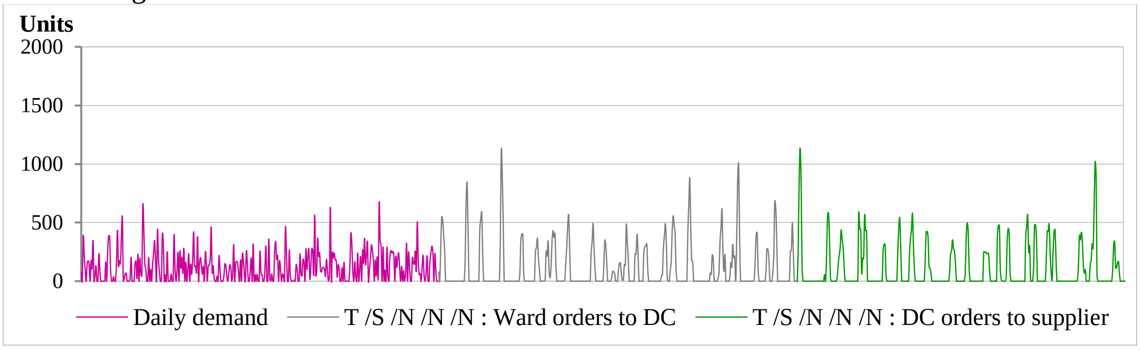
Over-ordering effect at the ward, no ordering effects at the DC:



Under-ordering effect at the ward, no ordering effects at the DC:



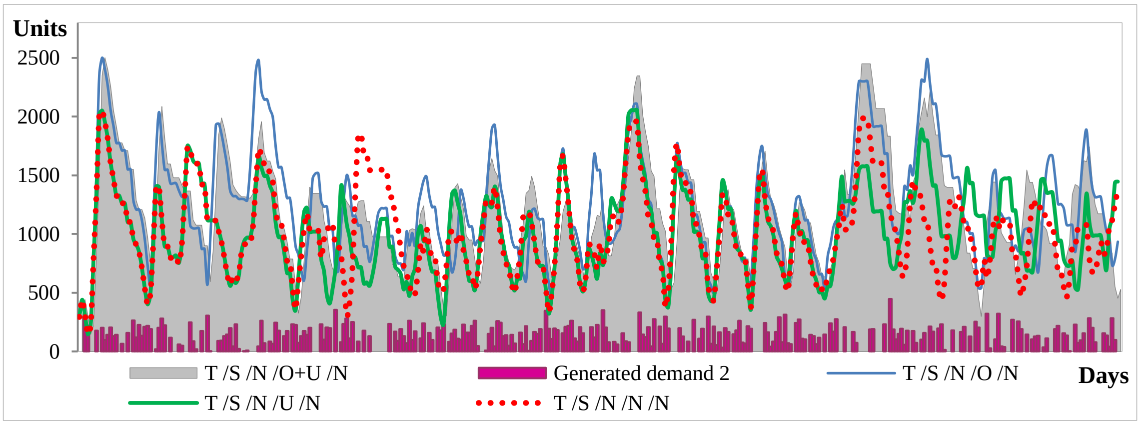
No ordering effects at the ward or at the DC:



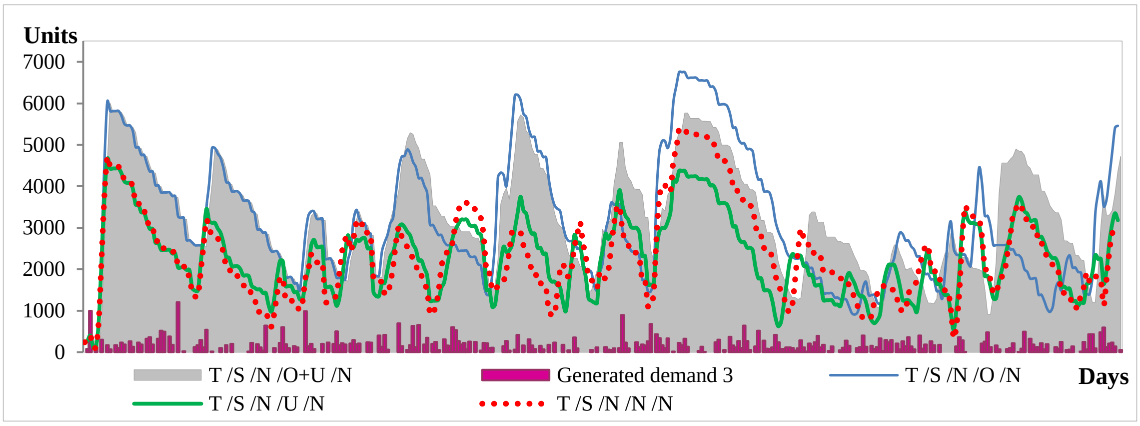
Appendix 4.11 – Traditional SC with one DC and one ward: simulation of over and under ordering effects at the ward - total inventory level

Comparison of total inventory level (Observation: The comparison of graphs obtained from the simulations of models using different generated demand must be cautious, since the corresponding scales are not the same.)

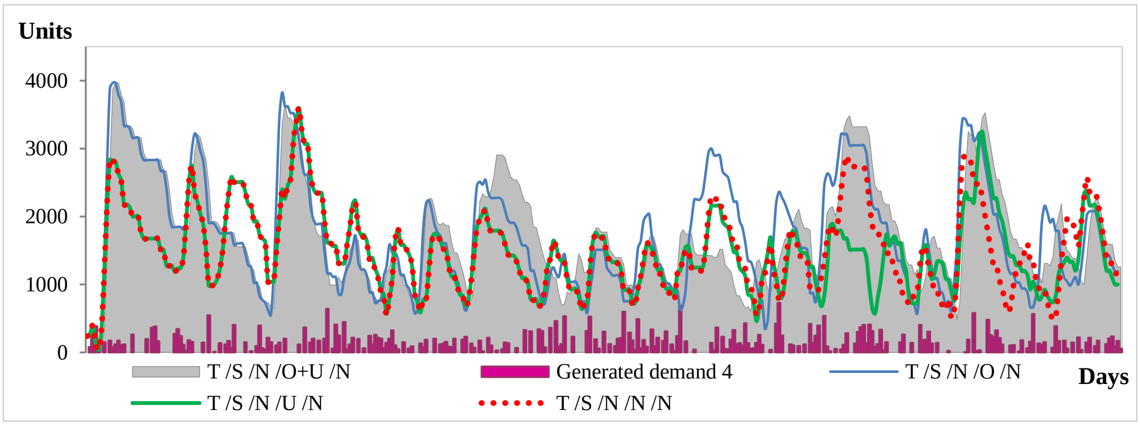
Generated demand 2



Generated demand 3



Generated demand 4

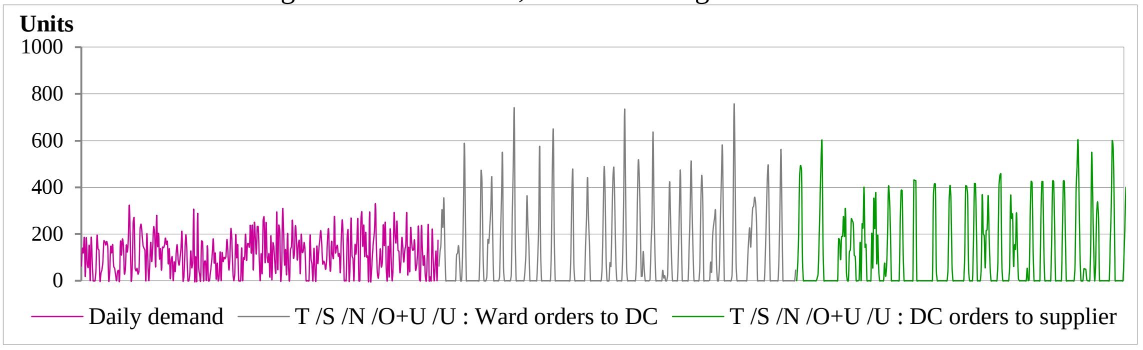


Appendix 4.12 – Traditional SC with one DC and one ward: simulation of under ordering effects at the DC - demand amplification in the supply chain

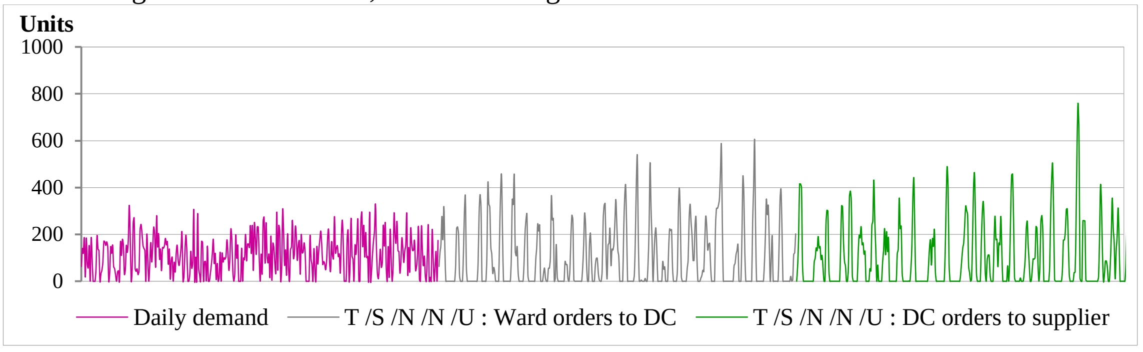
Comparison of the demand faced at the various SC echelons (Observation: The comparison of graphs obtained from the simulations of models using different generated demands must be cautious, since their scales are different; the graphs presented can/should be compared with those presented in Appendix 4.10.)

Generated demand 2

Over and under-ordering effects at the ward, under-ordering effect at the DC:

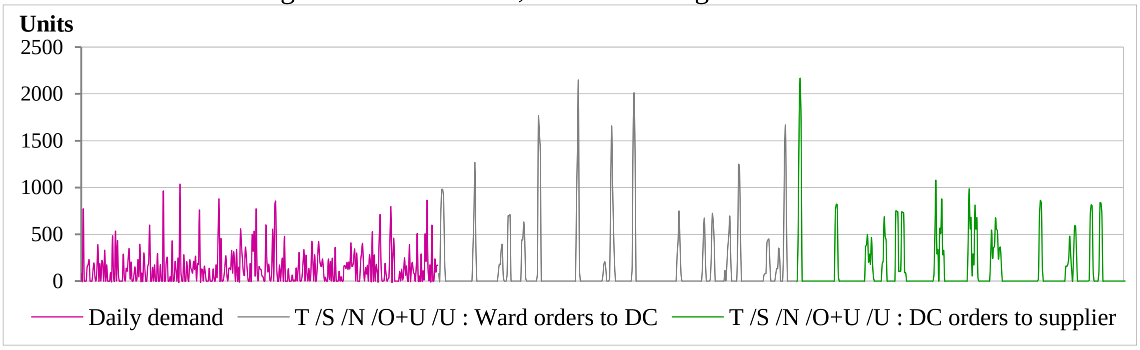


No ordering effects at the ward, under-ordering effect at the DC:

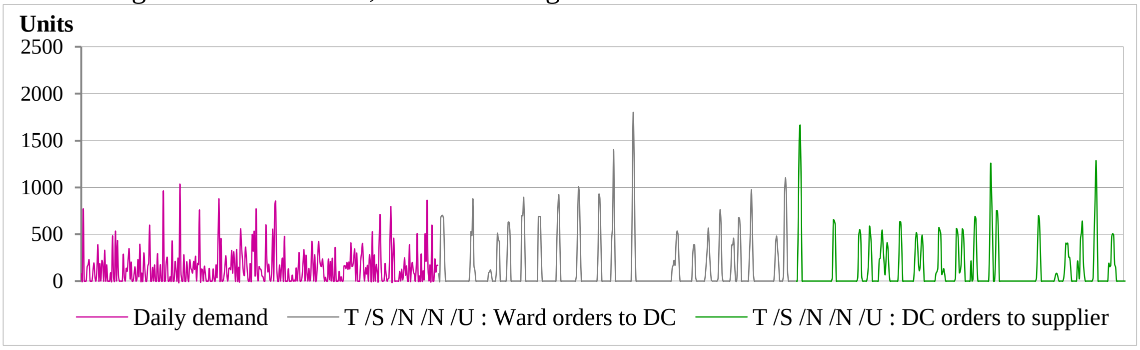


Generated demand 3

Over and under-ordering effects at the ward, under-ordering effect at the DC:

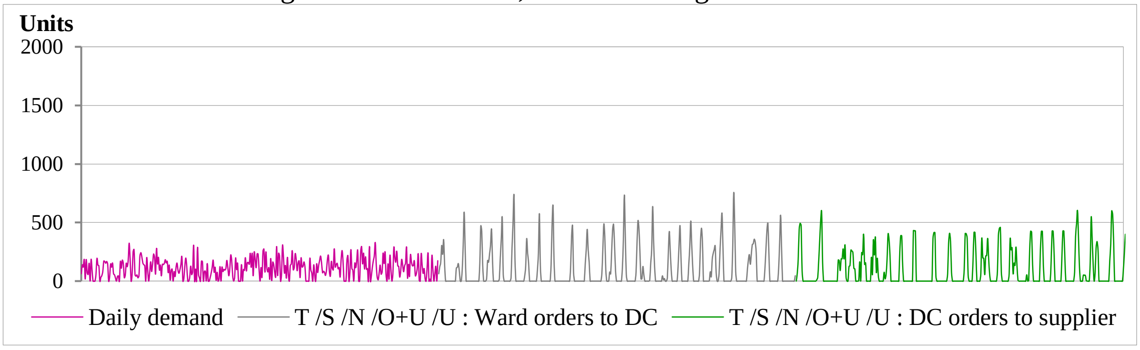


No ordering effects at the ward, under-ordering effect at the DC:

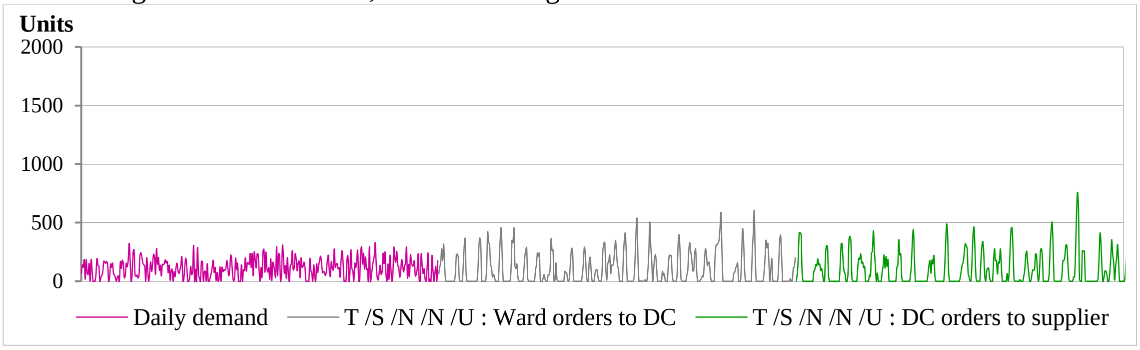


Generated demand 4

Over and under-ordering effects at the ward, under-ordering effect at the DC:



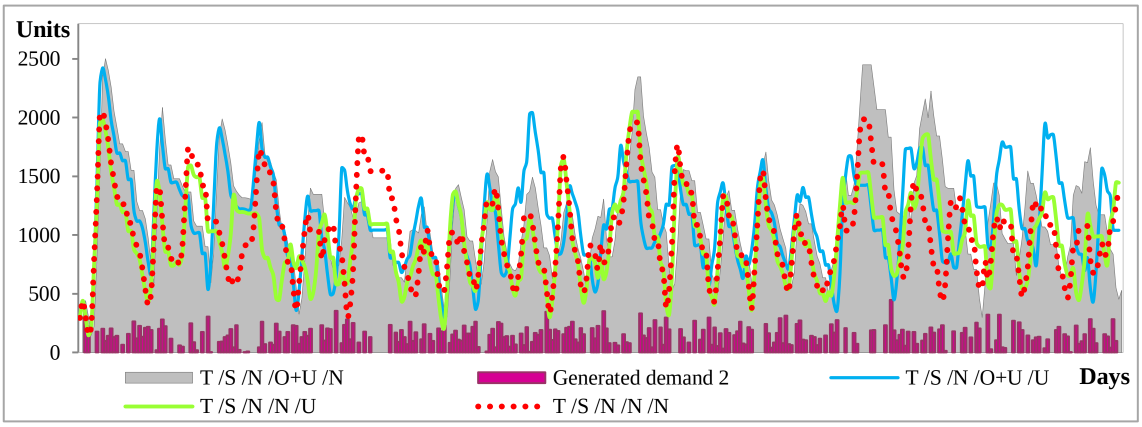
No ordering effects at the ward, under-ordering effect at the DC:



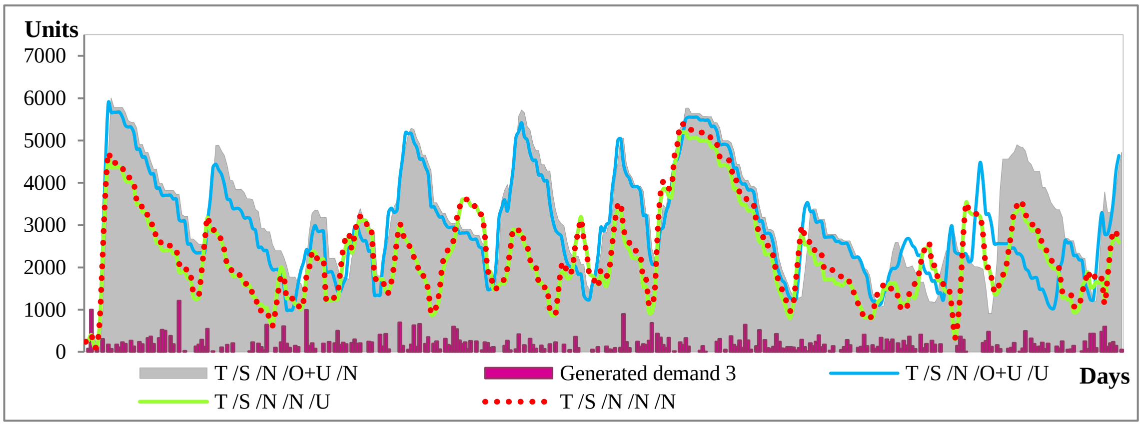
Appendix 4.13 – Traditional SC with one DC and one ward: simulation of under ordering effects at the DC - total inventory level

Comparison of total inventory level (Observation: The comparison of graphs obtained from the simulations of models using different generated demand must be cautious, since the corresponding scales are not the same.)

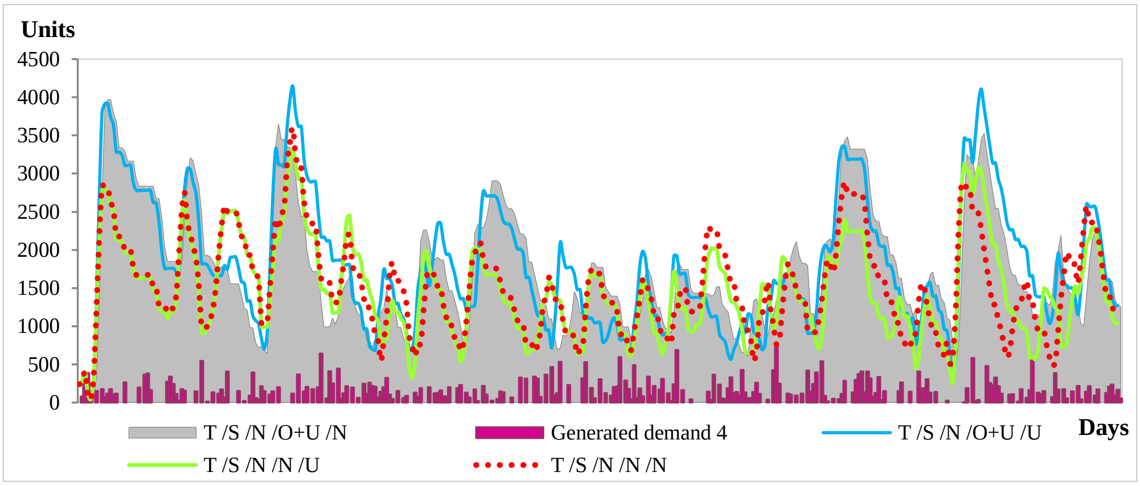
Generated demand 2



Generated demand 3



Generated demand 4

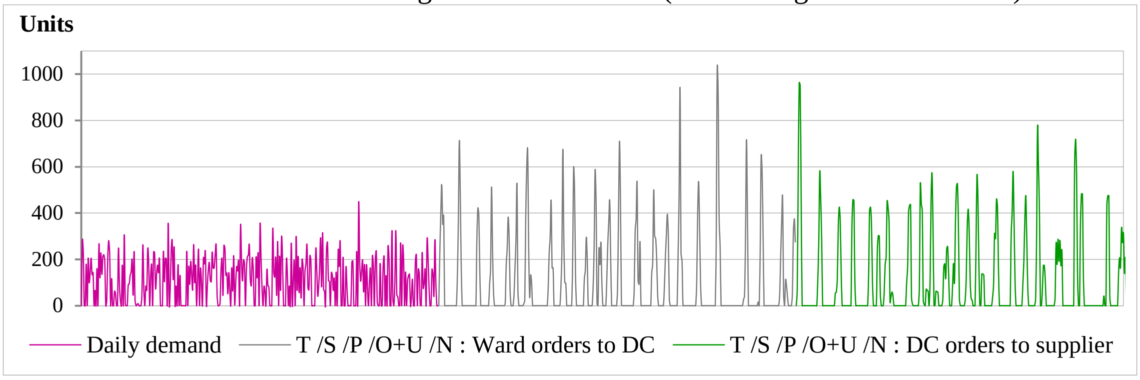


Appendix 4.14 – Traditional SC with one DC and one ward: with emergency deliveries from the DC - demand amplification in the supply chain

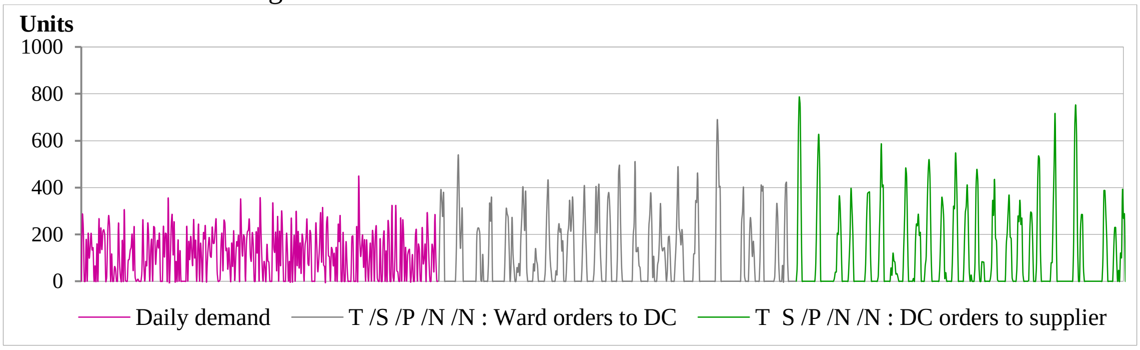
Comparison of the demand faced at the various SC echelons (Observation: The comparison of graphs obtained from the simulations of models using different generated demands must be cautious, since the corresponding scales are different; the graphs presented can/should be compared with those presented in Appendix 4.10.)

Generated demand 2

Model with over and under-ordering effects at the ward (no ordering effects at the DC):

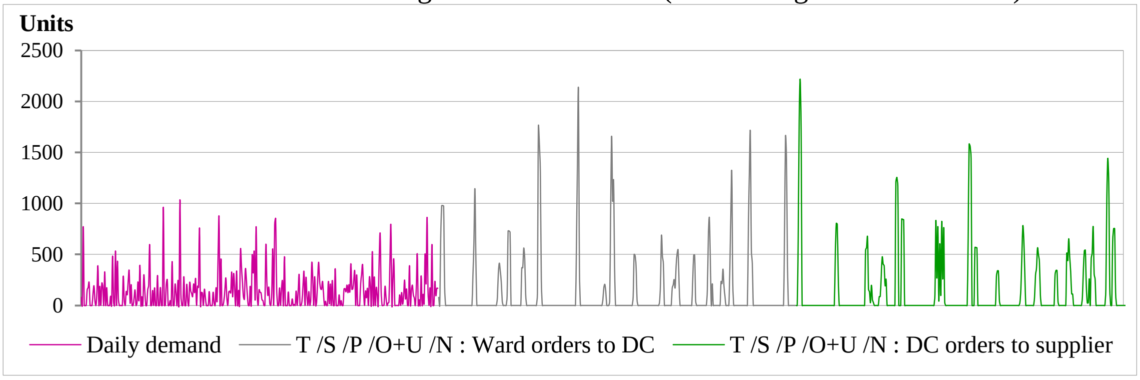


Model with no ordering effects:

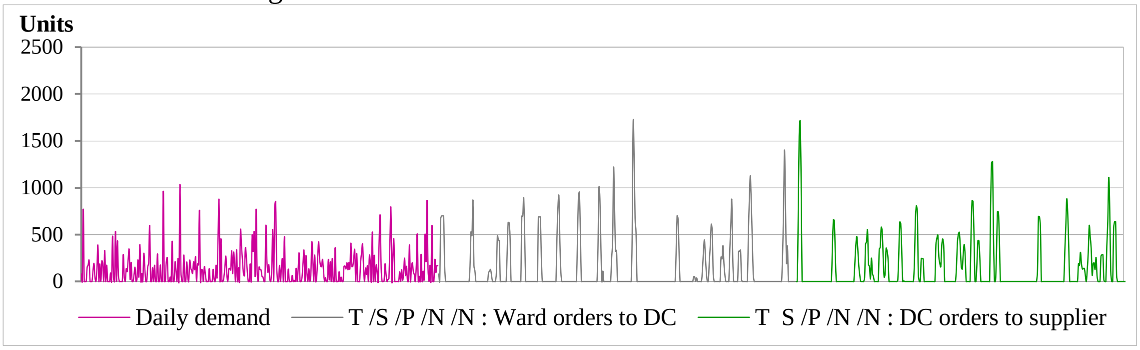


<u>Generated demand 3</u>

Model with over and under-ordering effects at the ward (no ordering effects at the DC):

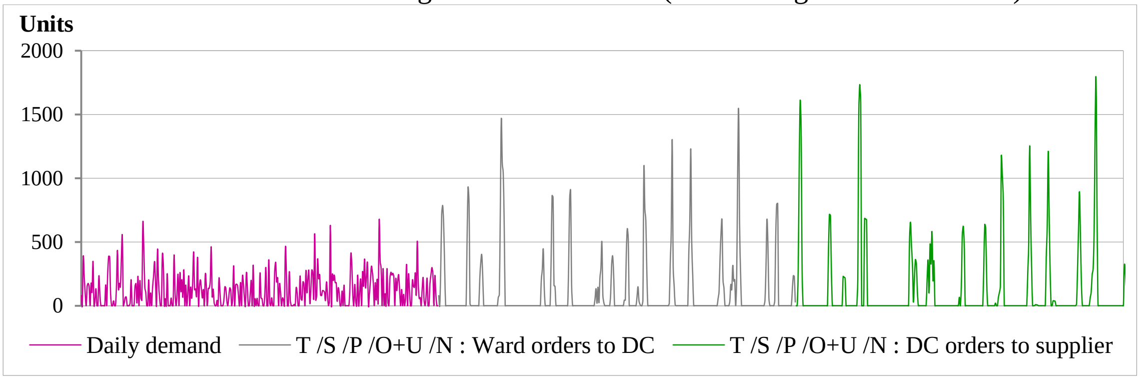


Model with no ordering effects:

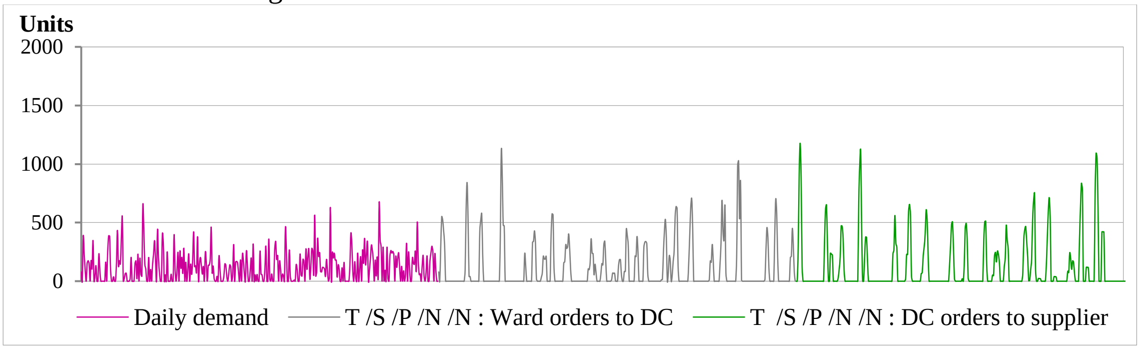


<u>Generated demand 4</u>

Model with over and under-ordering effects at the ward (no ordering effects at the DC):



Model with no ordering effects:

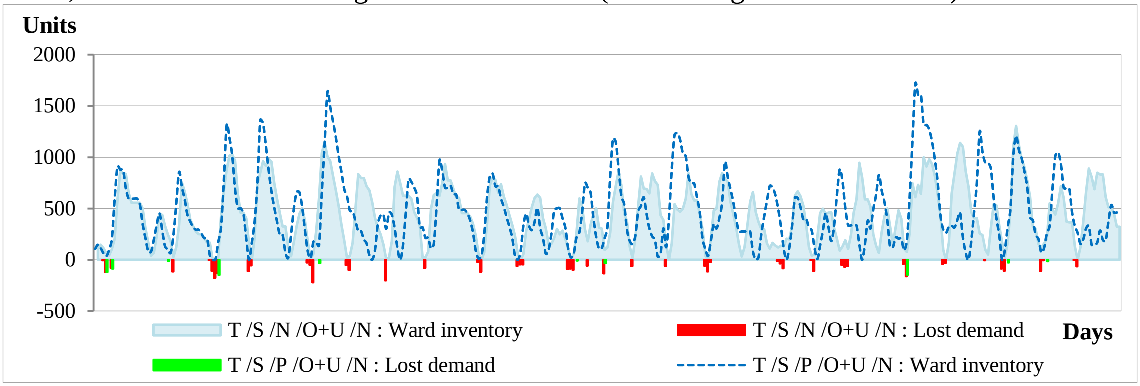


Appendix 4.15 – Traditional SC with one DC and one ward: inventory levels at the ward and at the DC – with versus without emergency deliveries from the DC

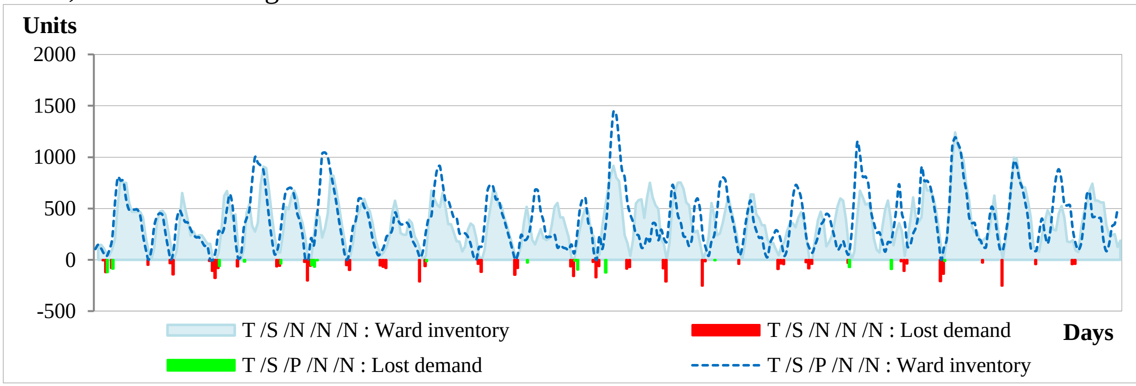
Comparison of inventory level at the ward and at the DC (Observation: The comparison of graphs obtained from the simulations of models using different generated demand must be cautious, since the corresponding scales are not the same; the scales of graphs of the ward and DC inventory levels relative to each generated demand are the same.)

<u>Generated demand 1</u>

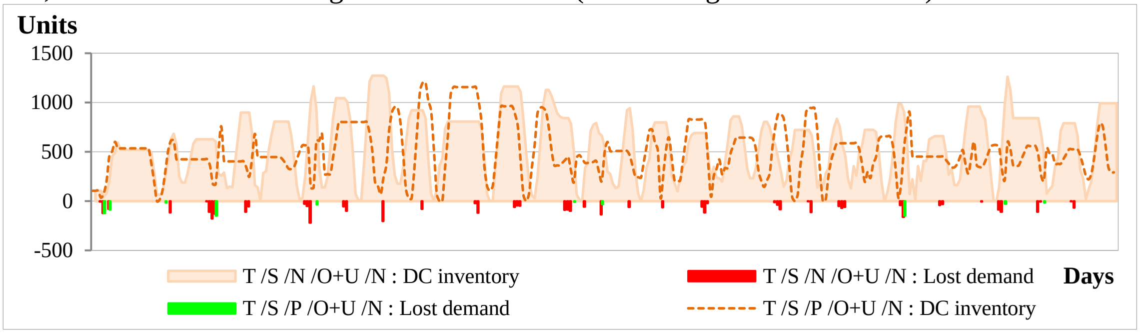
Ward, over and under-ordering effects at the ward (no ordering effects at the DC):



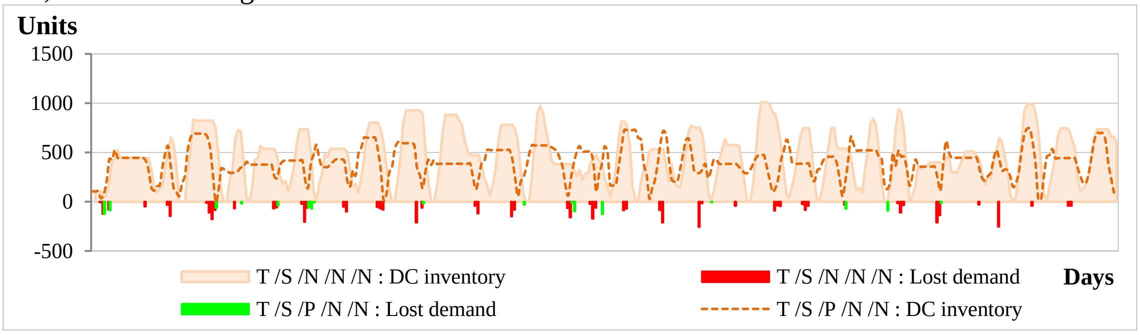
Ward, no over ordering effects:



DC, over and under-ordering effects at the ward (no ordering effects at the DC):

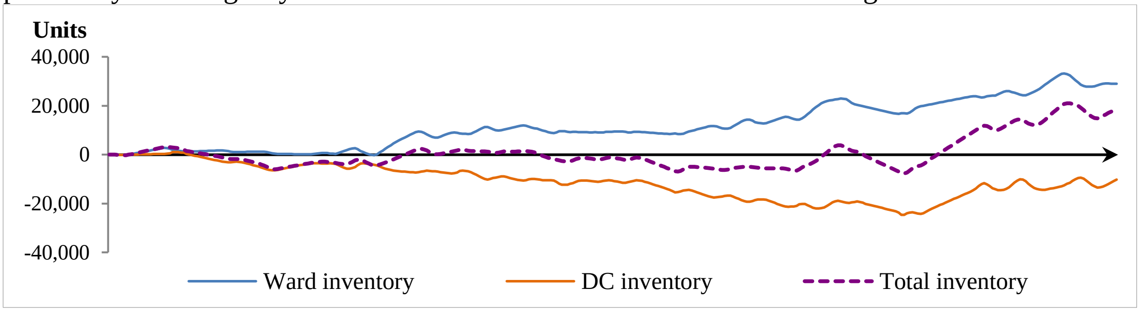


DC, no over ordering effects:

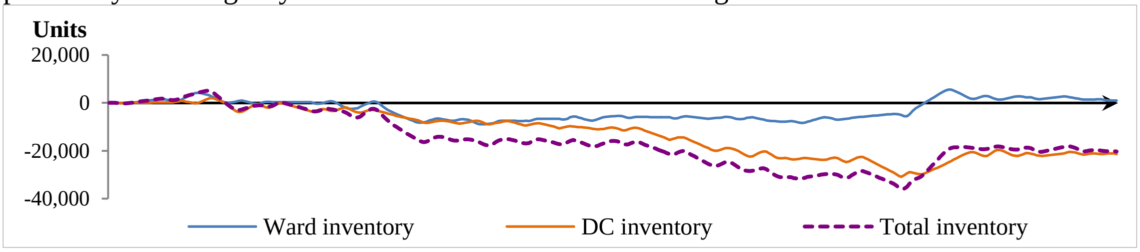


Generated demand 2

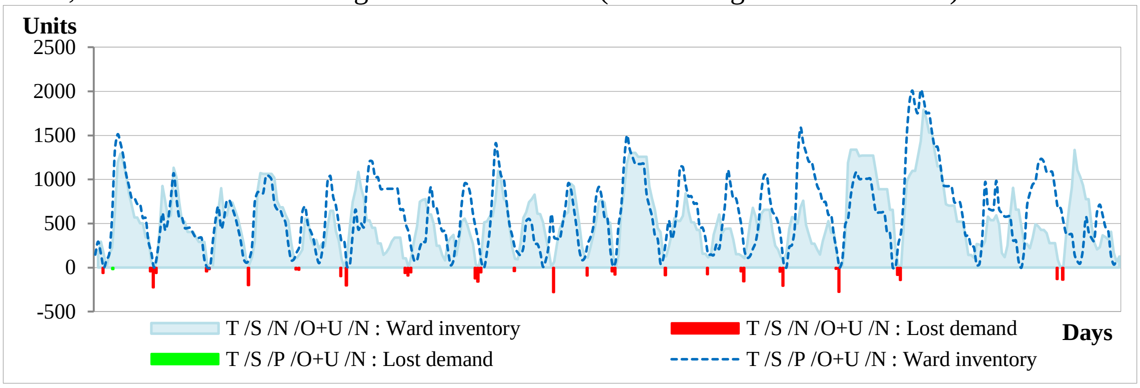
Accumulated differences between the inventory levels in the system with and without the possibility of emergency deliveries from the DC– over and under-ordering effects at the wards:



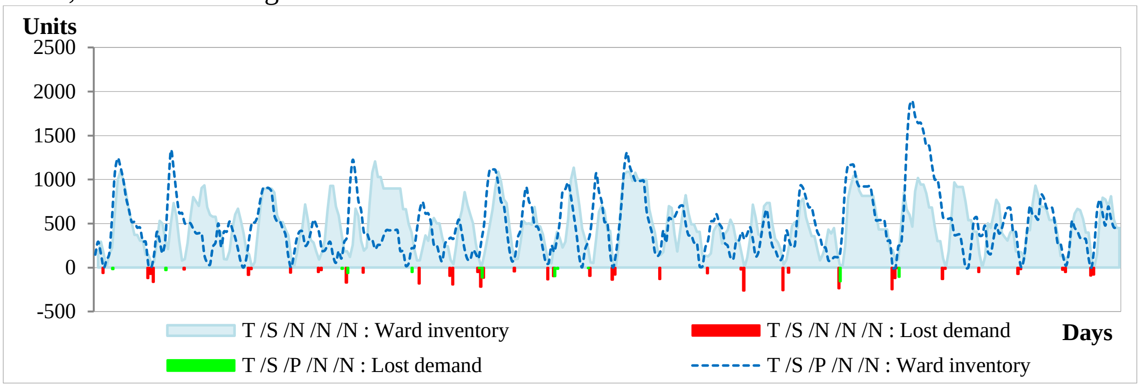
Accumulated differences between the inventory levels in the system with and without the possibility of emergency deliveries from the DC– no ordering effects:



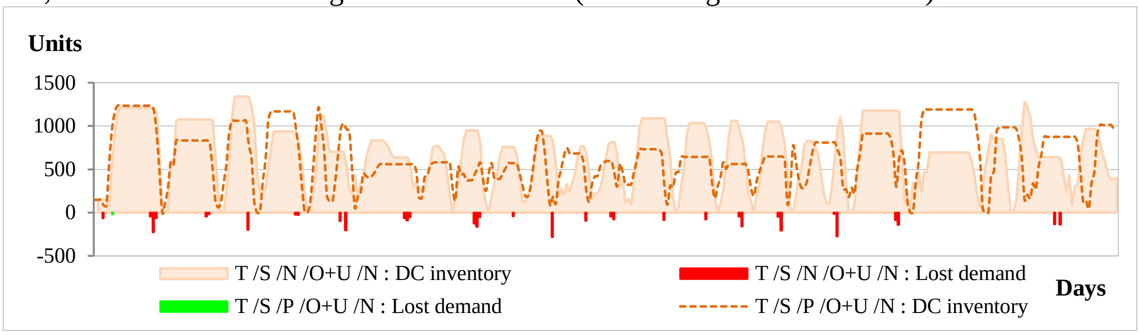
Ward, over and under-ordering effects at the ward (no ordering effects at the DC):



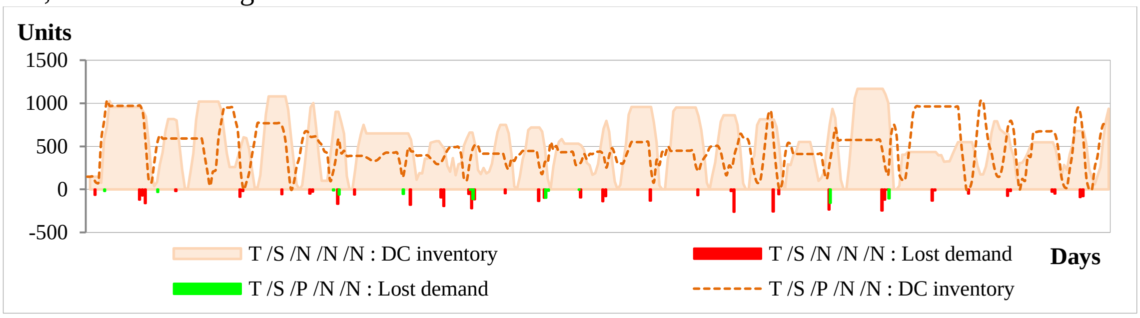
Ward, no over ordering effects:



DC, over and under-ordering effects at the ward (no ordering effects at the DC):

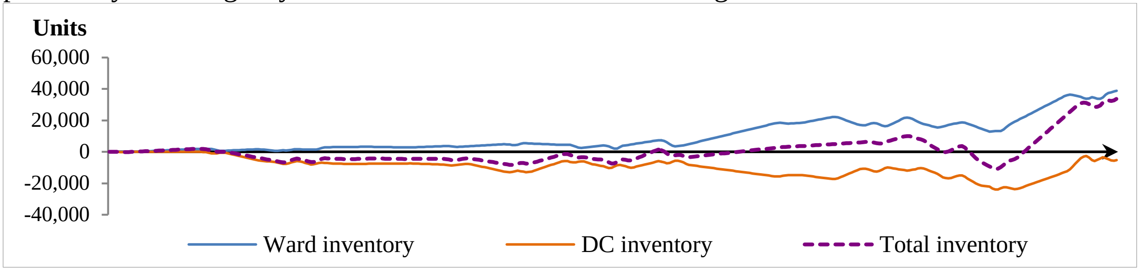


DC, no over ordering effects:

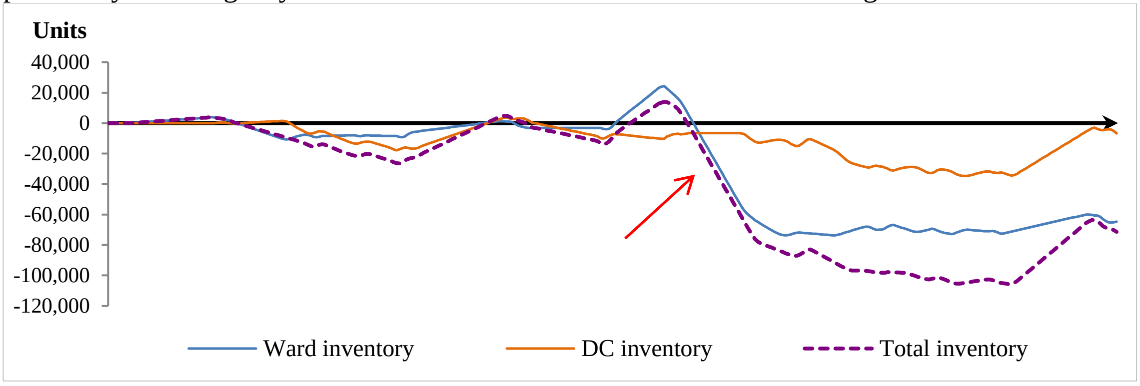


<u>Generated demand 3</u>

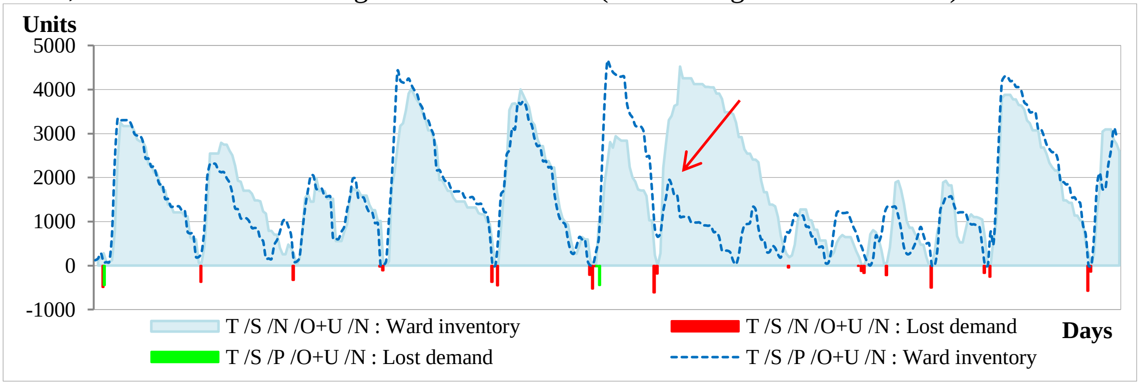
Accumulated differences between the inventory levels in the system with and without the possibility of emergency deliveries from the DC– no ordering effects:



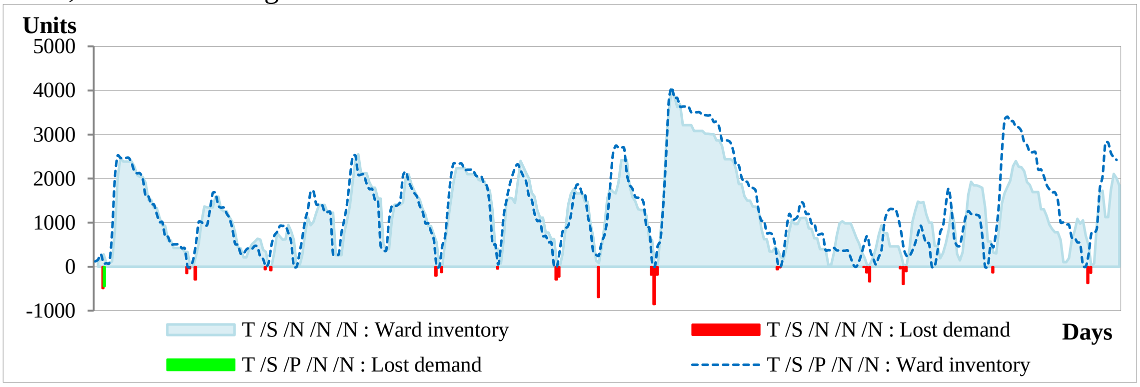
Accumulated differences between the inventory levels in the system with and without the possibility of emergency deliveries from the DC– over and under-ordering effects at the wards:



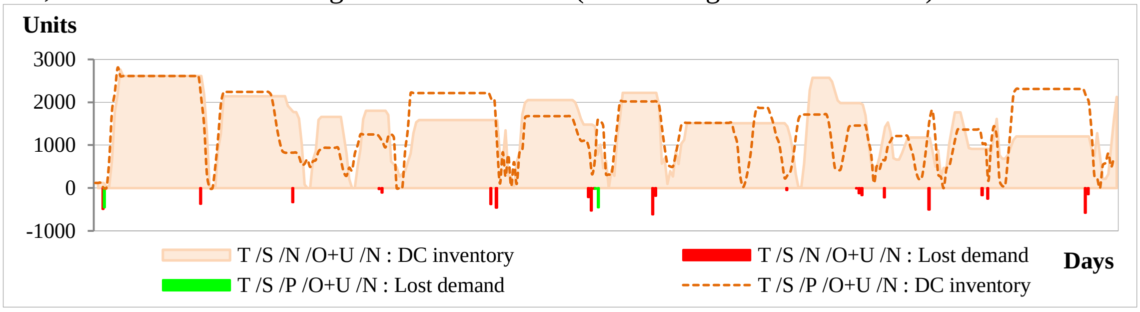
Ward, over and under-ordering effects at the ward (no ordering effects at the DC):



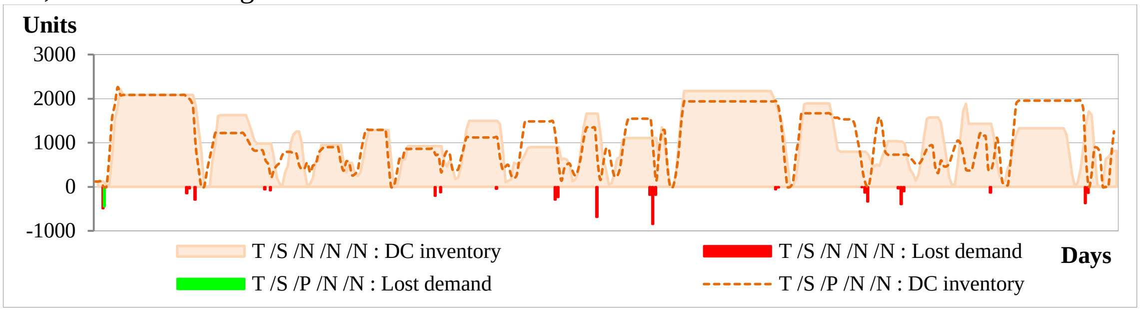
Ward, no over ordering effects:



DC, over and under-ordering effects at the ward (no ordering effects at the DC):

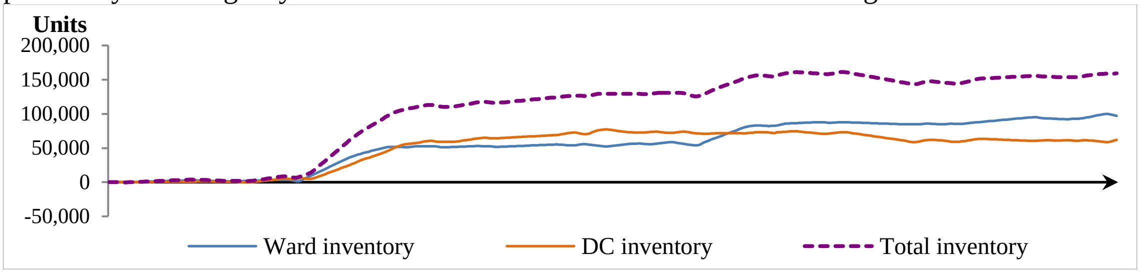


DC, no over ordering effects:

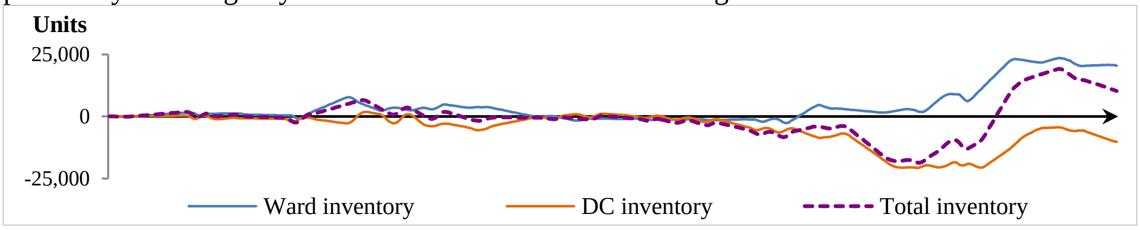


<u>Generated demand 4</u>

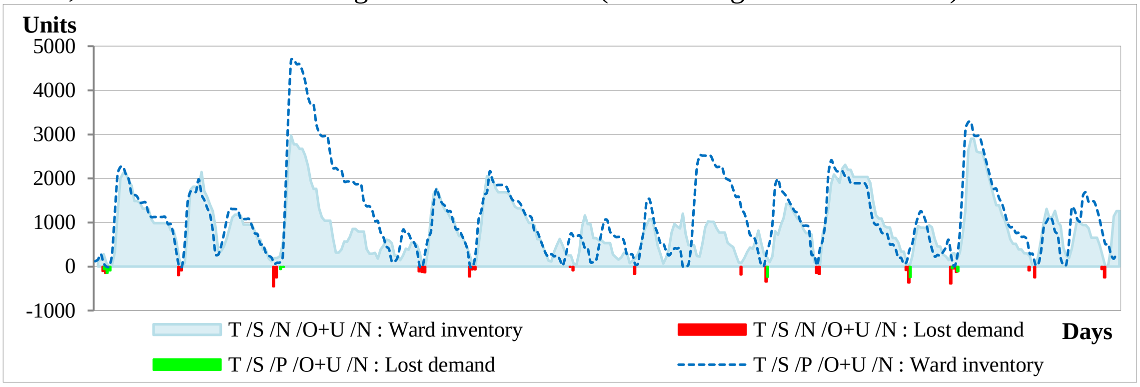
Accumulated differences between the inventory levels in the system with and without the possibility of emergency deliveries from the DC– over and under-ordering effects at the wards:



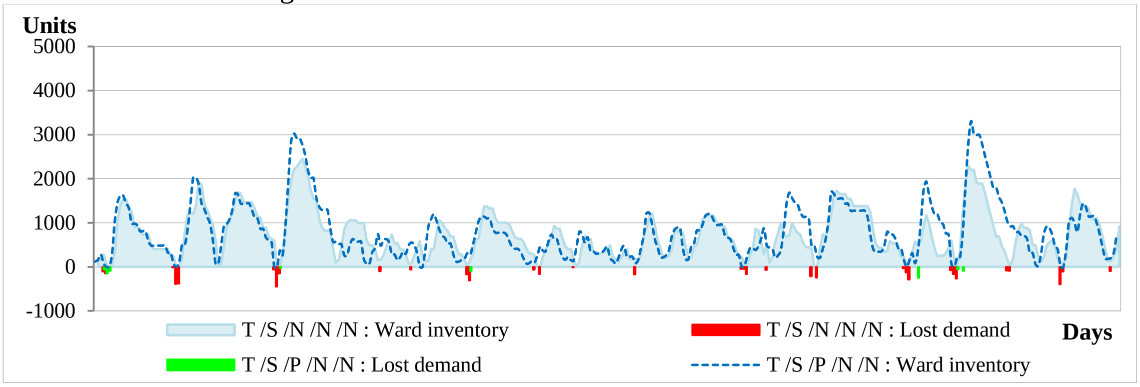
Accumulated differences between the inventory levels in the system with and without the possibility of emergency deliveries from the DC– no ordering effects:



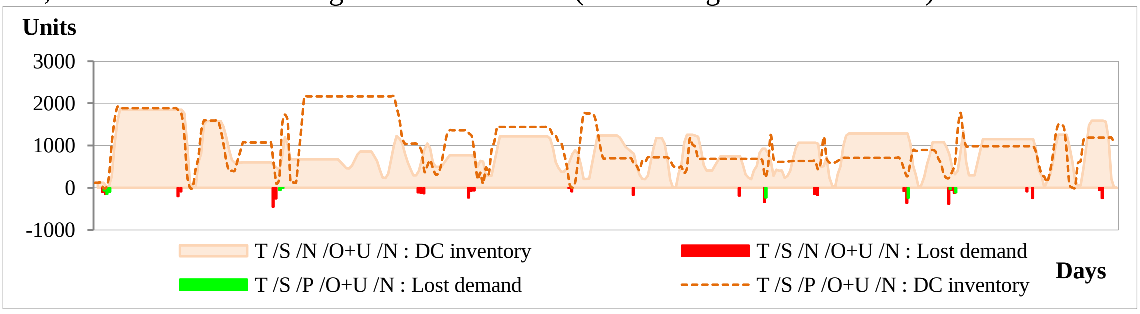
Ward, over and under-ordering effects at the ward (no ordering effects at the DC):



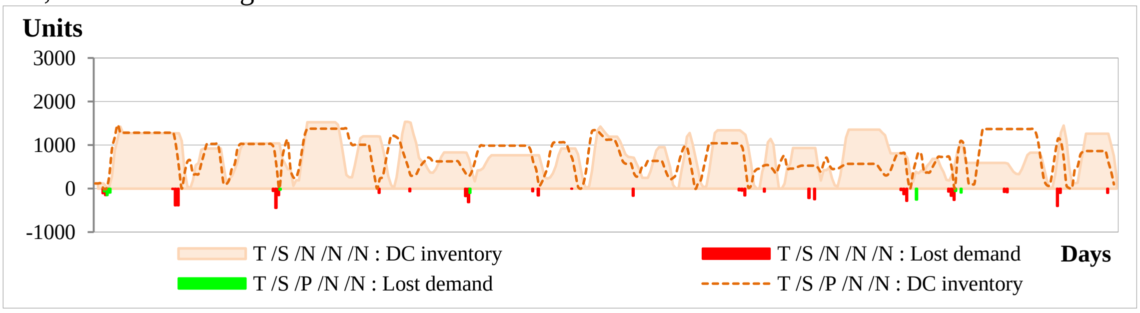
Models with no ordering effects at the ward or at the DC:



DC, over and under-ordering effects at the ward (no ordering effects at the DC):



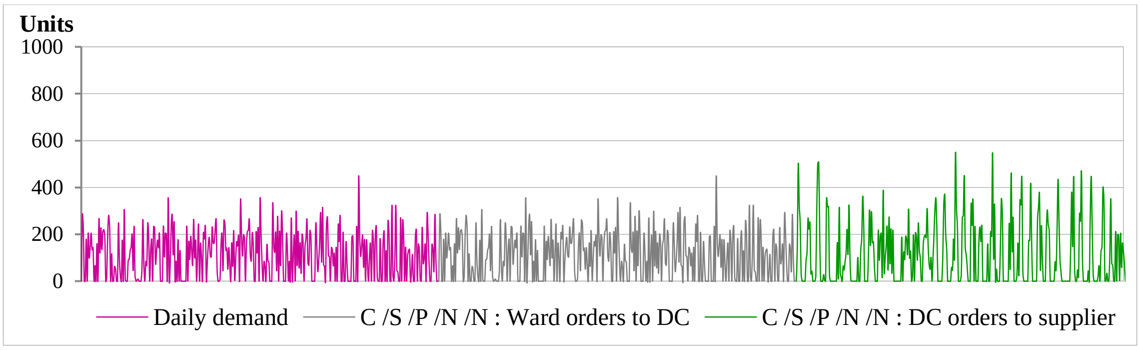
DC, no over ordering effects:



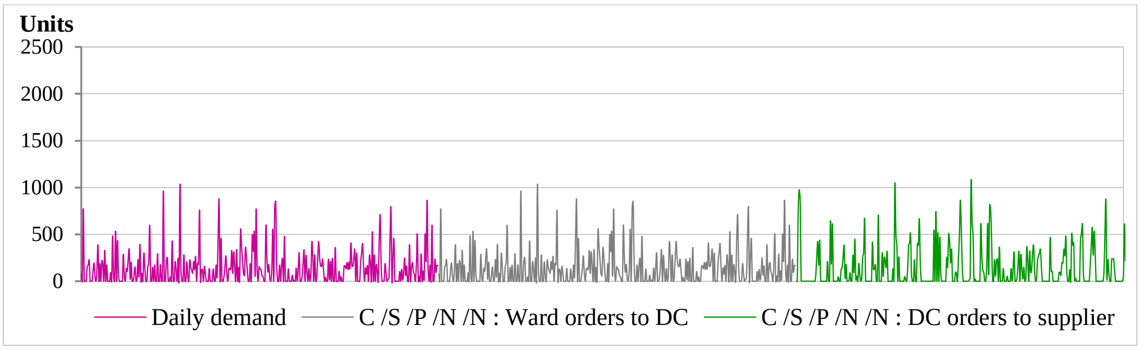
Appendix 4.16 – Centralised control SC with one DC and one ward with inventory visibility (with emergency deliveries from the DC), no ordering effects: demand amplification

Comparison of the demand faced at the various SC echelons (Observation: The comparison of graphs obtained from the simulations of models using different generated demands must be cautious, since the corresponding scales are different; the graphs presented can/should be compared with those presented in Appendix 4.14.)

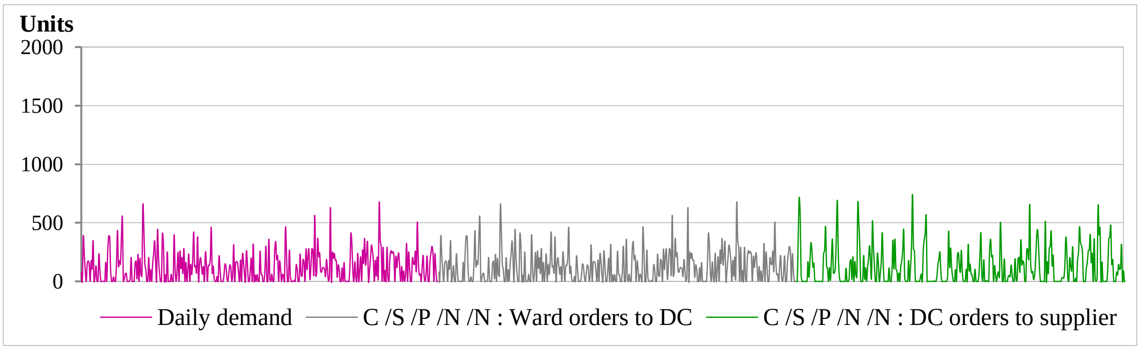
Generated demand 2



Generated demand 3



Generated demand 4

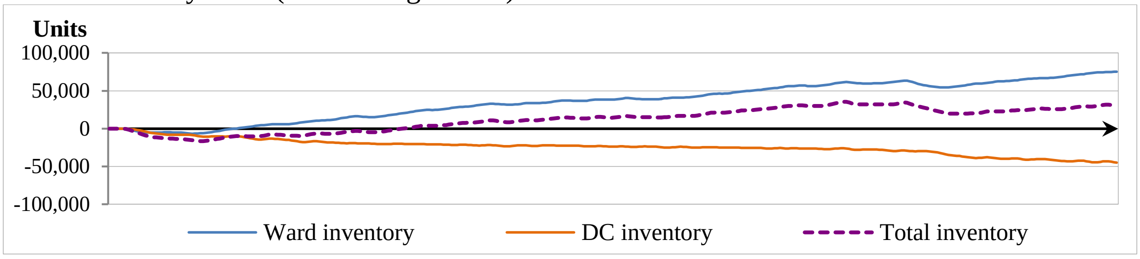


Appendix 4.17 – Centralised control SC with one DC and one ward, inventory visibility (with emergency deliveries from the DC): comparison with traditional SC – inventory levels at the ward and at the DC

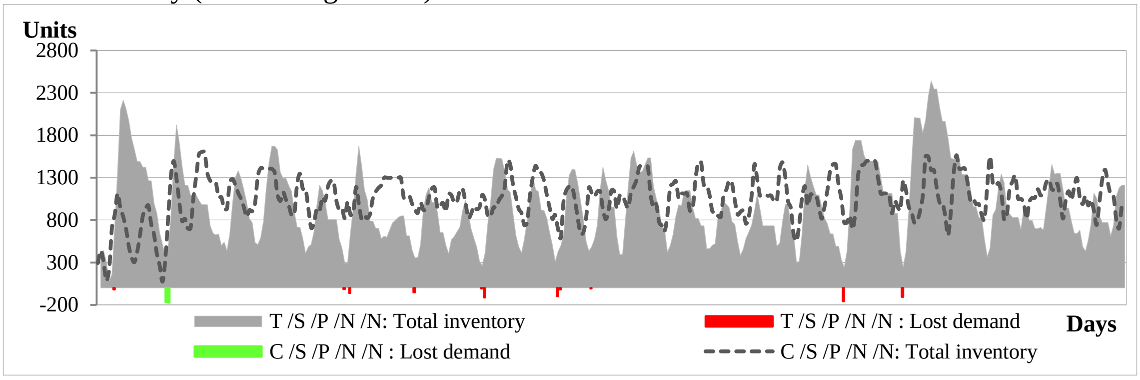
(Observations: Although the lengths of the Y axes of the graphs for each generated demand are different, the scales are the same; differently, the comparison of graphs relative to different generated demands must be cautious, since the corresponding scales are different.)

Generated demand 2

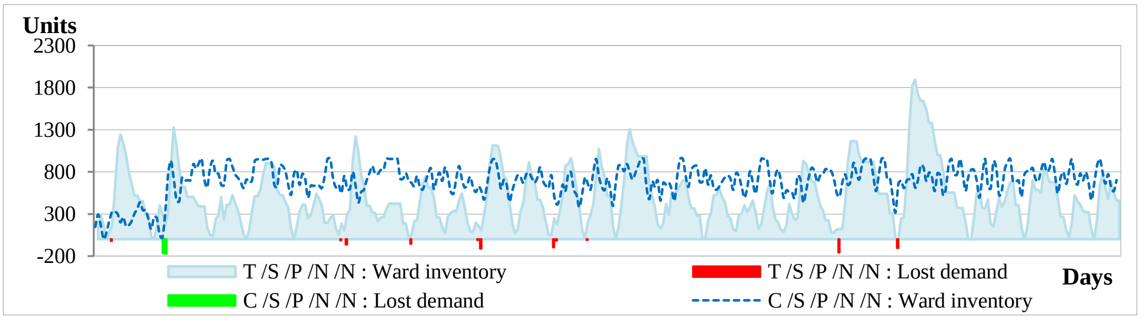
Accumulated differences between the inventory levels in the system between the centralised and the traditional systems (no ordering effects):



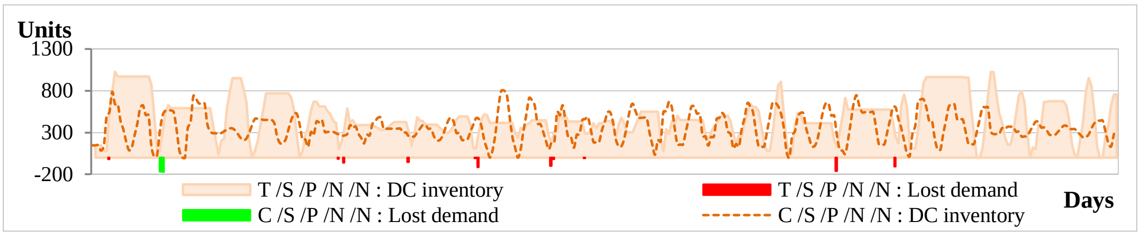
Total inventory (no ordering effects):



Ward inventory (no ordering effects):

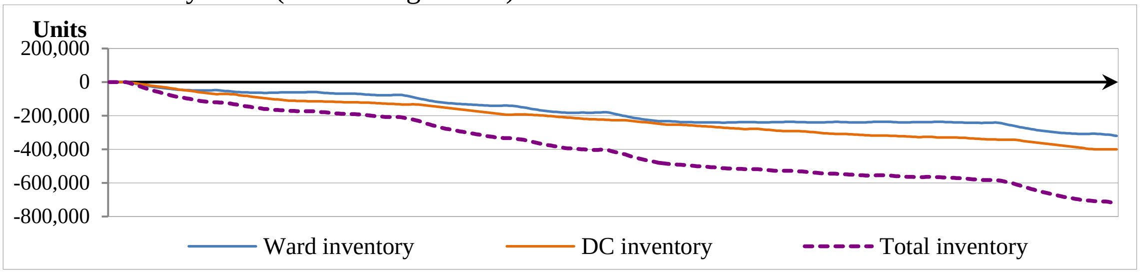


DC inventory (no ordering effects):

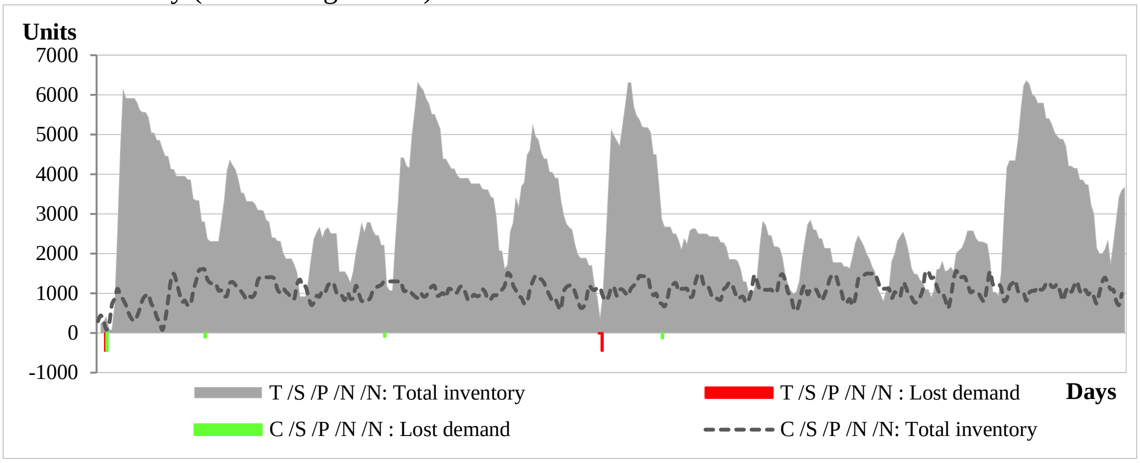


Generated demand 3

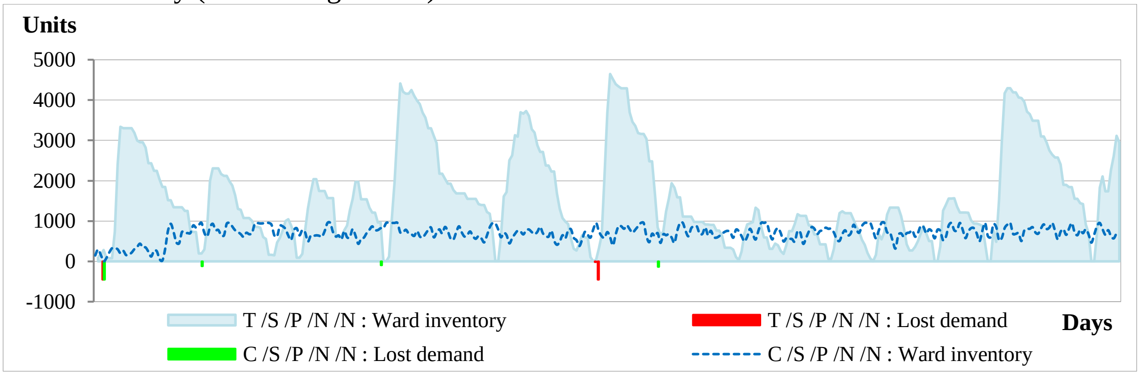
Accumulated differences between the inventory levels in the system between the centralised and the traditional systems (no ordering effects):



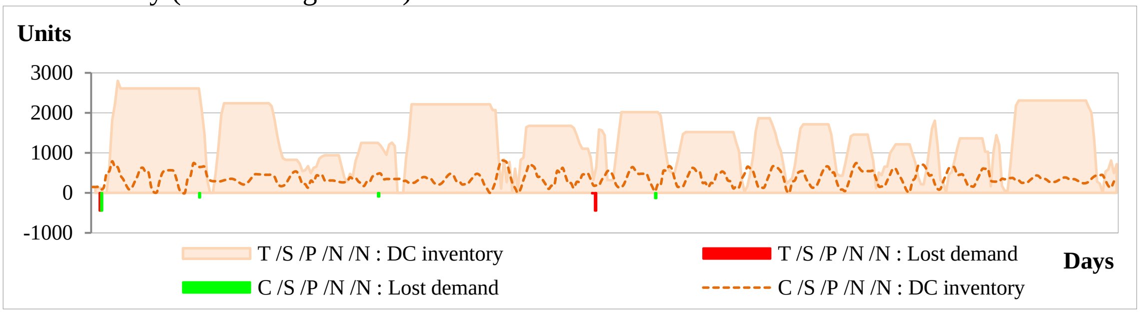
Total inventory (no ordering effects):



Ward inventory (no ordering effects):

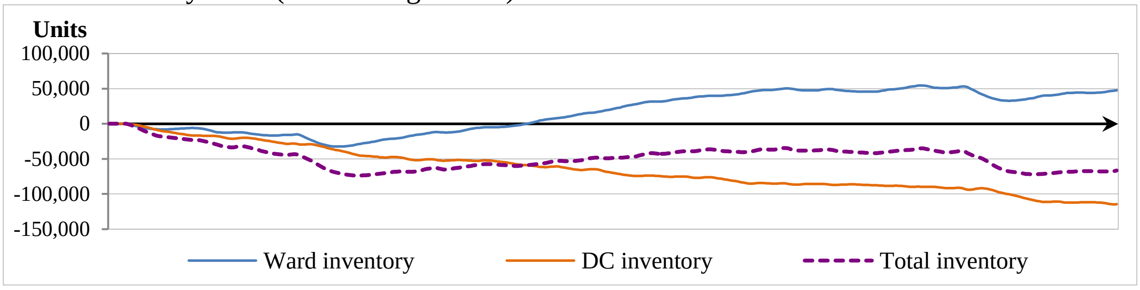


DC inventory (no ordering effects):

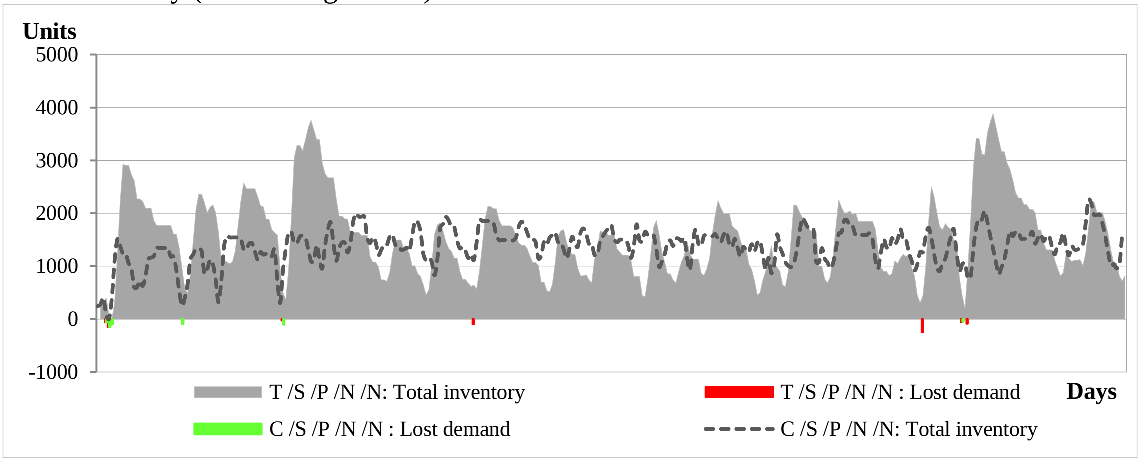


<u>Generated demand 4</u>

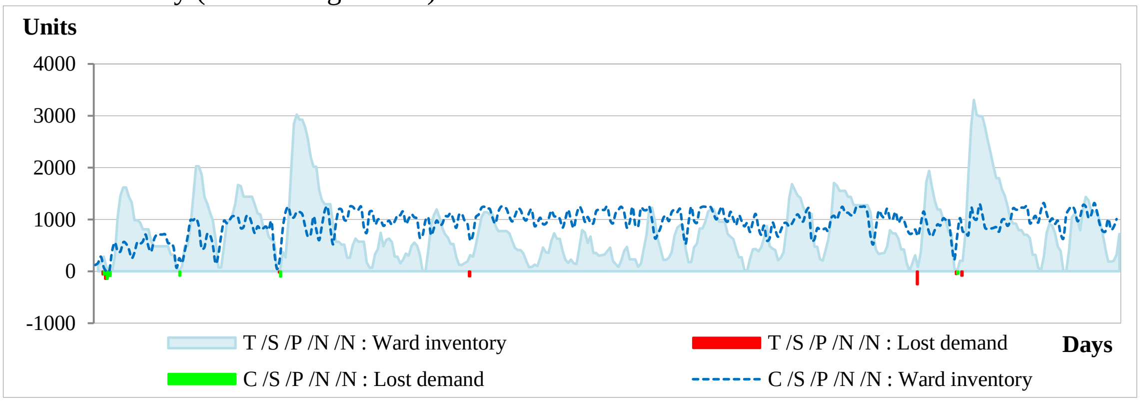
Accumulated differences between the inventory levels in the system between the centralised and the traditional systems (no ordering effects):



Total inventory (no ordering effects):

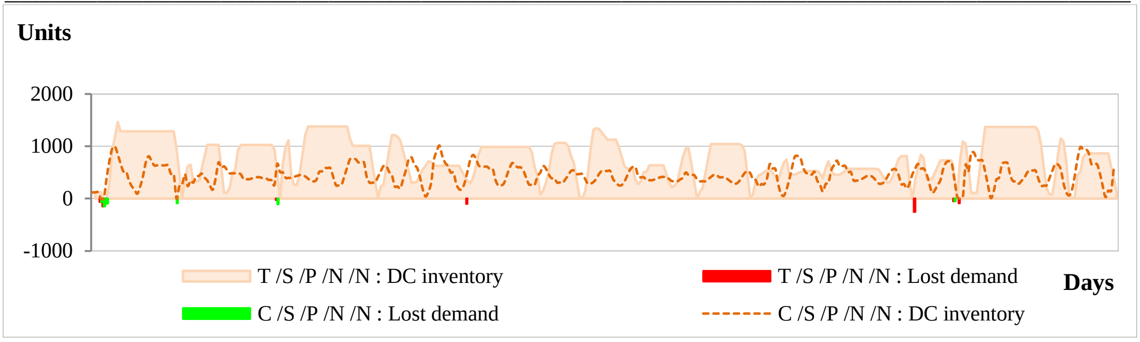


Ward inventory (no ordering effects):



DC inventory (no ordering effects):

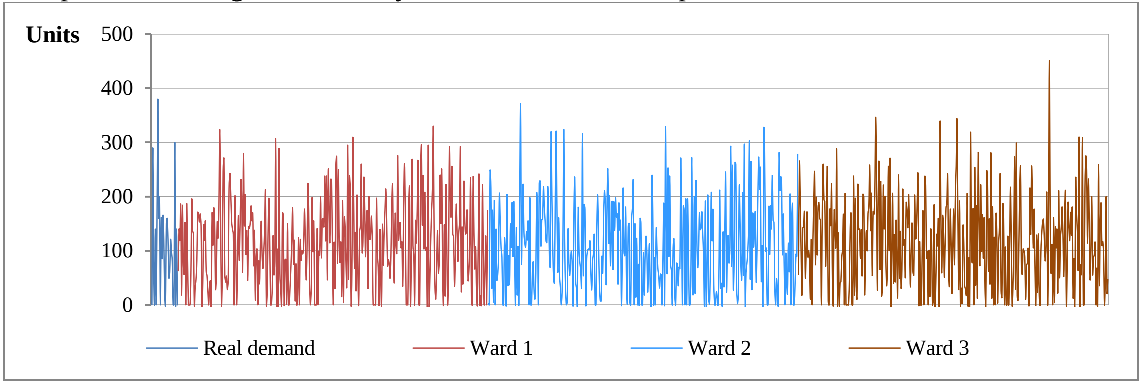
Appendix 4.17 – Centralised control SC with one DC and one ward, inventory visibility (with emergency deliveries from the DC): comparison with traditional SC – inventory levels at the ward and at the DC



Appendix 4.18 – Description of the generated demands for SC models considering wards with identically distributed daily demands

Ward daily demands generated using Process 1

Comparison of the generated daily demands with the sample:

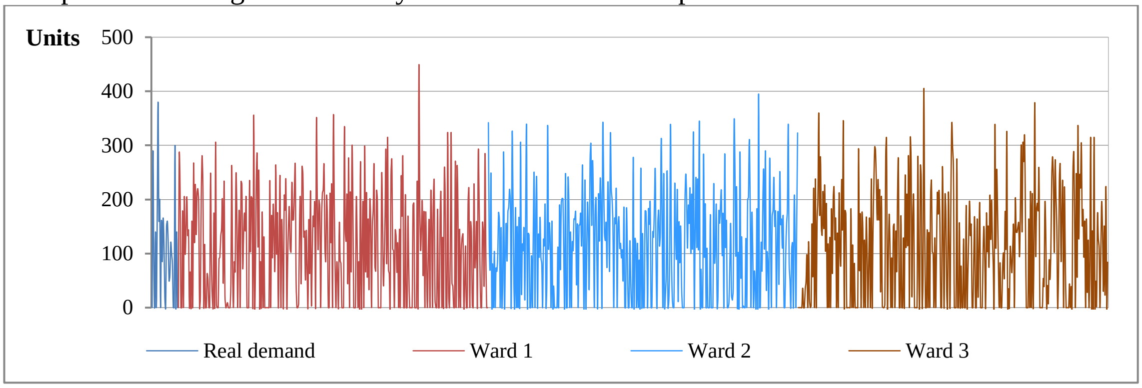


Measures of location and dispersion describing ward 1 daily demand sample and related daily demands generated using Process 1:

	Minimum	1st quartile	Median	3rd quartile	Maximum	Average	Standard deviation
Sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8
Ward 1	0.0	45.0	110.0	168.0	329.0	112.2	81.5
Ward 2	0.0	31.5	96.0	171.3	369.0	106.8	84.4
Ward 3/ ER	0.0	40.0	112.5	176.5	451.0	115.8	85.4

Ward daily demands generated using Process 2

Comparison of the generated daily demands with the sample:

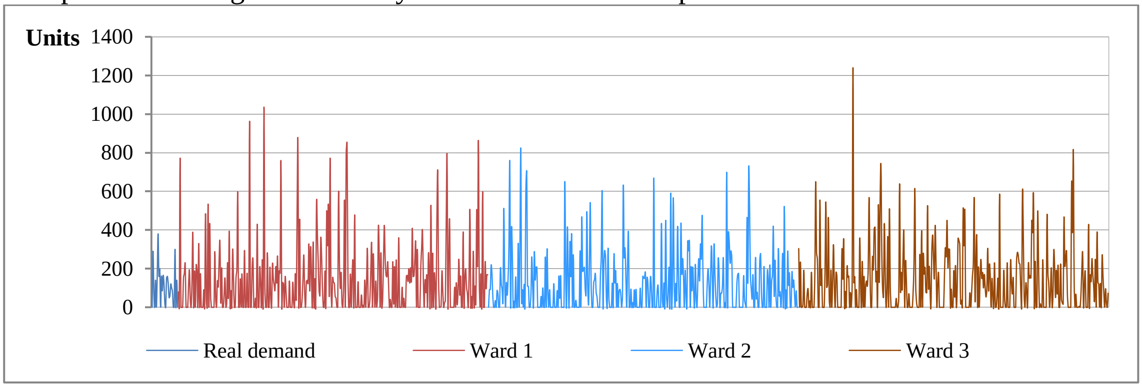


Measures of location and dispersion describing ward 1 daily demand sample and related daily demands generated using Process 2:

	Minimum	1st quartile	Median	3rd quartile	Maximum	Average	Standard deviation
Sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8
Ward 1	0.0	0.0	103.0	193.0	447.0	110.3	99.2
Ward 2	0.0	0.0	114.0	180.0	395.0	115.0	96.5
Ward 3/ ER	0.0	0.0	105.0	180.8	405.0	110.1	101.1

<u>Ward daily demands generated using Process 3</u>

Comparison of the generated daily demands with the sample:

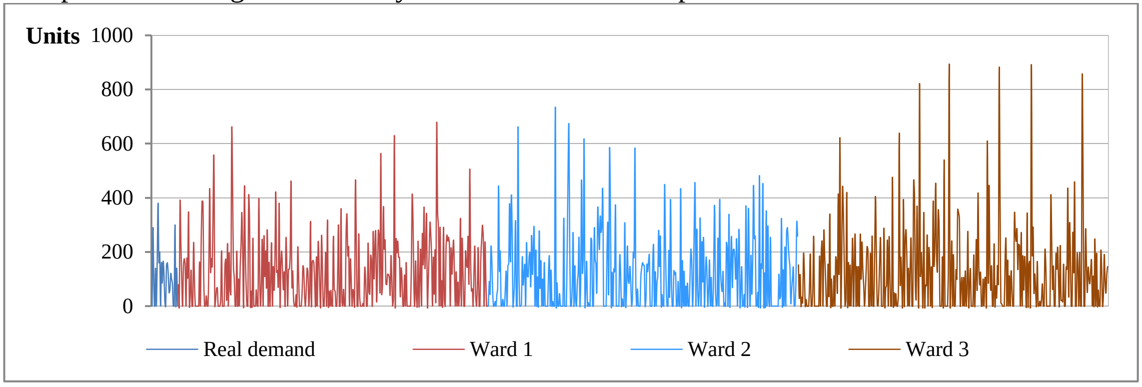


Measures of location and dispersion describing ward 1 daily demand sample and related daily demands generated using Process 3:

	Minimum	1st quartile	Median	3rd quartile	Maximum	Average	Standard deviation
Sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8
Ward 1	0.0	0.0	87.0	204.0	1036.0	141.8	186.8
Ward 2	0.0	0.0	79.5	182.8	822.0	125.4	159.6
Ward 3/ ER	0.0	0.0	89.0	222.0	1240.0	140.9	172.0

Ward daily demands generated using Process 4

Comparison of the generated daily demands with the sample:



Measures of location and dispersion describing ward 1 daily demand sample and related daily demands generated using Process 3:

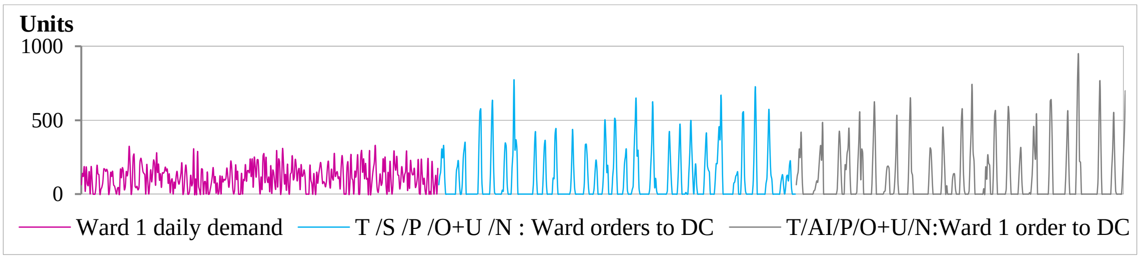
	Minimum	1st quartile	Median	3rd quartile	Maximum	Average	Standard deviation
Sample	0.0	0.0	100.0	160.0	380.0	104.5	96.8
Ward 1	0.0	0.0	94.0	203.0	672.0	123.4	131.4
Ward 2	0.0	0.0	83.5	182.0	735.0	118.1	138.5
Ward 3/ ER	0.0	0.0	83.5	190.0	894.0	125.3	156.6

Appendix 4.19 – Traditional SC with one DC and three identical wards (and emergency deliveries from the DC) – daily demands faced at the various SC echelons

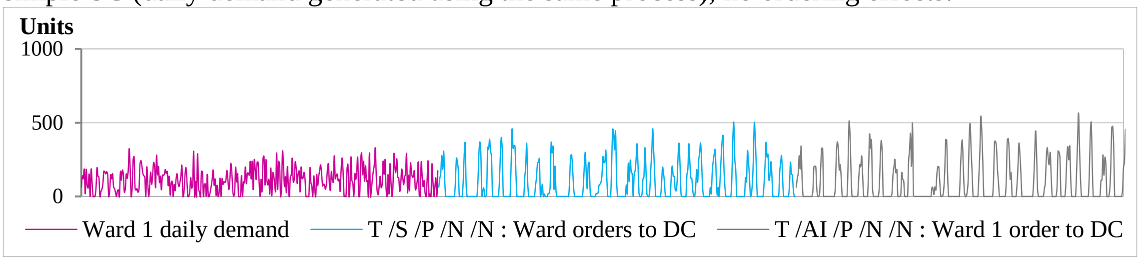
(Observations: Although the lengths of the Y axes of the graphs for each generated demand are different, the scales are the same; differently, the comparison of graphs relative to different generated demands must be cautious, since the corresponding scales are sometimes different.)

<u>Daily demand of the wards generated using Process 1</u>

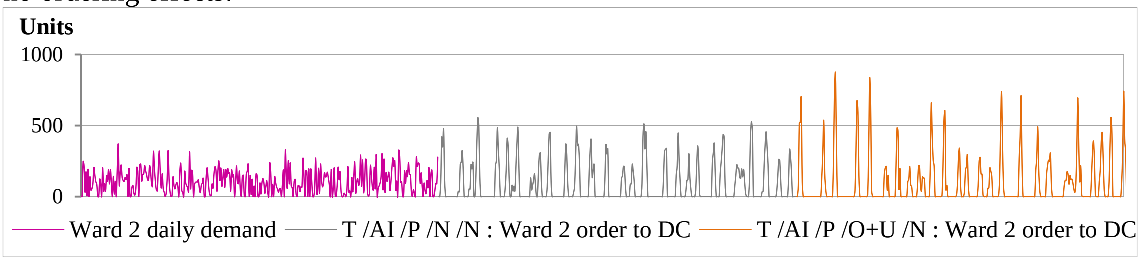
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), over and under-ordering effects at the ward:



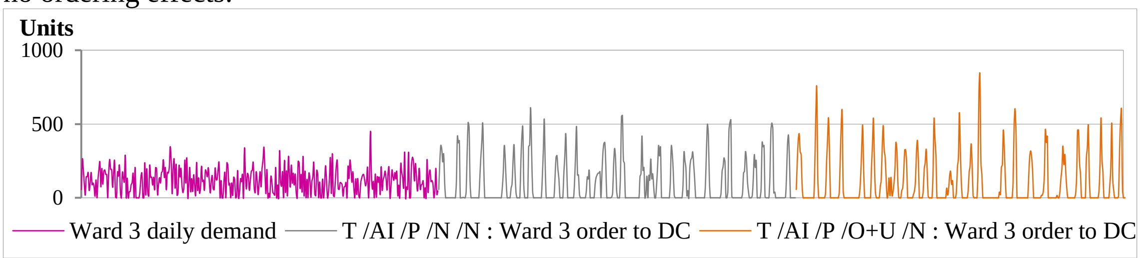
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), no ordering effects:



Ward 2 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



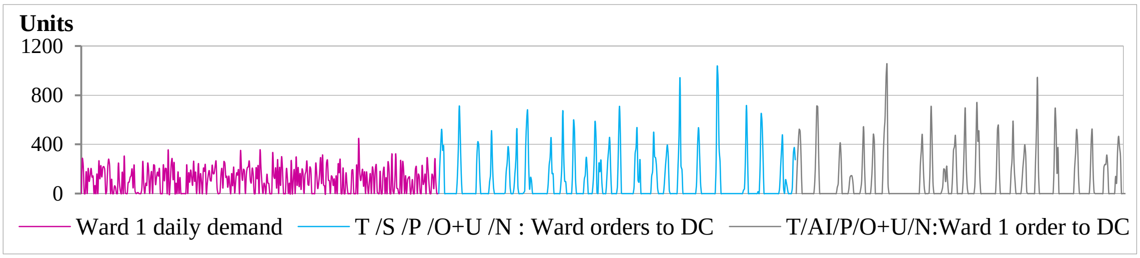
Ward 3 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



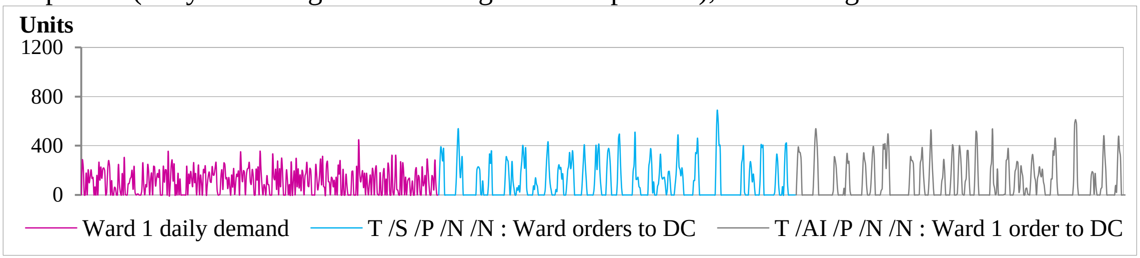
Graphs presented in section 4.6: Ward 1 – demand faced and orders to DC and Demand faced by the DC (sum of ward orders) and orders by the DC to the supplier – over and under-ordering effects at the ward versus no ordering effects.

Daily demand of the wards generated using Process 2

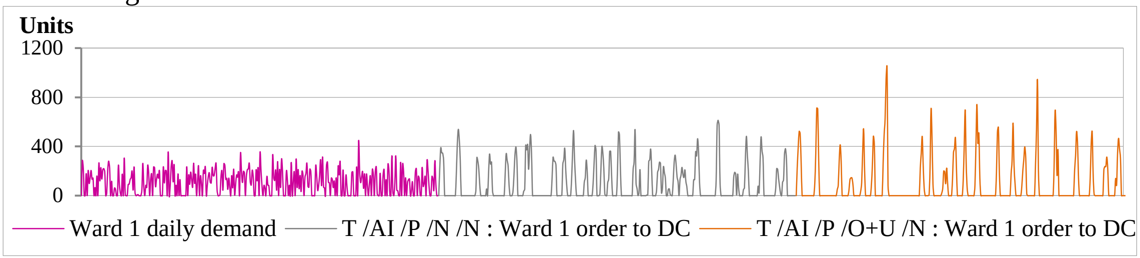
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), over and under-ordering effects at the ward:



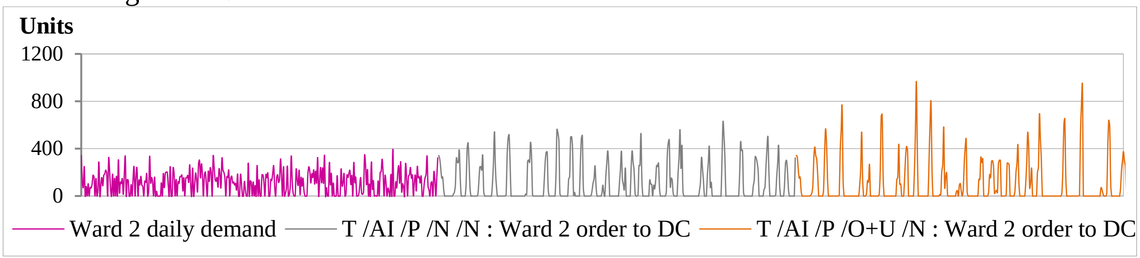
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), no ordering effects:



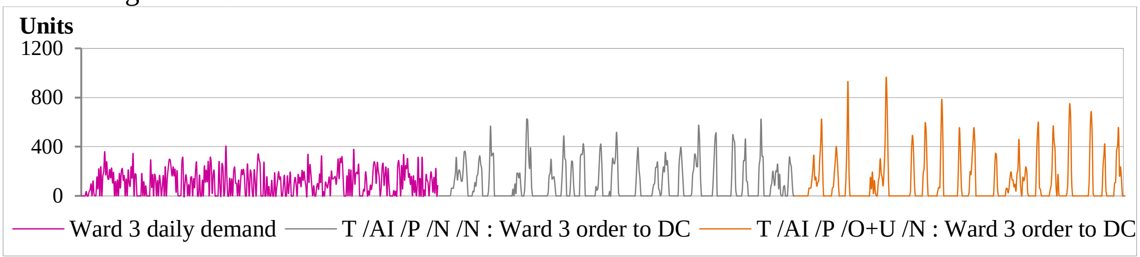
Ward 1 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



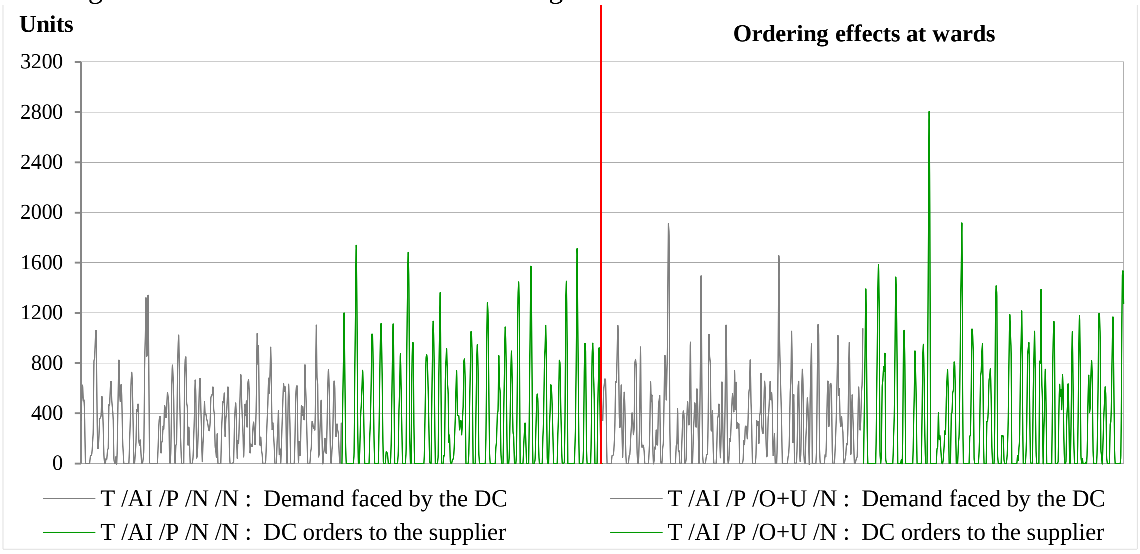
Ward 2 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



Ward 3 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:

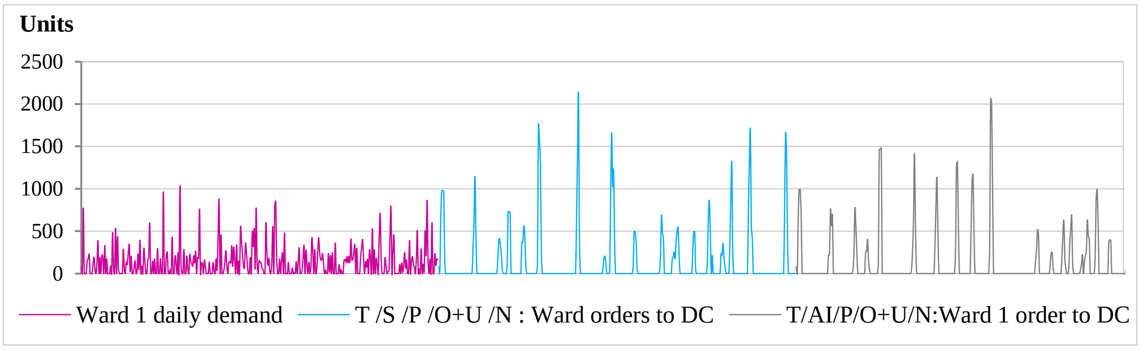


Demand faced by the DC (sum of ward orders) and orders by the DC to the supplier – no ordering effects versus over and under-ordering effects at the ward:

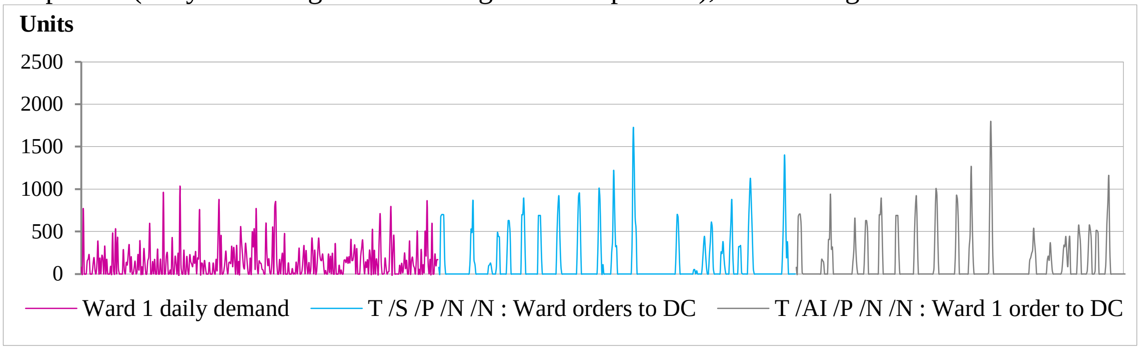


<u>Daily demand of the wards generated using Process 3</u>

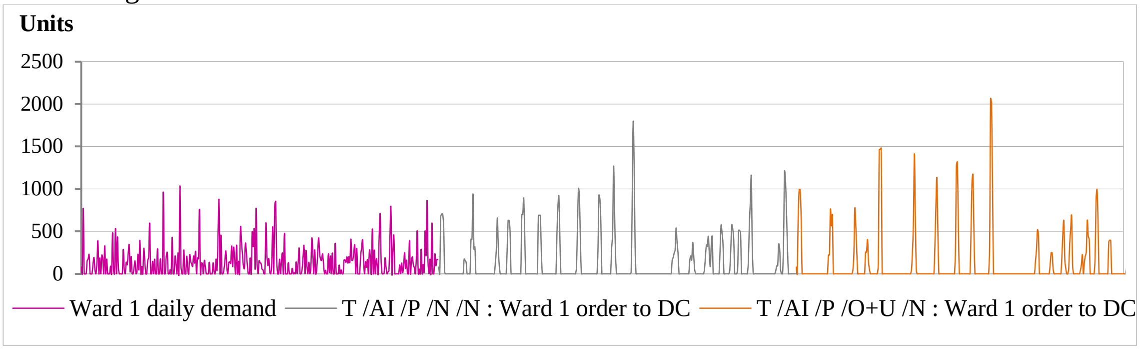
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), over and under-ordering effects at the ward:



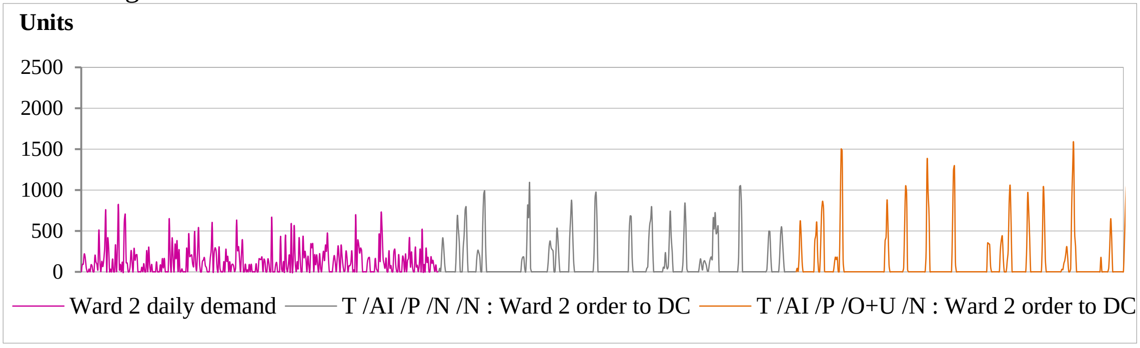
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), no ordering effects:



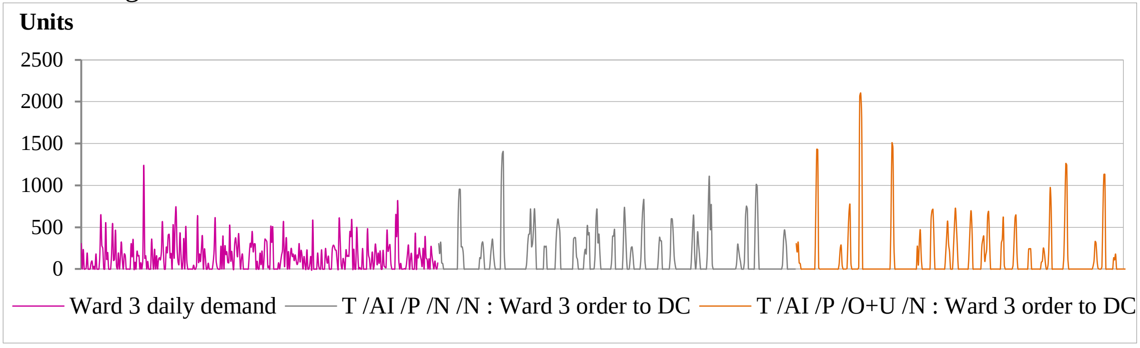
Ward 1 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



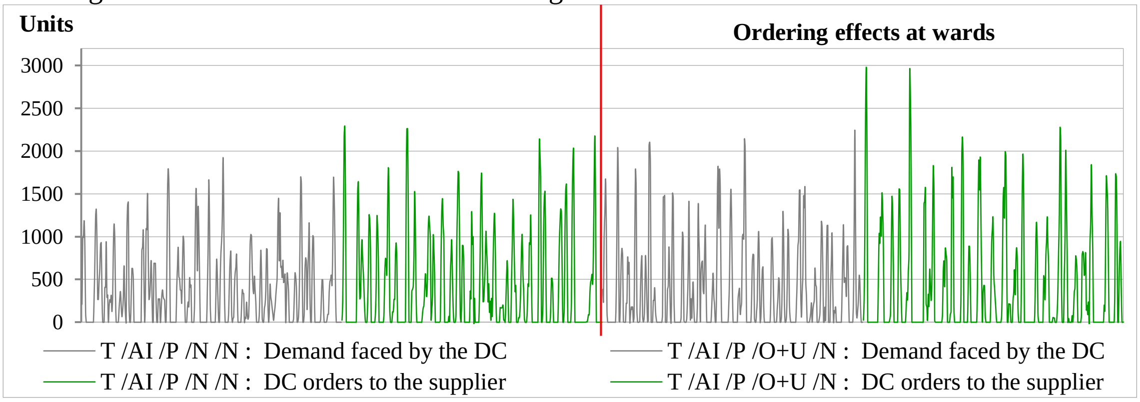
Ward 2 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



Ward 3 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:

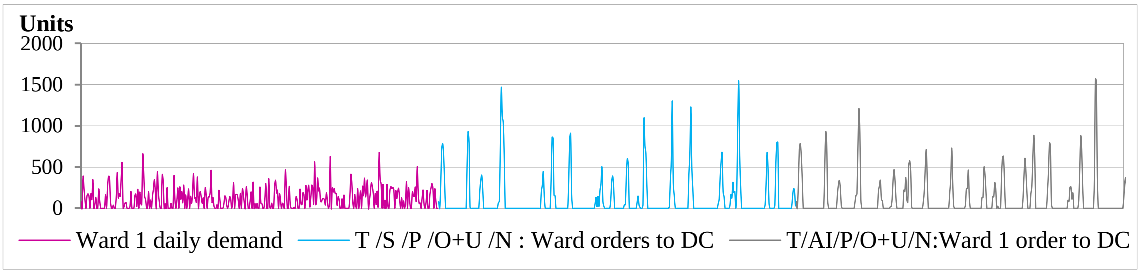


Demand faced by the DC (sum of ward orders) and orders by the DC to the supplier – no ordering effects versus over and under-ordering effects at the ward:

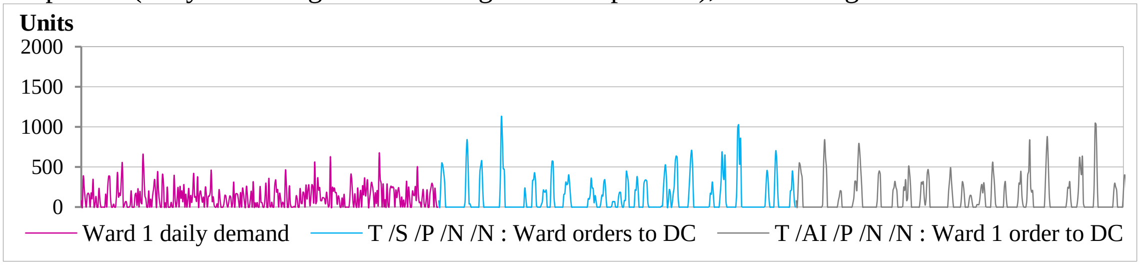


Daily demand of the wards generated using Process 4

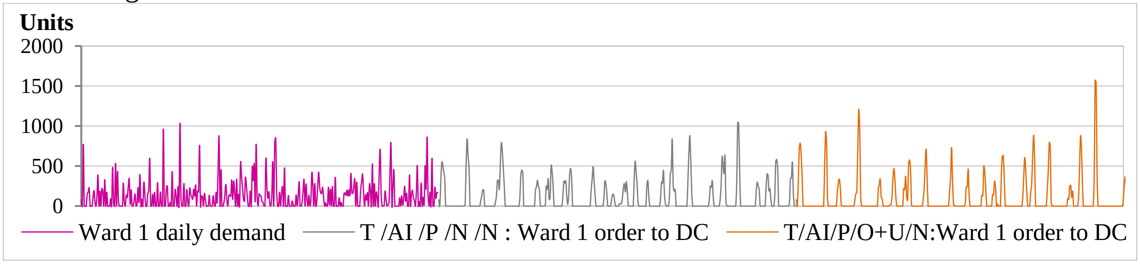
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), over and under-ordering effects at the ward:



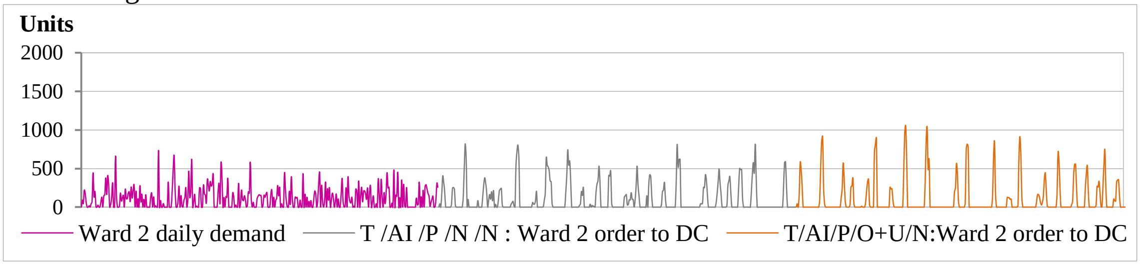
Ward 1 orders to DC: traditional quasi-arborescent (N identical wards) SC versus traditional simple SC (daily demand generated using the same process), no ordering effects:



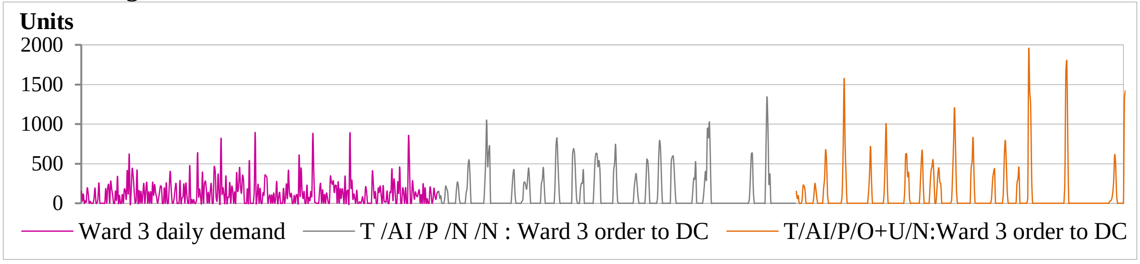
Ward 1 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



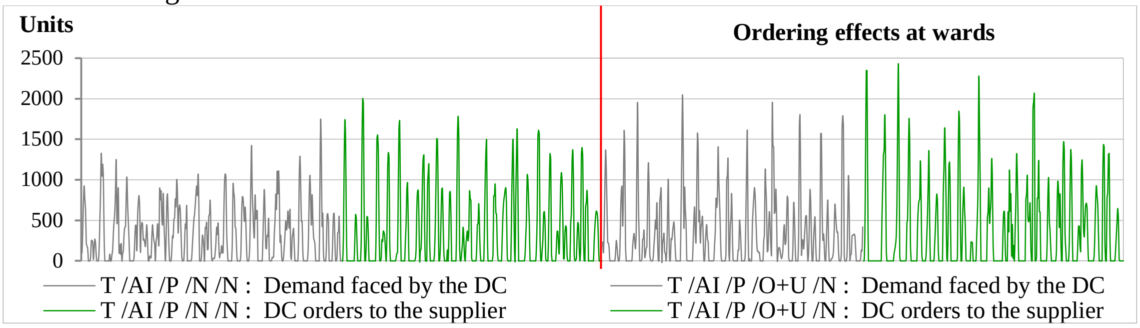
Ward 2 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



Ward 3 – demand faced and orders to DC – over and under-ordering effects at the ward versus no ordering effects:



Demand faced by the DC (sum of ward orders) and orders by the DC to the supplier – over and under-ordering effects at the ward:

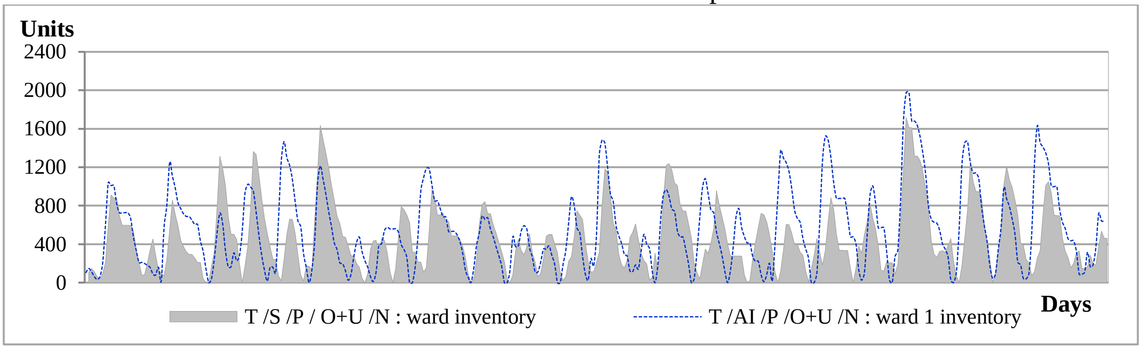


Appendix 4.20 – Traditional SC with one DC and three identical wards (and emergency deliveries from the DC) – inventory level evolution at the various SC echelons

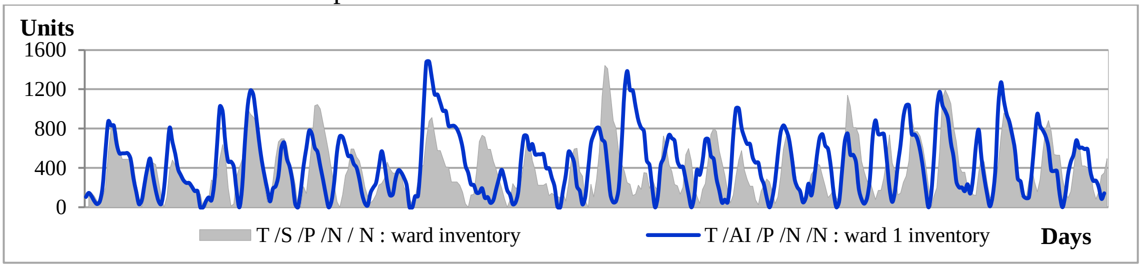
(Observations: Although the lengths of the Y axes of the graphs for each generated demand are different, the scales are the same; differently, the comparison of graphs relative to different generated demands must be cautious, since the corresponding scales are sometimes different.)

Daily demand of the wards generated using Process 1 (the remaining graphs are presented in subsection 4.6.2)

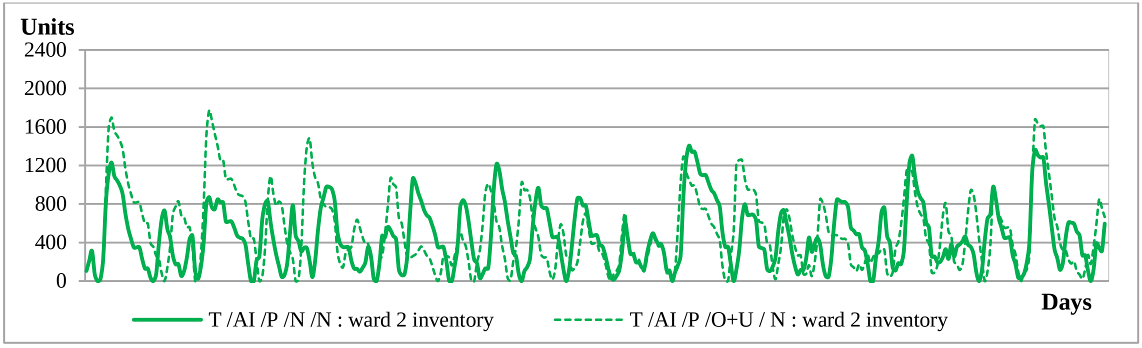
Ward 1 inventory level, over and under-ordering effects at the ward – traditional quasi-arborescent SC with 3 identical wards versus traditional simple serial SC:



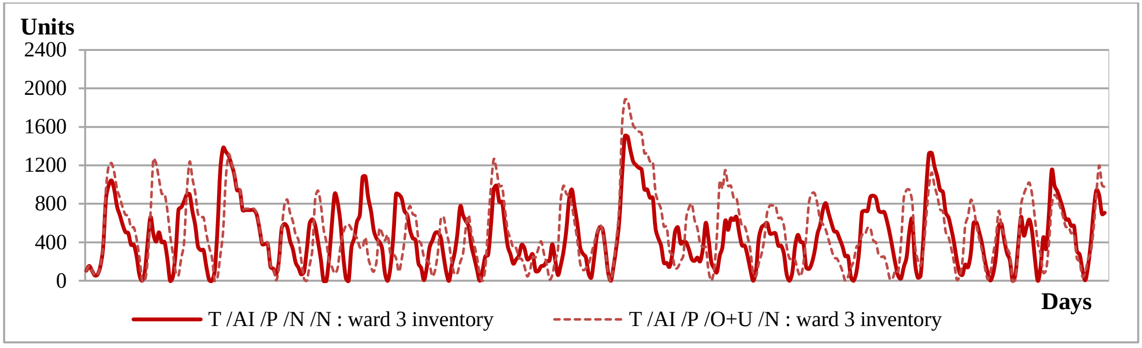
Ward 1 inventory level, no ordering effects – traditional quasi-arborescent SC with 3 identical wards versus traditional simple serial SC:



Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:

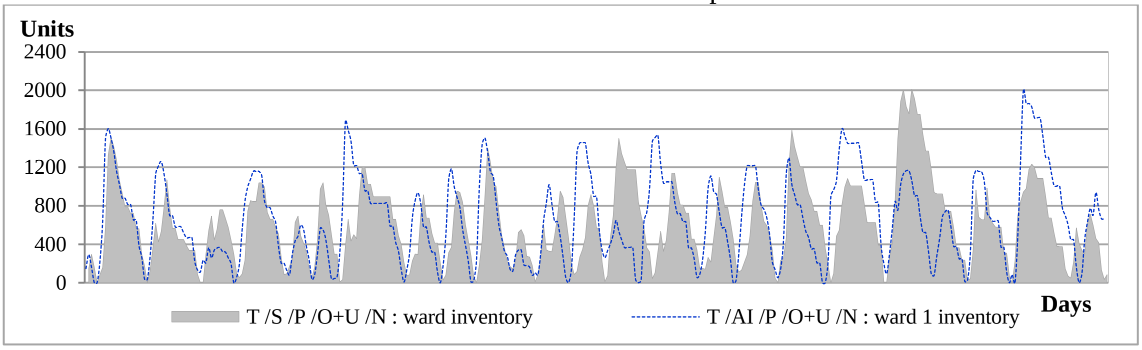


Ward 3 inventory level – over and under-ordering effects at the wards versus no ordering effects:

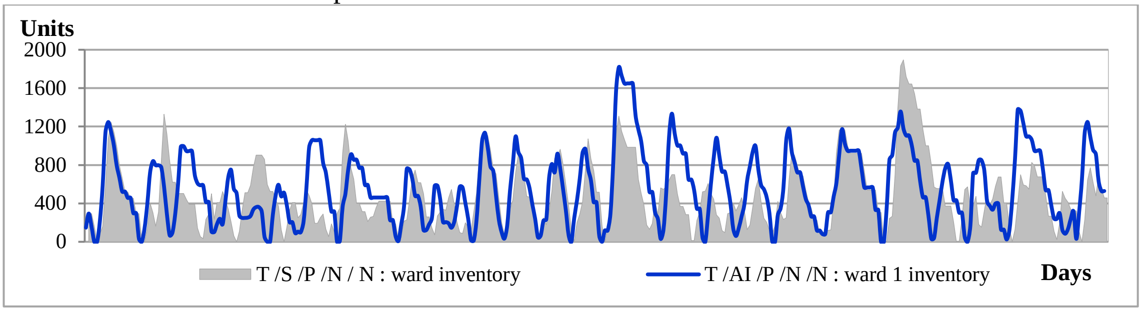


<u>Daily demand of the wards generated using Process 2</u>

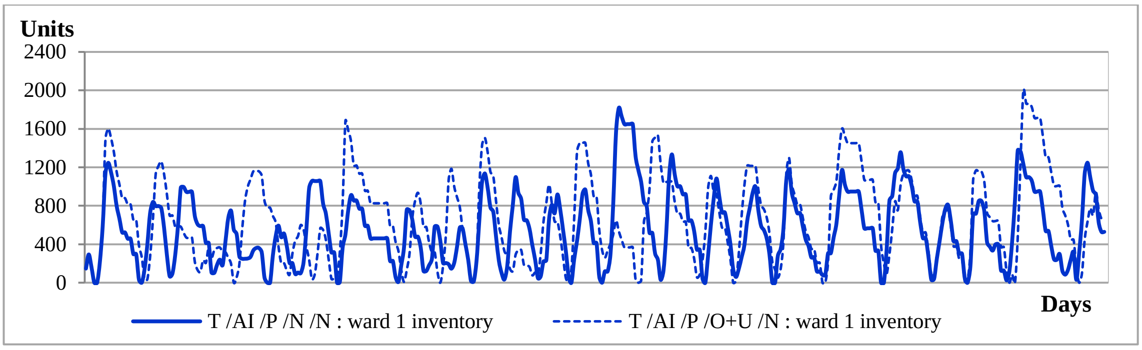
Ward 1 inventory level, over and under-ordering effects at the ward – traditional quasi-arborescent SC with 3 identical wards versus traditional simple serial SC:



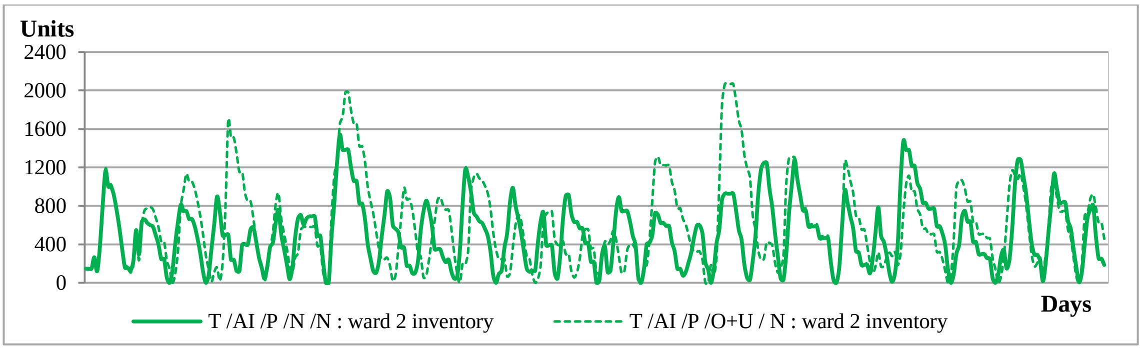
Ward 1 inventory level, no ordering effects – traditional quasi-arborescent SC with 3 identical wards versus traditional simple serial SC:



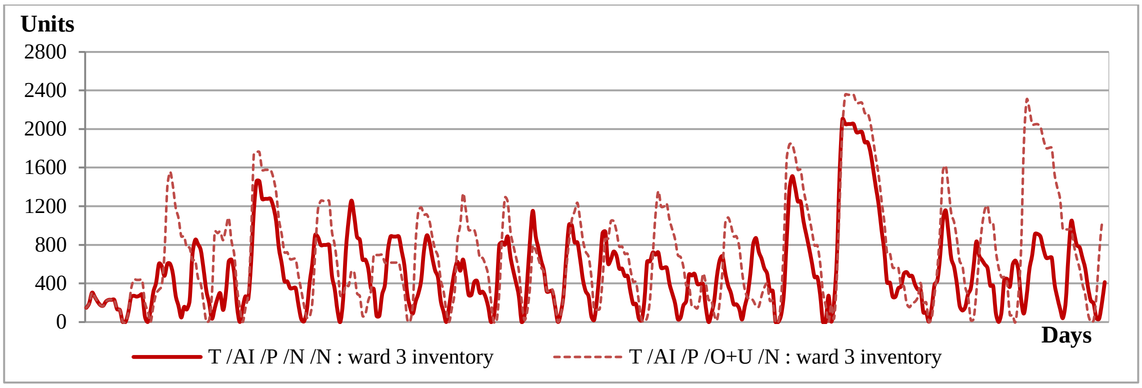
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



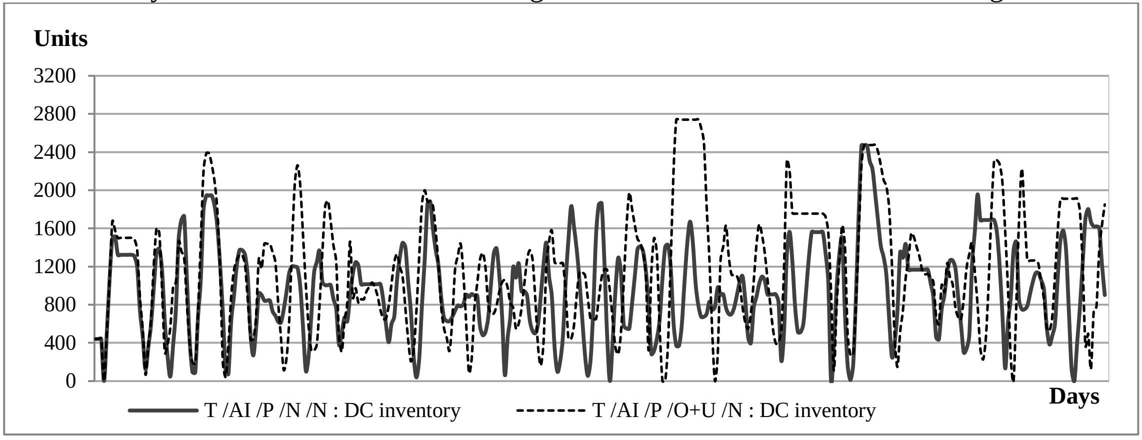
Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:



Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:

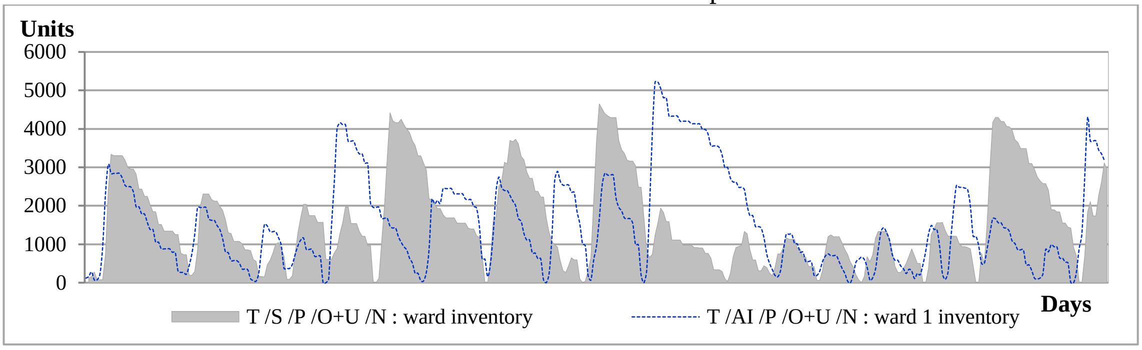


DC inventory level – over and under-ordering effects at the wards versus no ordering effects:

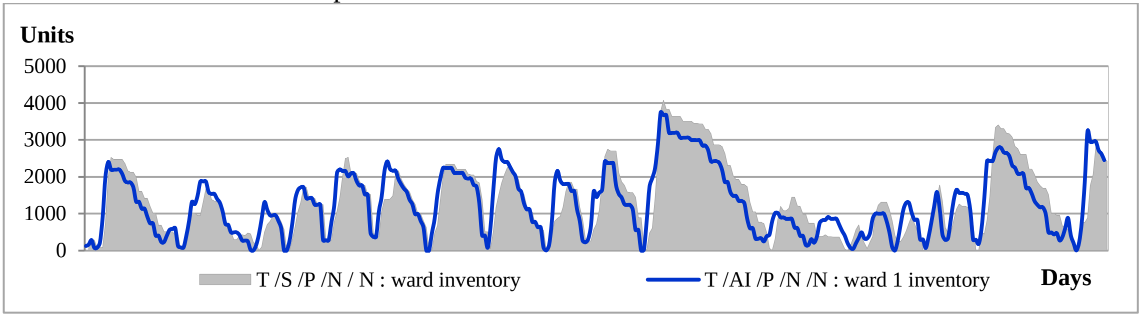


Daily demand of the wards generated using Process 3

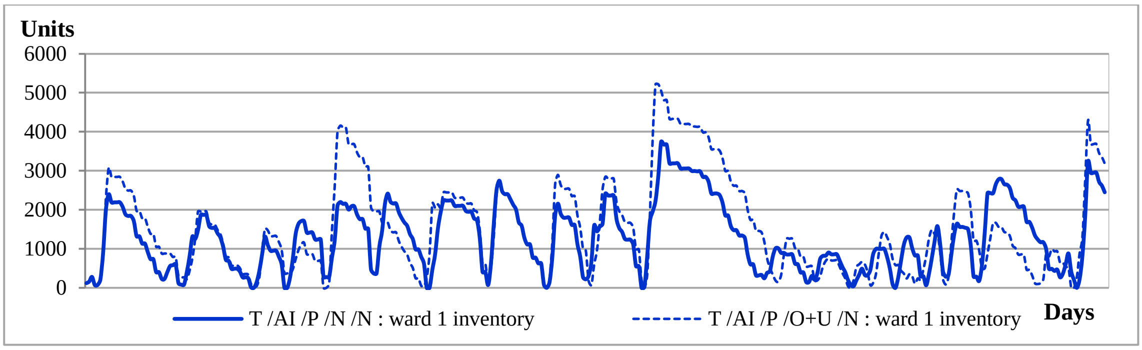
Ward 1 inventory level, over and under-ordering effects at the ward – traditional quasi-arborescent SC with 3 identical wards versus traditional simple serial SC:



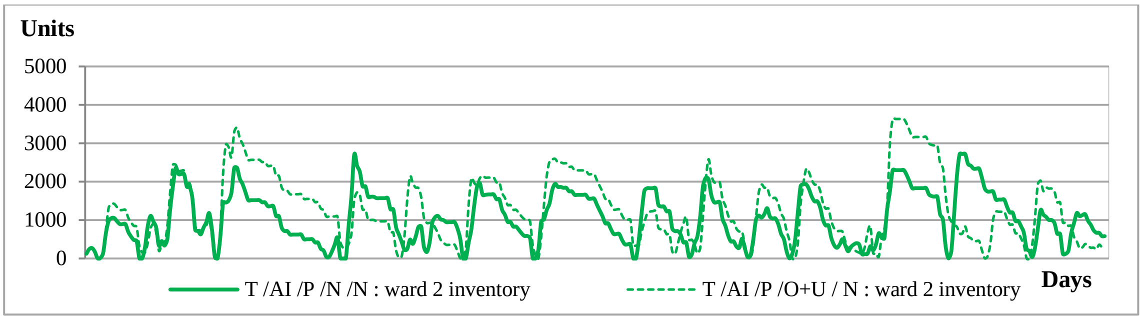
Ward 1 inventory level, no ordering effects – traditional quasi-arborescent SC with 3 identical wards versus traditional simple serial SC:



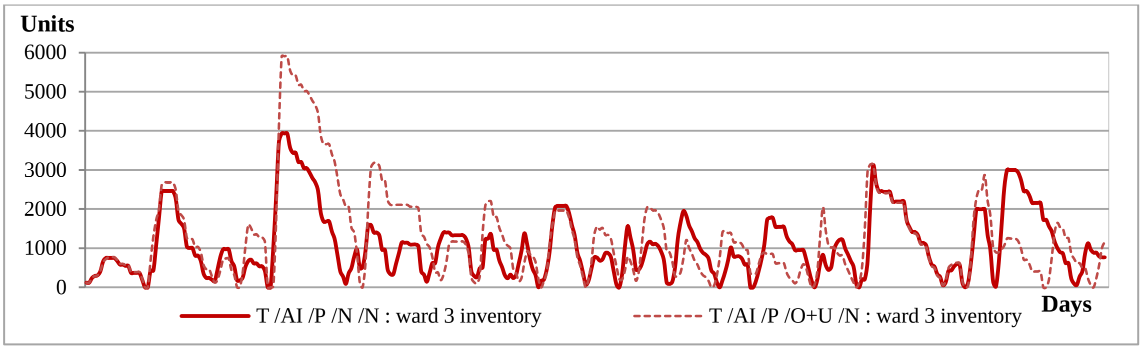
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



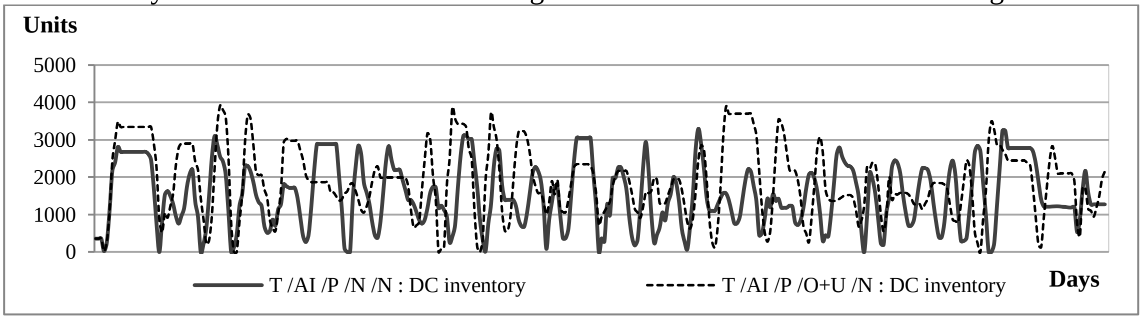
Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:



Ward 3 inventory level – over and under-ordering effects at the wards versus no ordering effects:

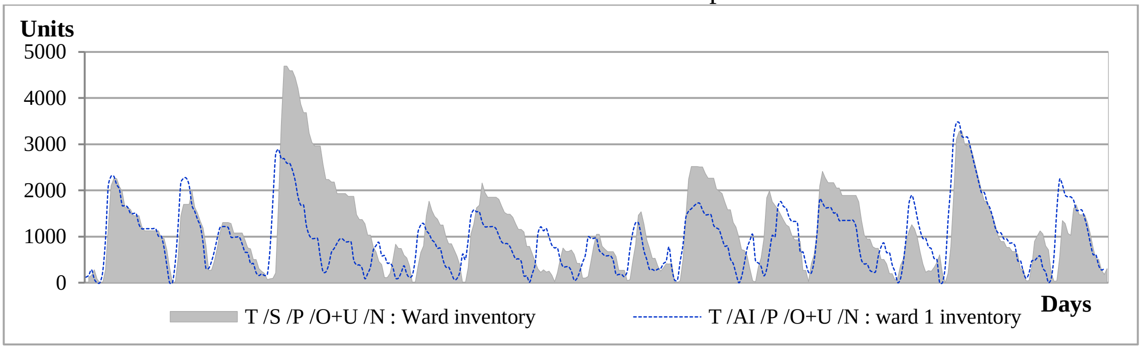


DC inventory level – over and under-ordering effects at the wards versus no ordering effects:

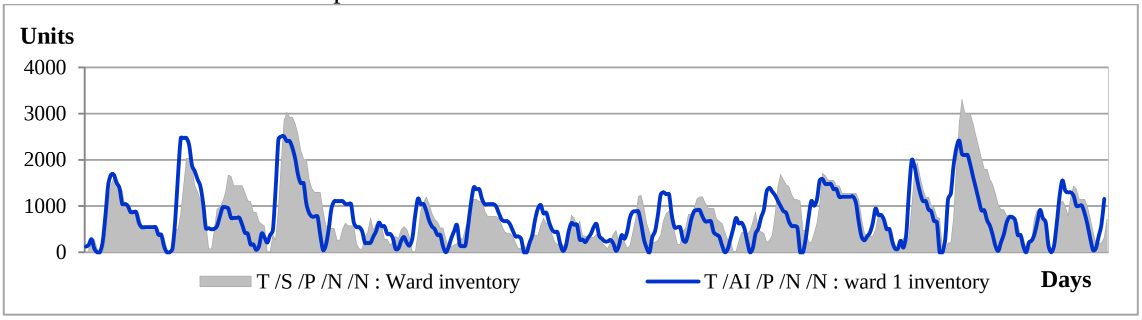


Daily demand of the wards generated using Process 4

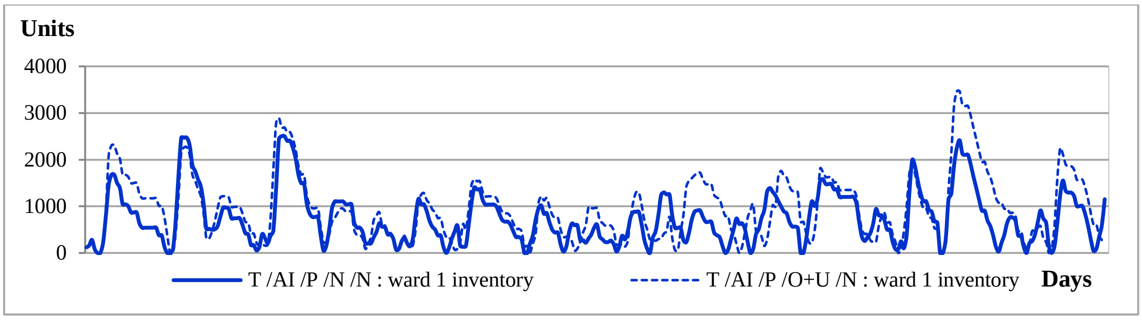
Ward 1 inventory level, over and under-ordering effects at the ward – traditional quasi-arborescent SC with 3 identical wards versus traditional simple SC:



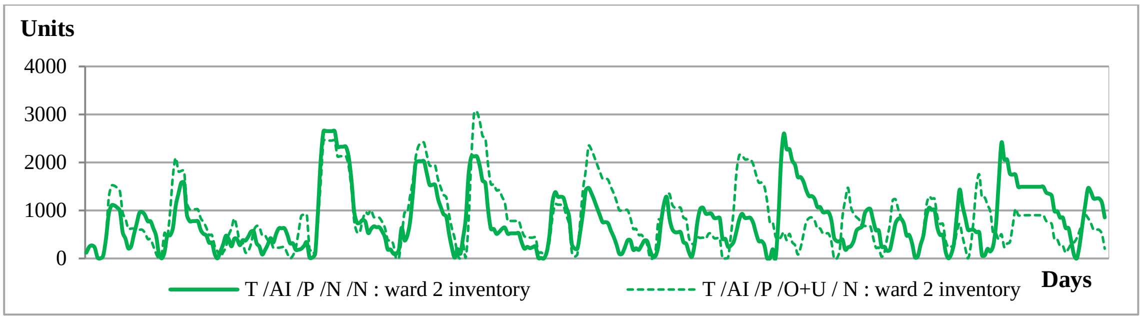
Ward 1 inventory level, no ordering effects – traditional quasi-arborescent SC with 3 identical wards versus traditional simple SC:



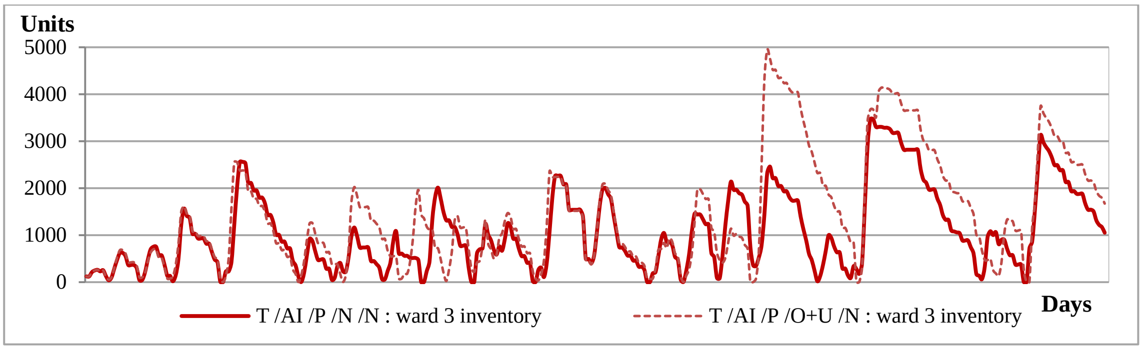
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



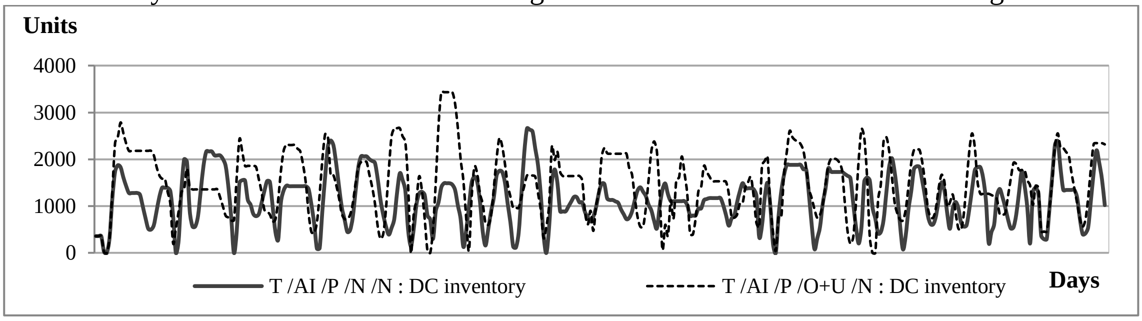
Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:



Ward 3 inventory level – over and under-ordering effects at the wards versus no ordering effects:



DC inventory level – over and under-ordering effects at the wards versus no ordering effects:

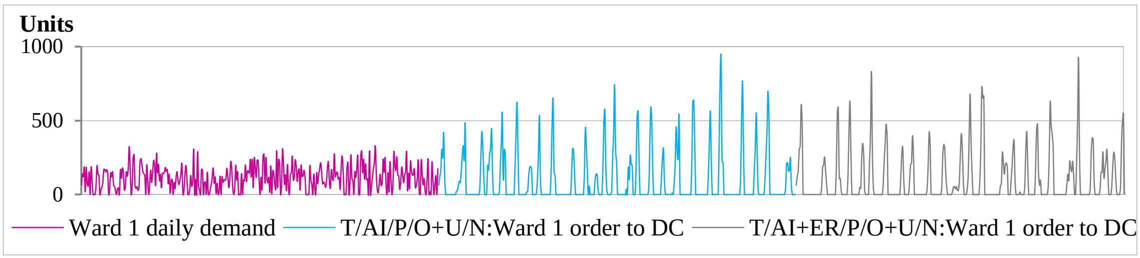


Appendix 4.21 – Traditional SC with one DC, and three identical wards, one of which an ER (and emergency deliveries from the DC) – daily demands faced at the various SC echelons

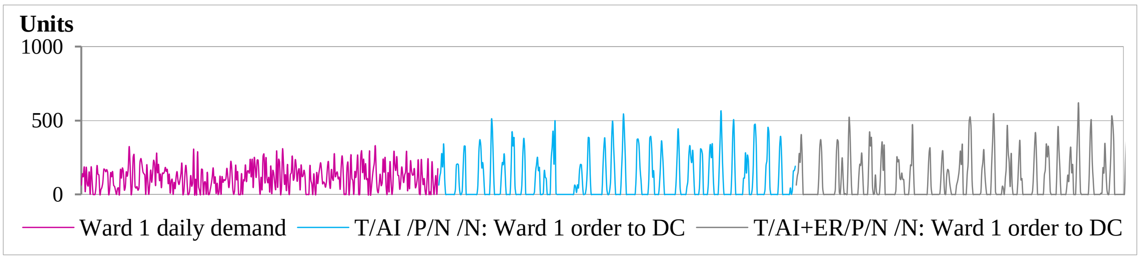
(Observations: Although the lengths of the Y axes of the graphs for each generated demand are different, the scales are the same; differently, the comparison of graphs relative to different generated demands must be cautious, since the corresponding scales are sometimes different.)

Daily demand of the wards generated using Process 1

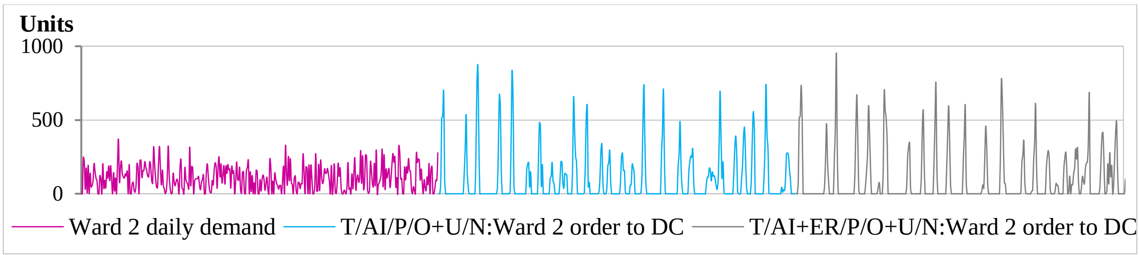
Ward 1, over and under-ordering effects at the wards - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



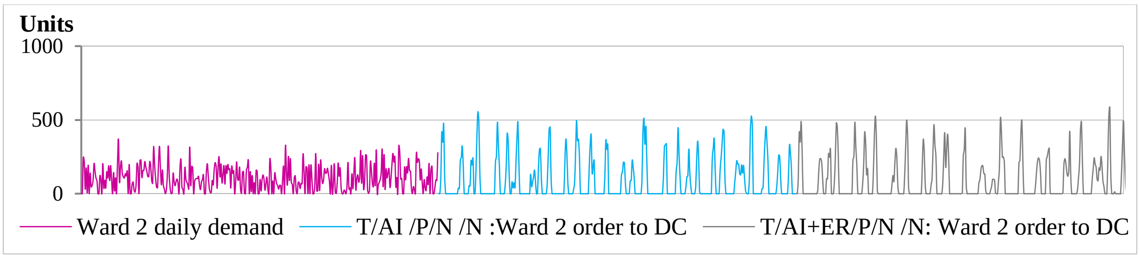
Ward 1, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



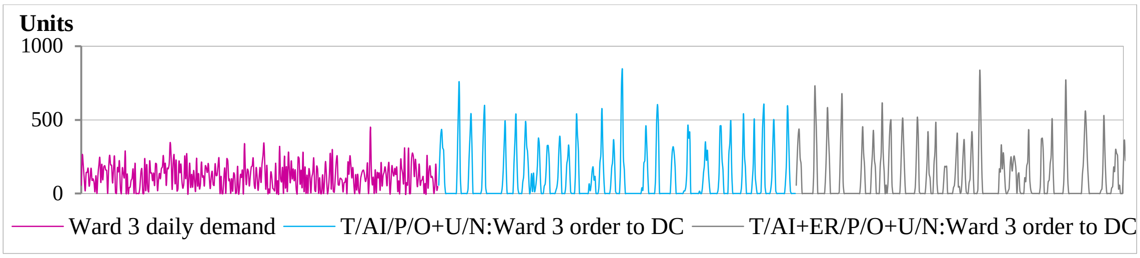
Ward 2, over and under-ordering effects at the wards - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



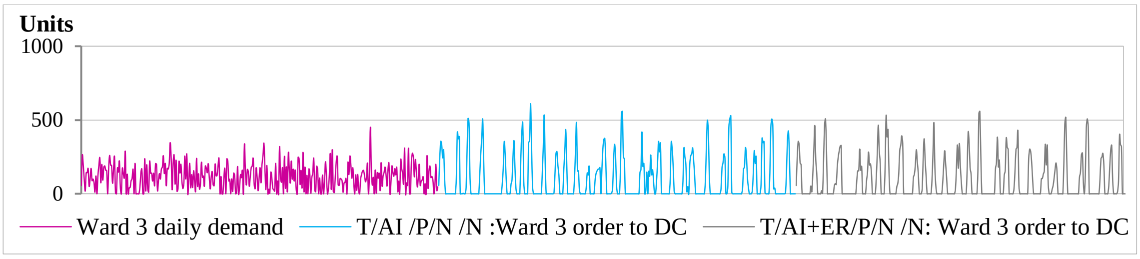
Ward 2, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



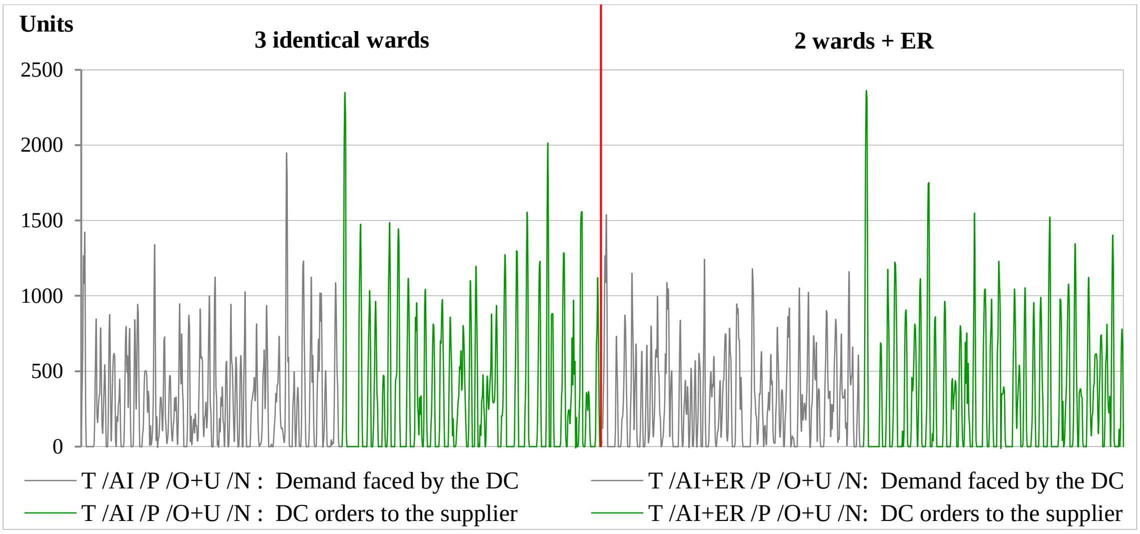
ER (ward 3), over and under-ordering effects at the wards - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



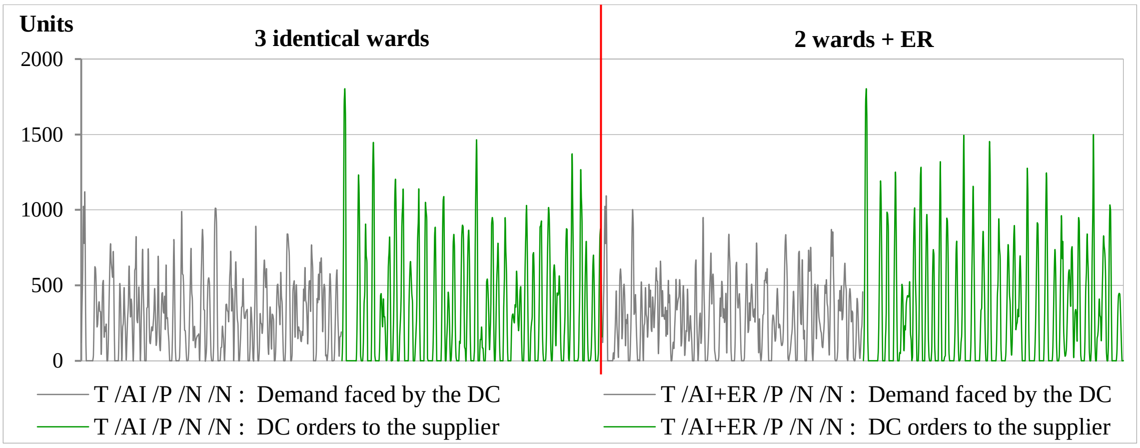
ER (ward 3), no ordering effects - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



DC, over and under-ordering effects at the wards - SC with with 3 identical wards versus SC with an ER and 2 identical wards:

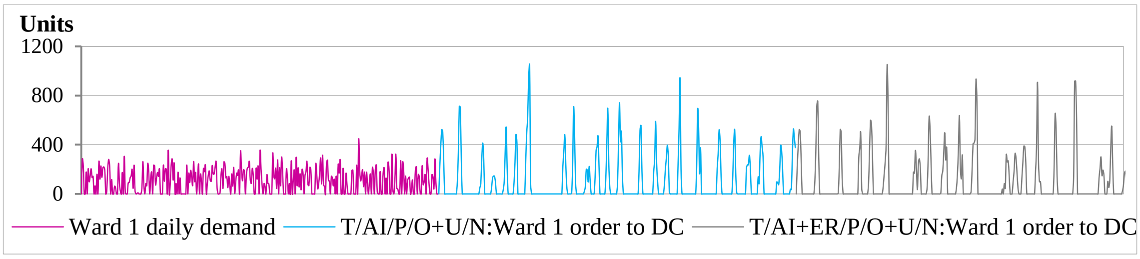


DC, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:

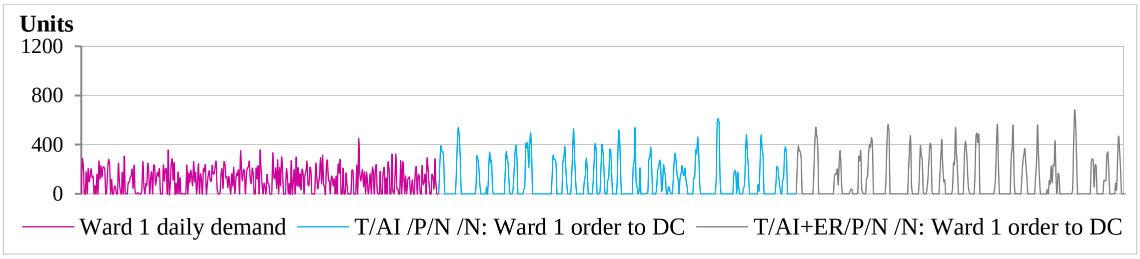


Daily demand of the wards generated using Process 2

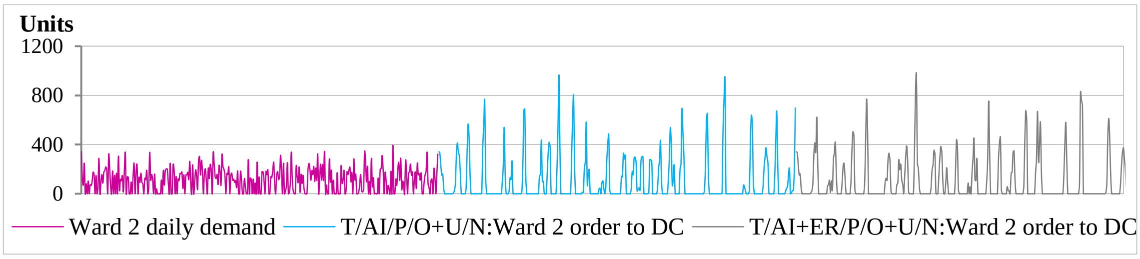
Ward 1, over and under-ordering effects at the wards - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



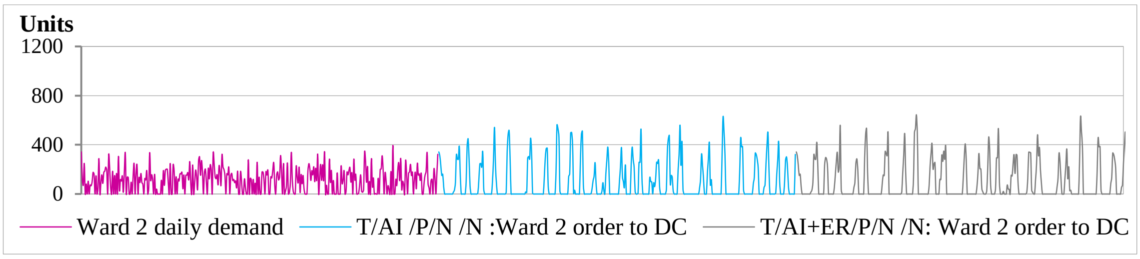
Ward 1, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



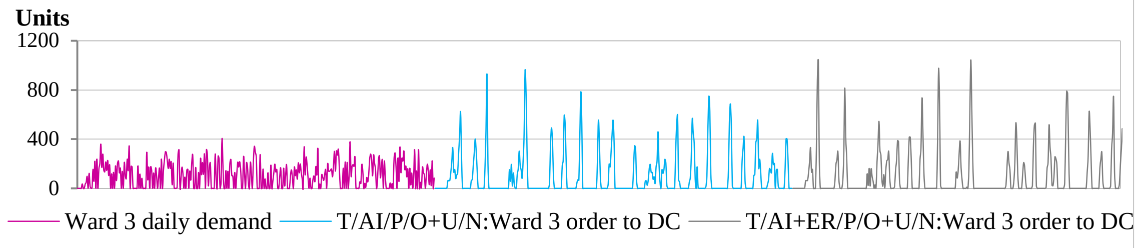
Ward 2, over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



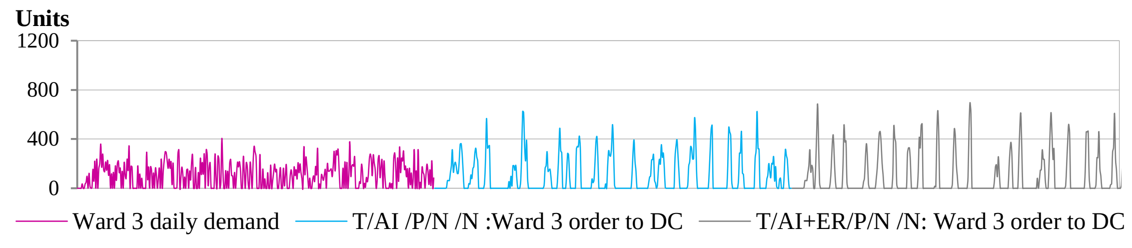
Ward 2, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



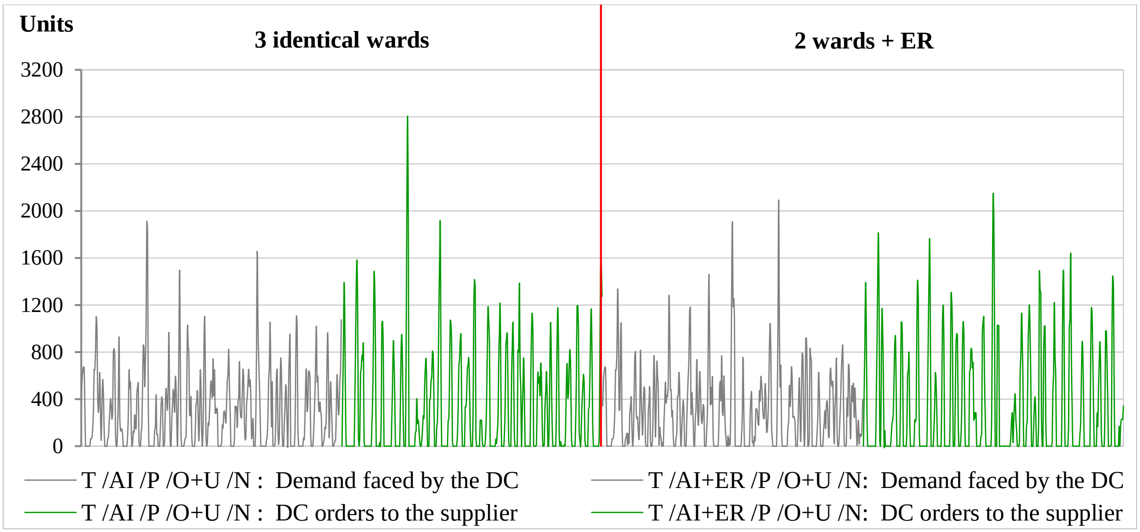
ER (ward 3), over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



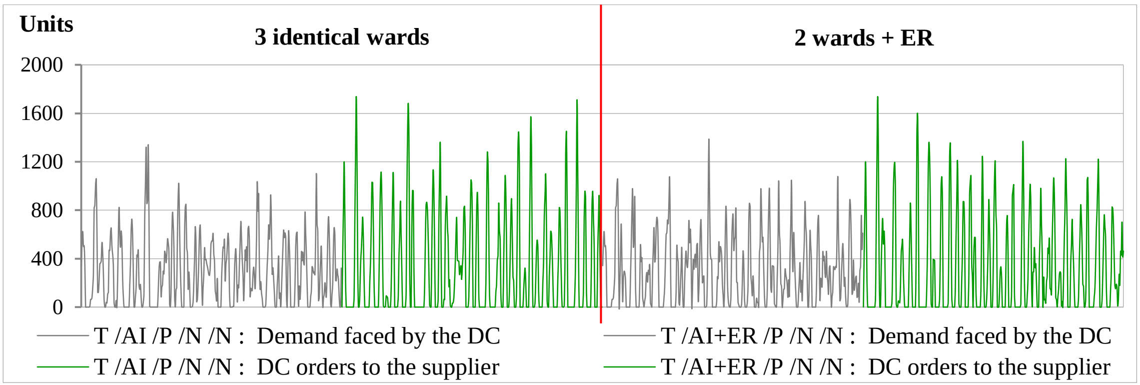
ER (ward 3), no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



DC, over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:

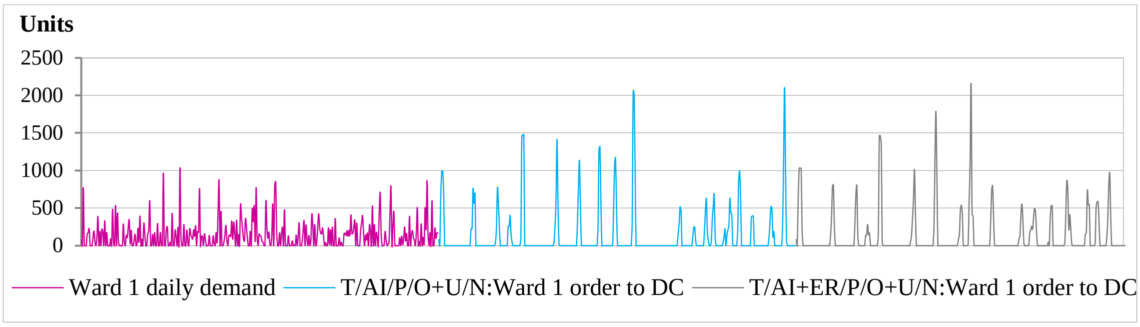


DC, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:

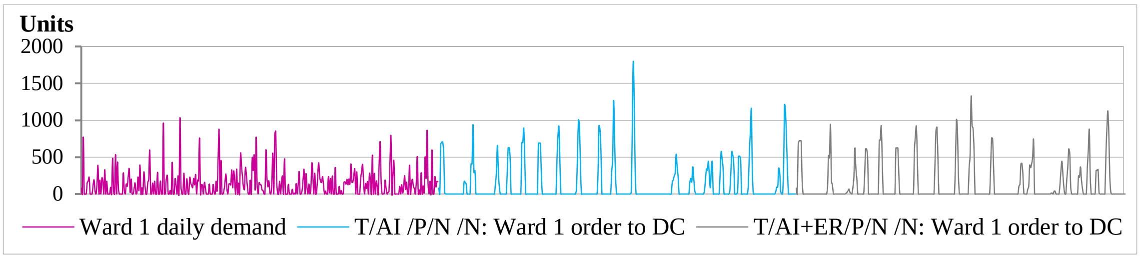


Daily demand of the wards generated using Process 3

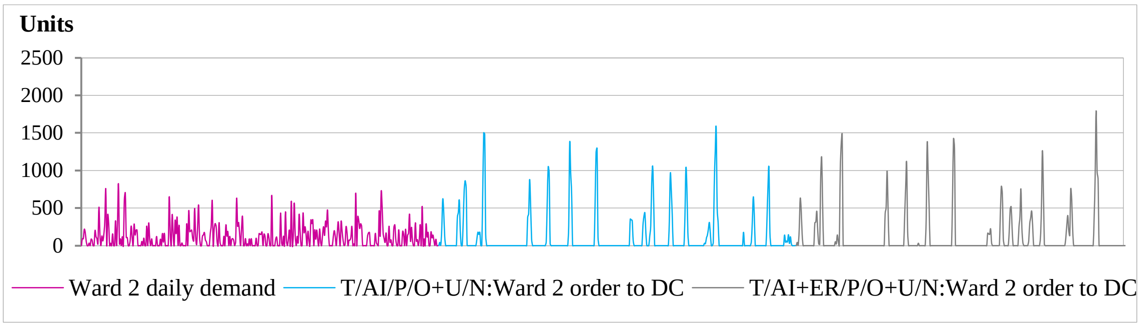
Ward 1, over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



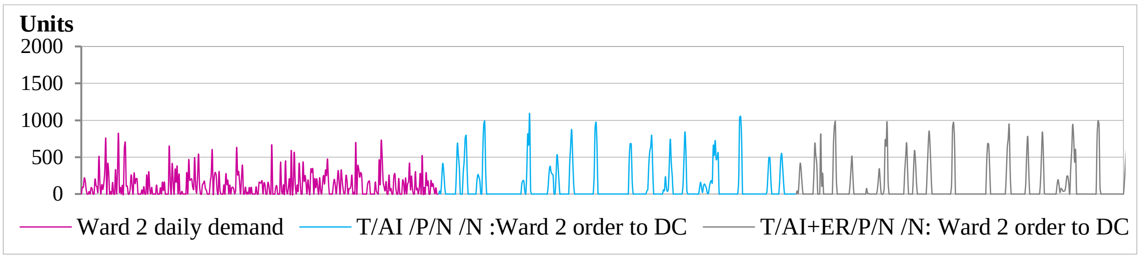
Ward 1, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



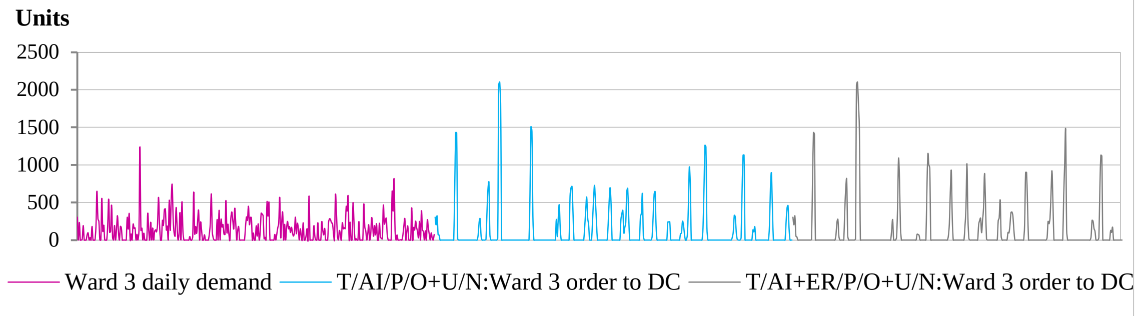
Ward 2, over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



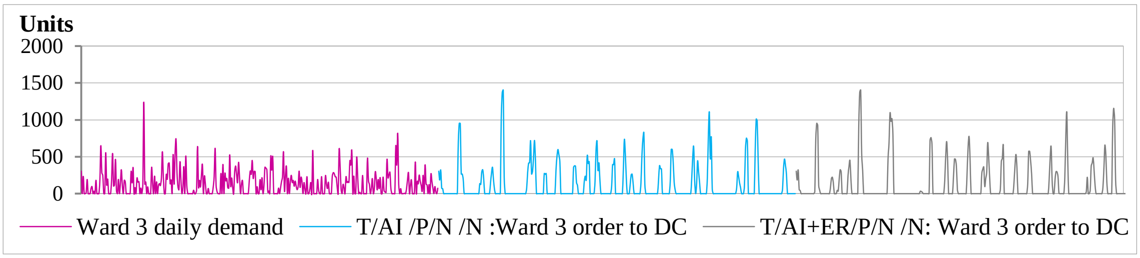
Ward 2, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



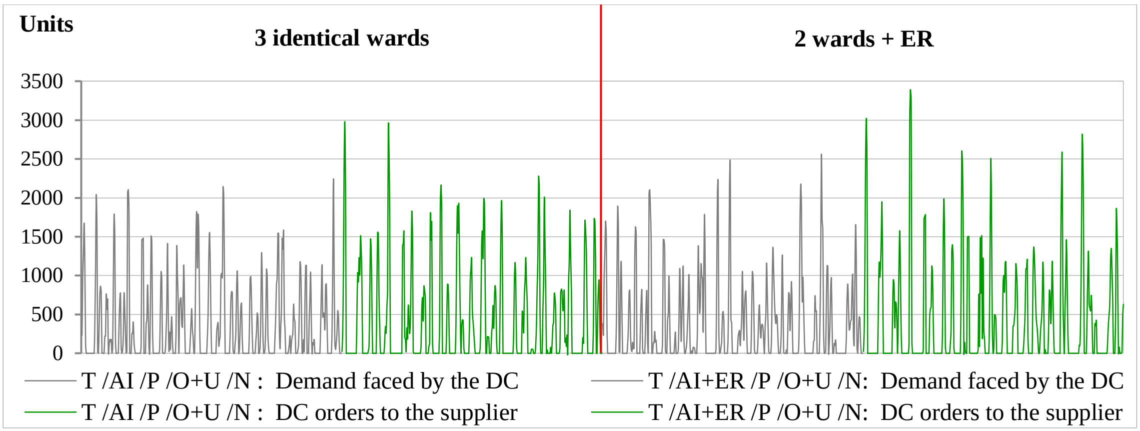
ER (ward 3), over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



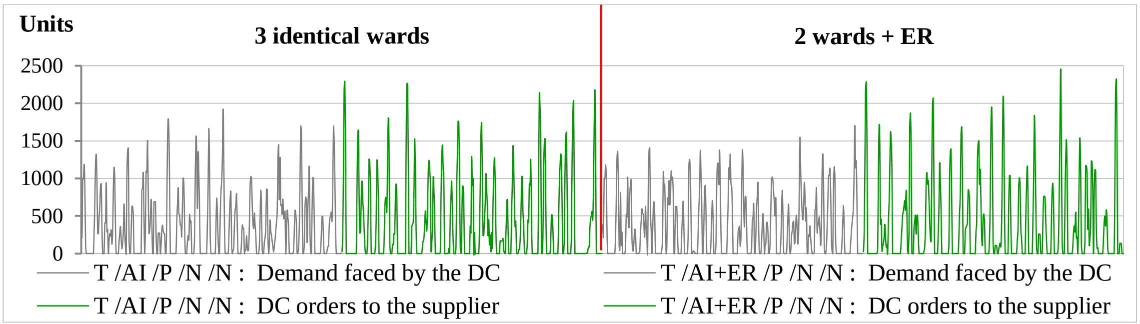
ER (ward 3), no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:



DC, over and under-ordering effects at the ward - SC with with 3 identical wards versus SC with an ER and 2 identical wards:

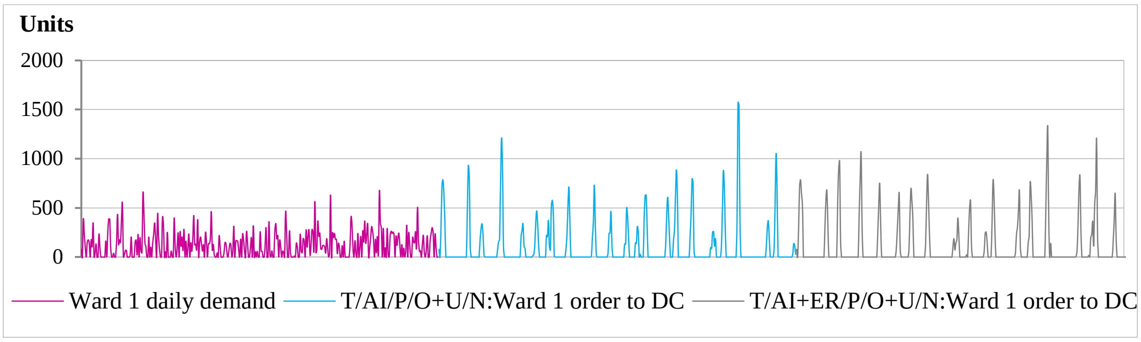


DC, no ordering effects - SC with with 3 identical wards versus SC with an ER and 2 identical wards:

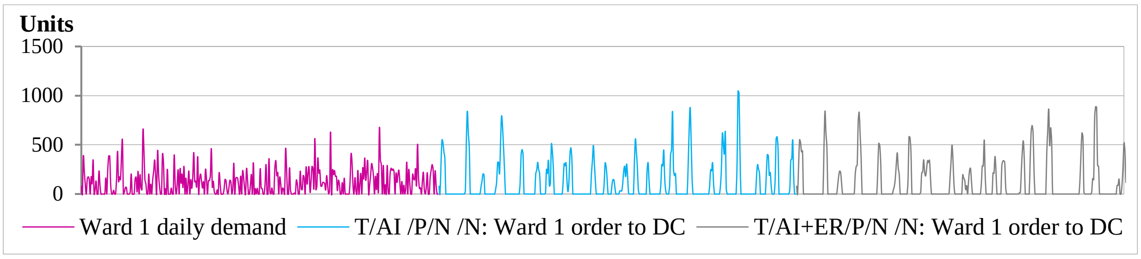


Daily demand of the wards generated using Process 4

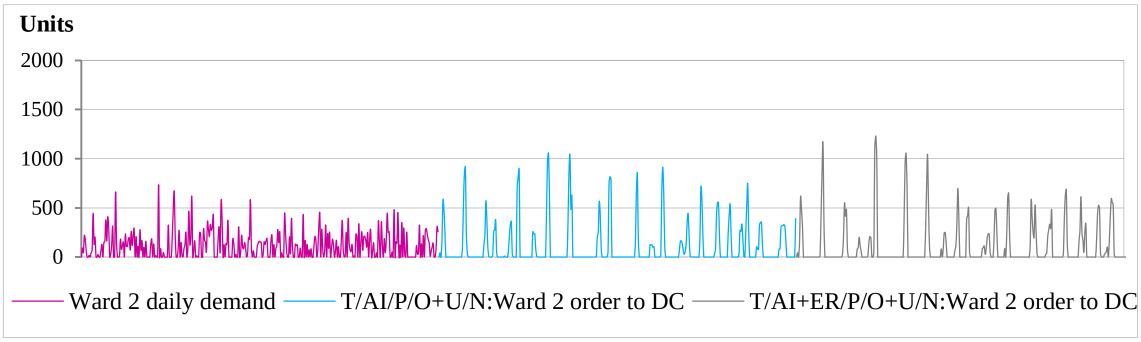
Ward 1, over and under-ordering effects at the ward - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



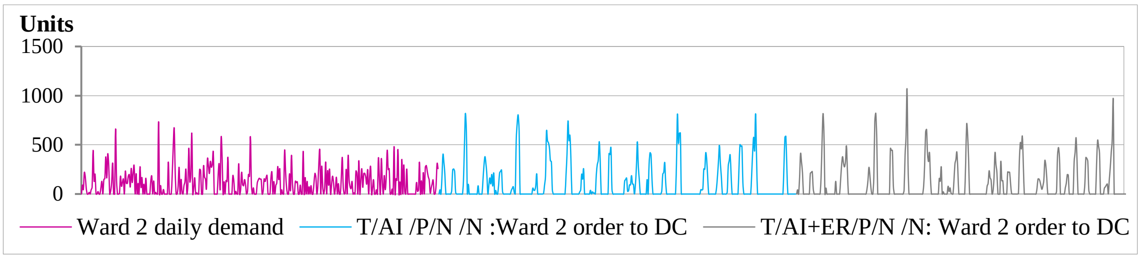
Ward 1, no ordering effects - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



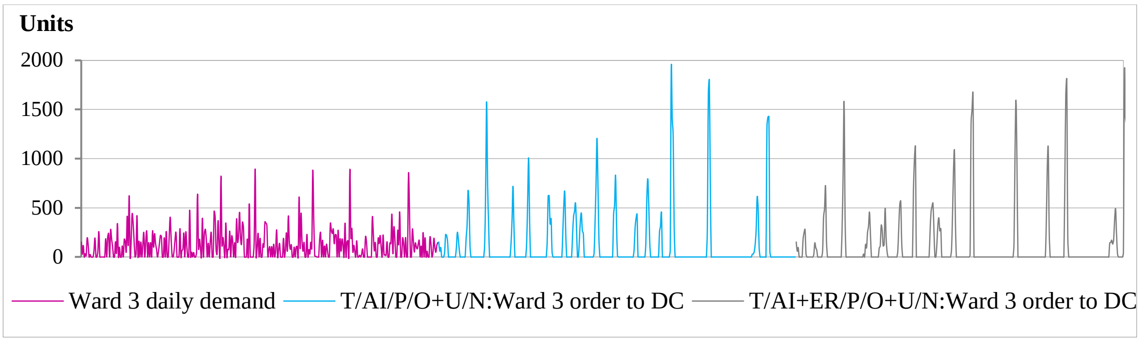
Ward 2, over and under-ordering effects at the ward - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



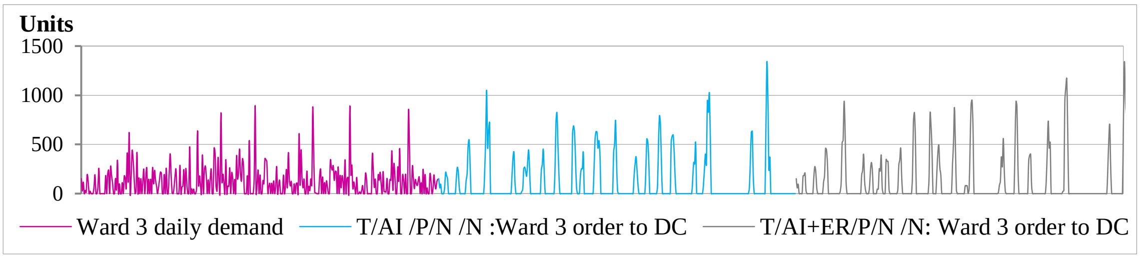
Ward 2, no ordering effects - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



ER (ward 3), over and under-ordering effects at the ward - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



ER (ward 3), no ordering effects - SC with an ER plus 2 identical wards versus SC with 3 identical wards:



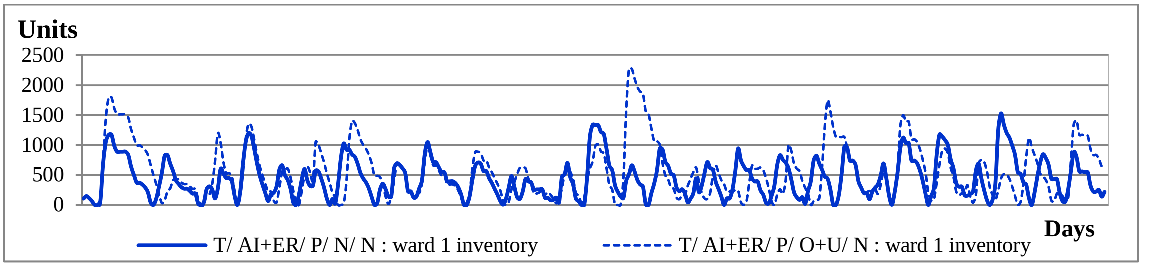
DC, over and under-ordering effects at the ward and with no ordering effects - SC with an ER plus 2 identical wards versus SC with 3 identical wards: graphs presented in subsection 4.6.3.

Appendix 4.22 – Traditional SC with one DC, and three identical wards, one of which an ER (and emergency deliveries from the DC) – inventory level evolution at the various SC echelons

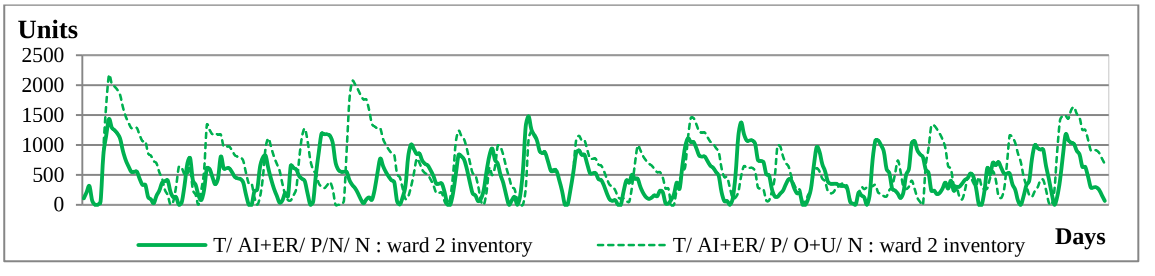
(Observations: Although the lengths of the Y axes of the graphs for each generated demand are different, the scales are the same; differently, the comparison of graphs relative to different generated demands must be cautious, since the corresponding scales are sometimes different; the graphs of the inventory level evolution can/should be compared with those in section 4.6 and Appendix 4.20.)

Daily demand of the wards generated using Process 1

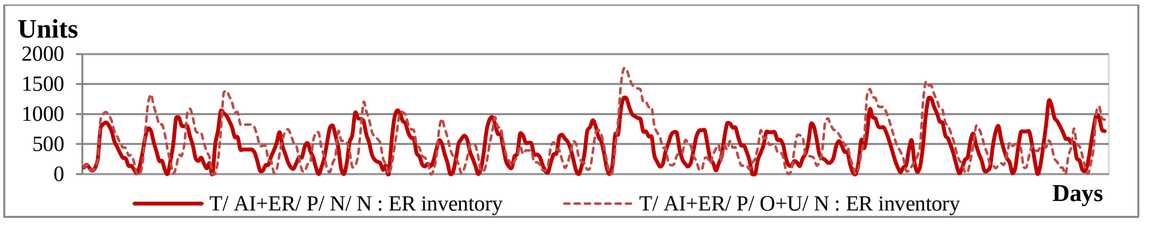
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:

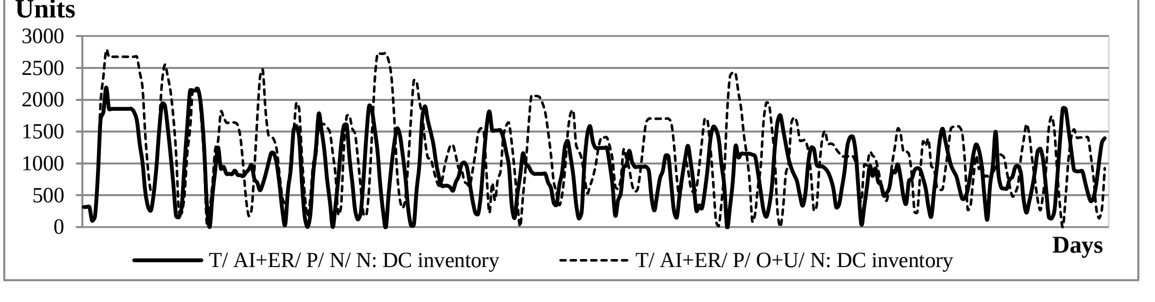


ER (ward 3) inventory level – over and under-ordering effects at the wards versus no ordering effects:

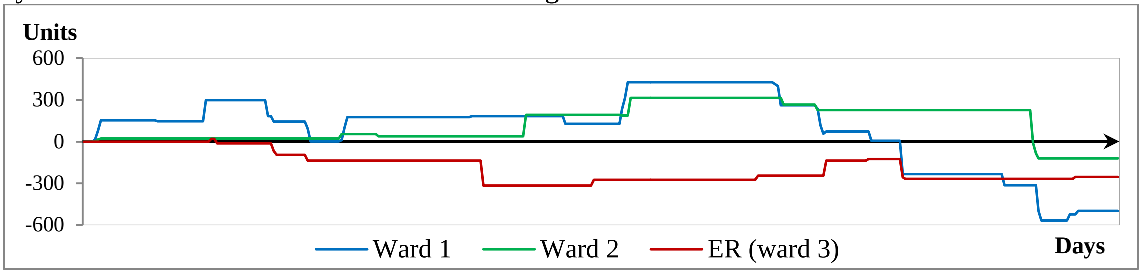


Observation: The ER inventory level is lower at the ER than at the other two wards.

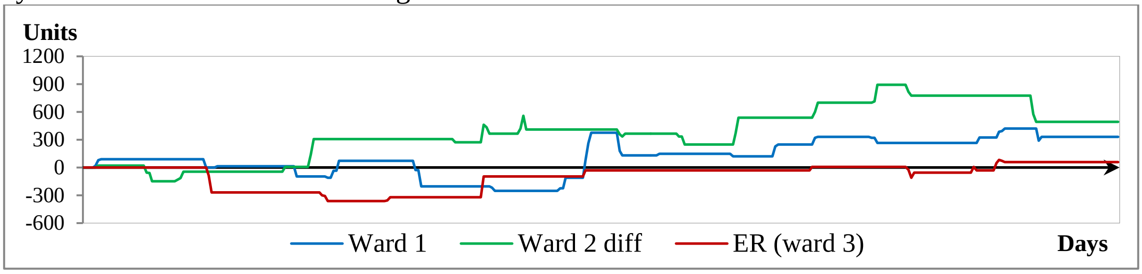
DC inventory level – over and under-ordering effects at the wards versus no ordering effects:



Lost demand: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – over and under-ordering effects at the wards:

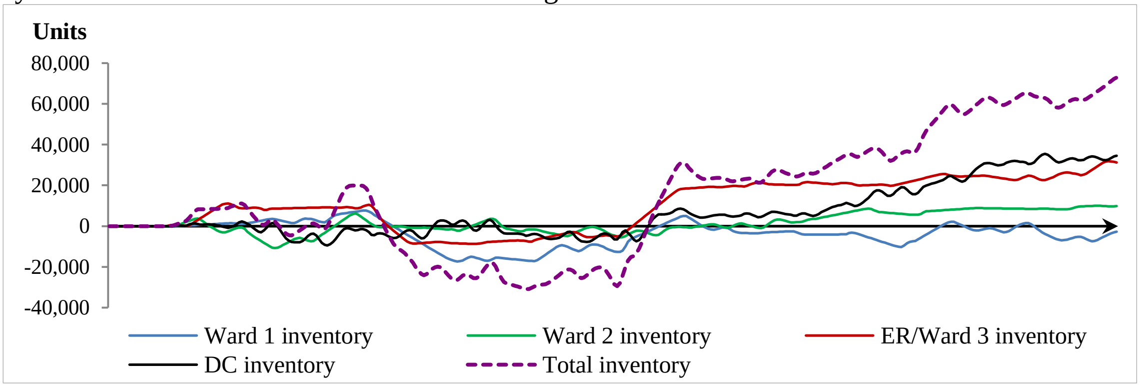


Lost demand: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – no ordering effects:

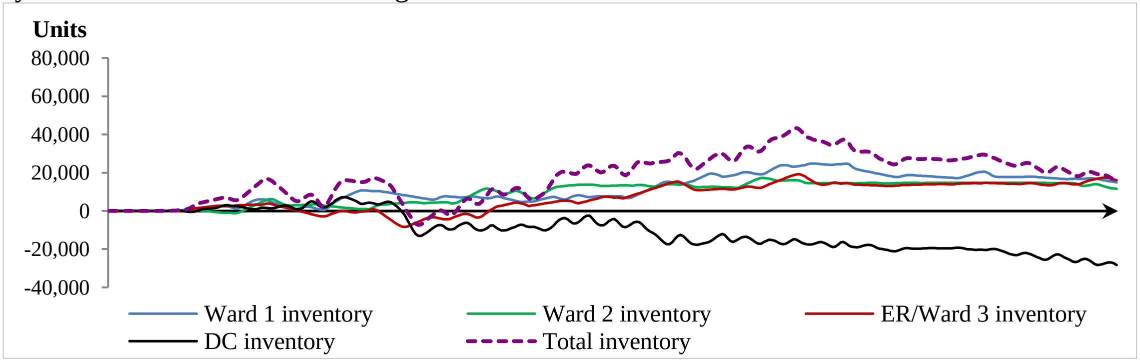


Daily demand of the wards generated using Process 2

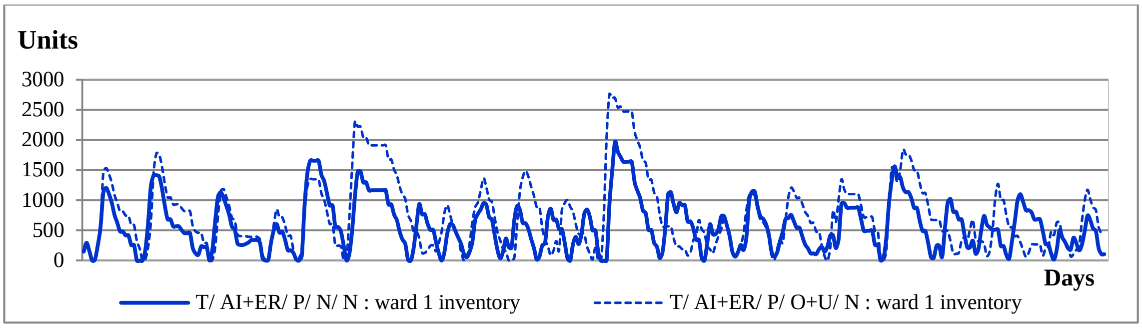
Inventory levels: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – over and under-ordering effects at the wards:



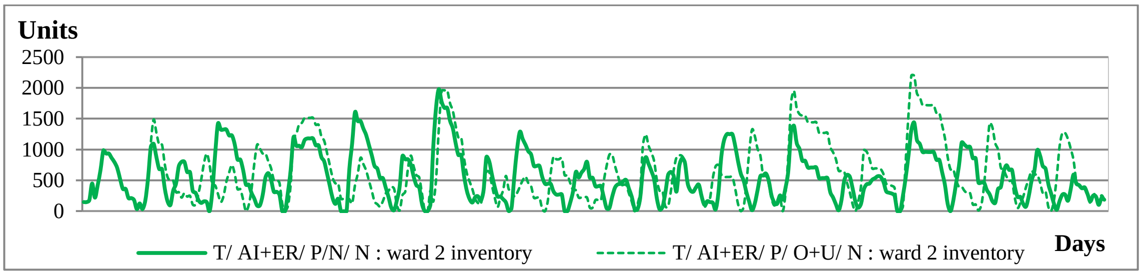
Inventory levels: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – no ordering effects:



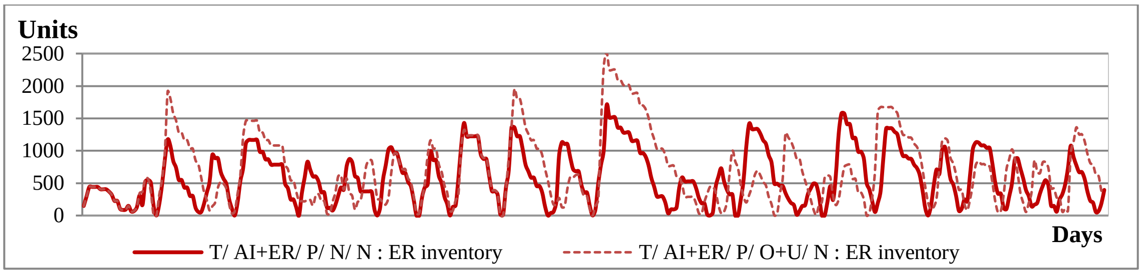
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



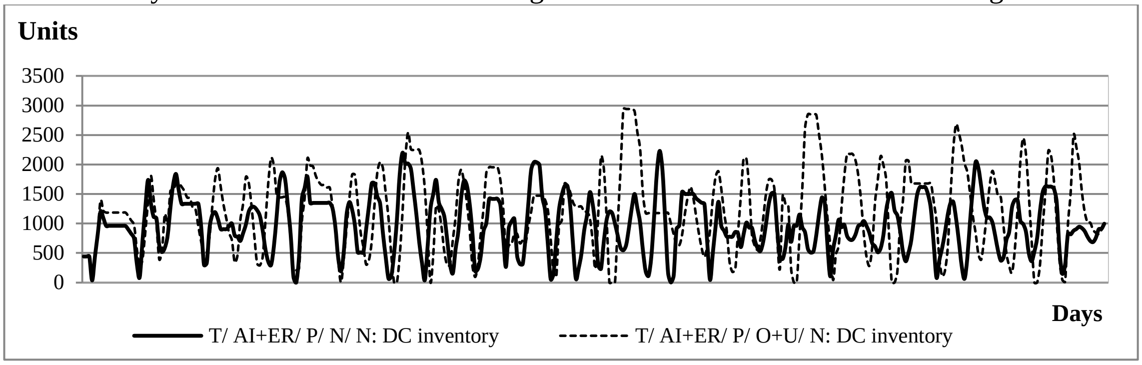
Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:



Ward 3 inventory level – over and under-ordering effects at the wards versus no ordering effects:

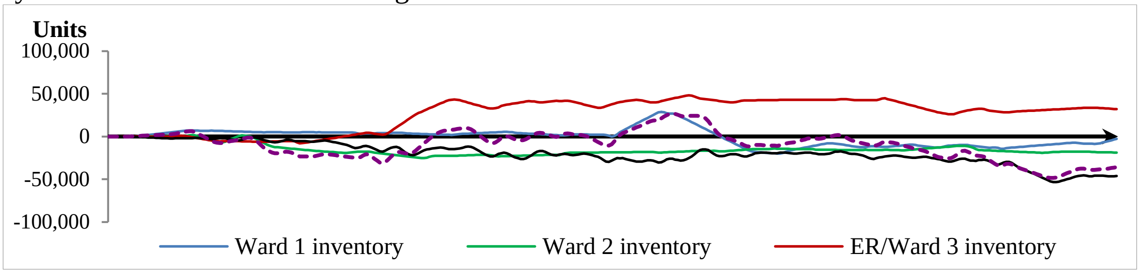


DC inventory level – over and under-ordering effects at the wards versus no ordering effects:

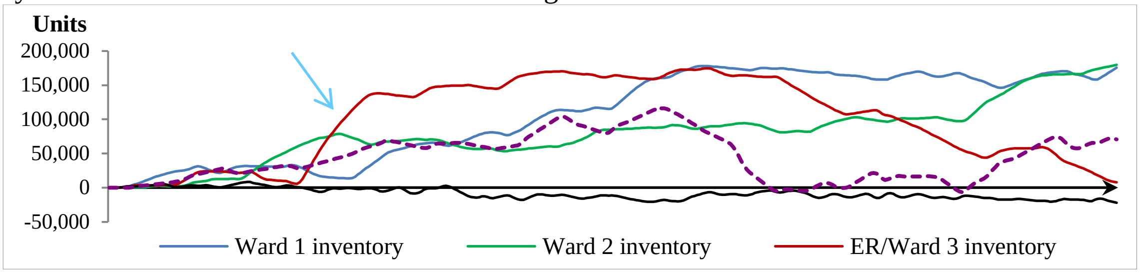


<u>Daily demand of the wards generated using Process 3</u>

Inventory levels: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – no ordering effects:

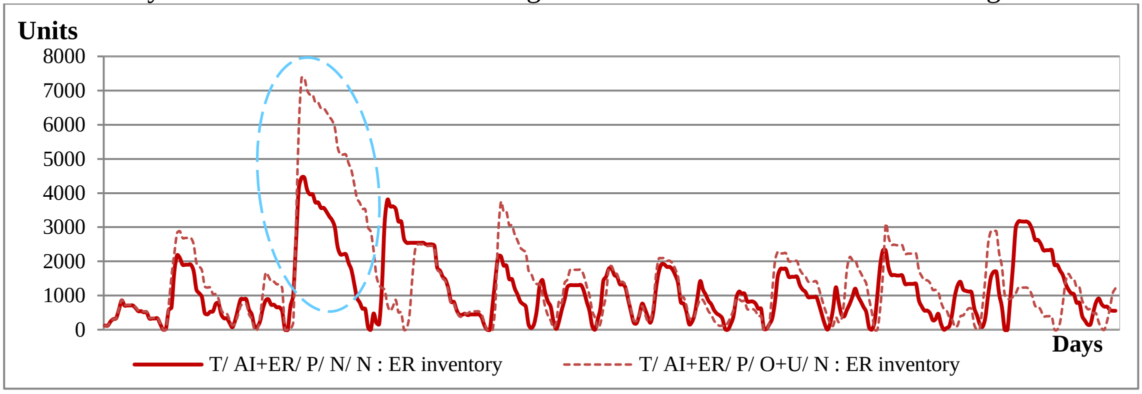


Inventory levels: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – over and under-ordering effects at the wards:



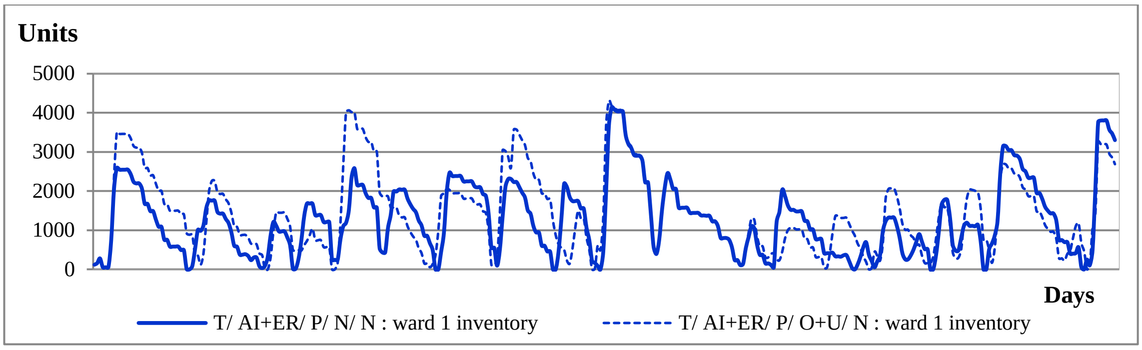
Observation: The strong increase in the accumulated difference of the ER inventory level was caused by a exceptionally high inventory entry (see graph representing the ER inventory level evolution below).

ER inventory level – over and under-ordering effects at the wards versus no ordering effects:

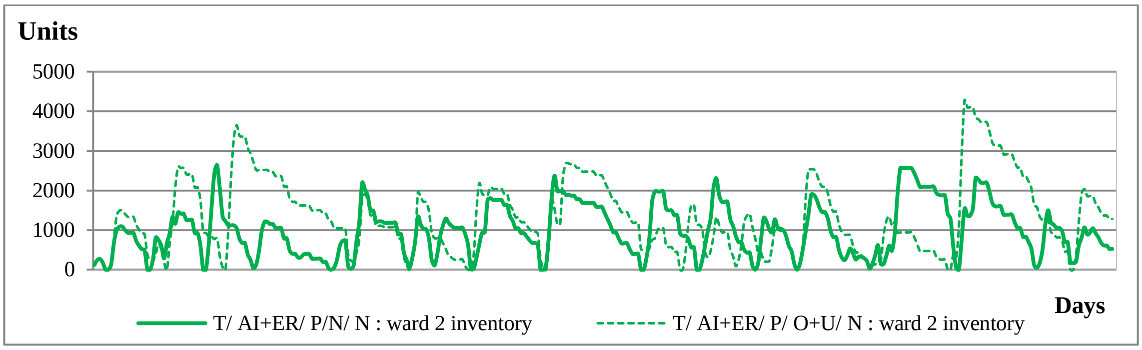


Observation: One of inventory cycle seems is very different from the others.

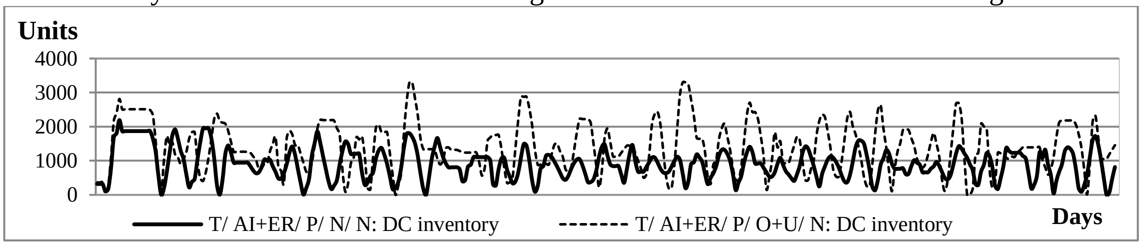
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



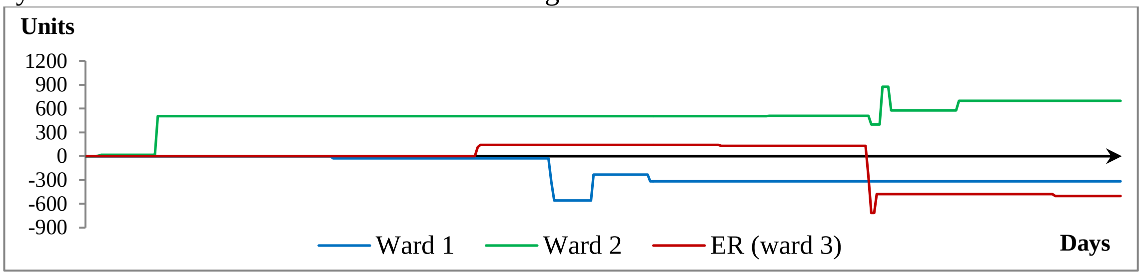
Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:



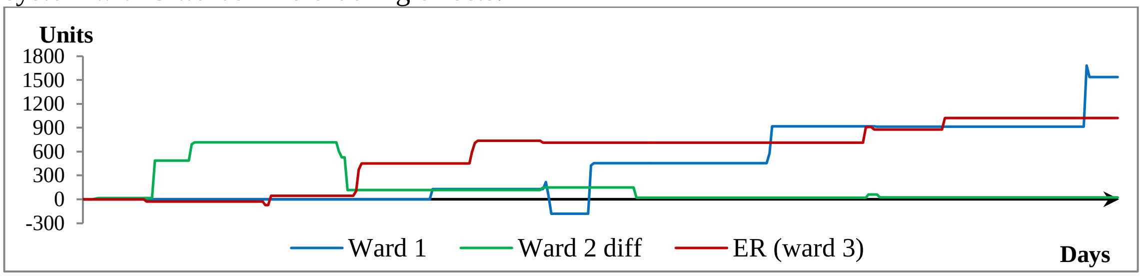
DC inventory level – over and under-ordering effects at the wards versus no ordering effects:



Lost demand: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – over and under-ordering effects at the wards:

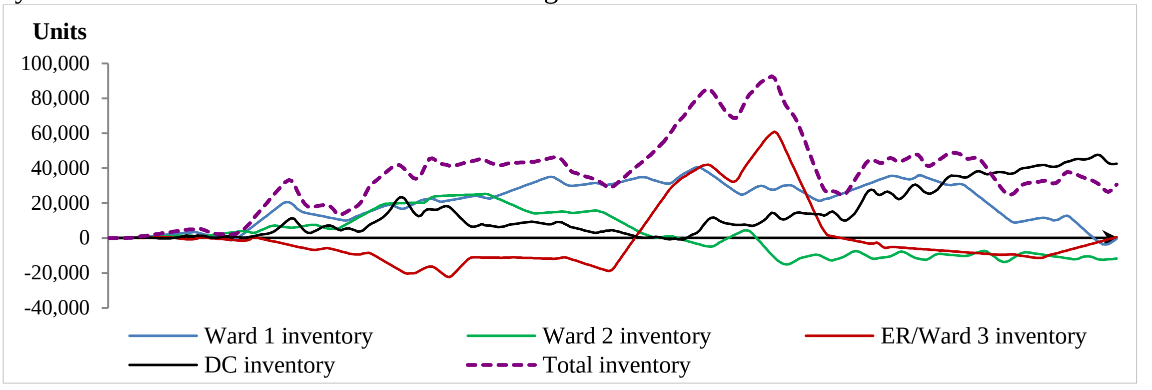


Lost demand: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – no ordering effects:

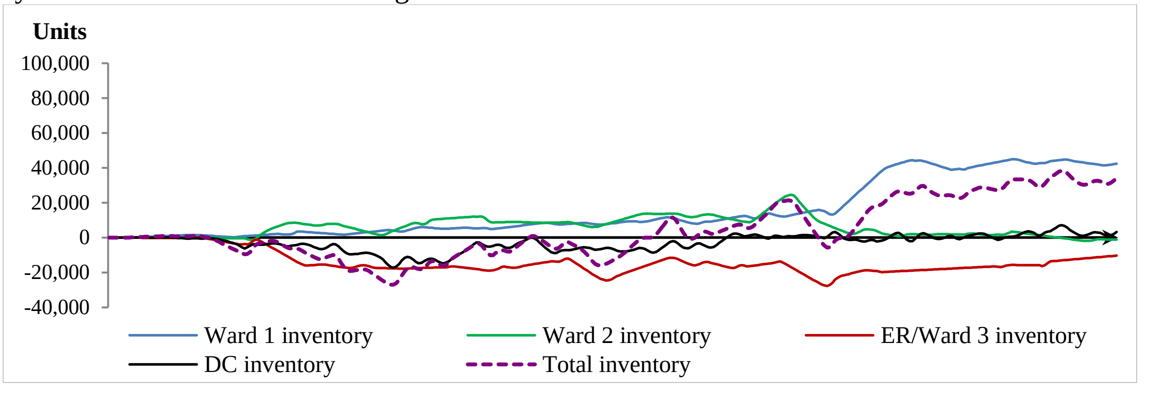


Daily demand of the wards generated using Process 4

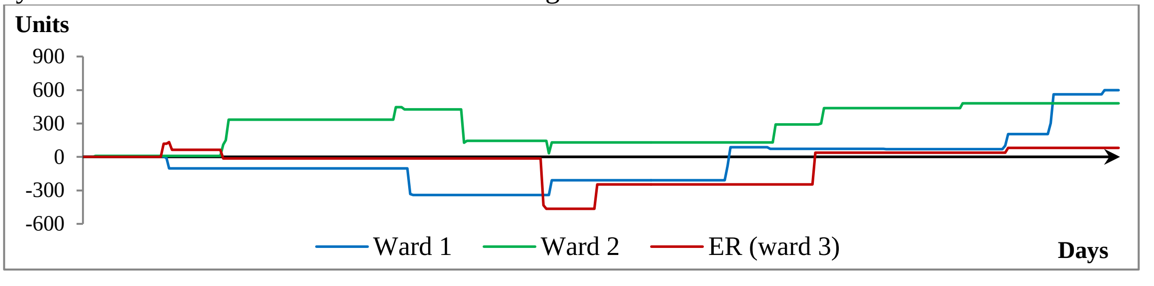
Inventory levels: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – over and under-ordering effects at the wards:



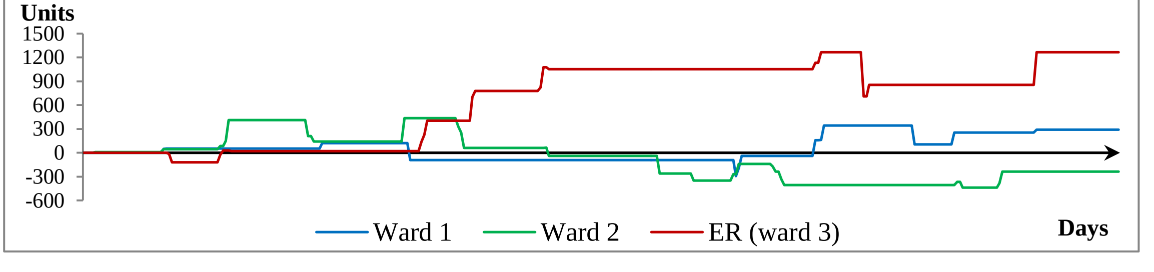
Inventory levels: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – no ordering effects:



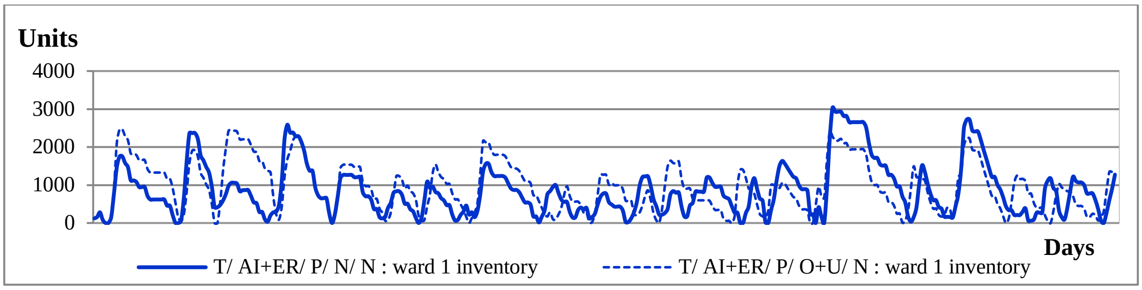
Lost demand: accumulated differences between the system with 2 wards and an ER and the system with 3 wards – over and under-ordering effects at the wards:



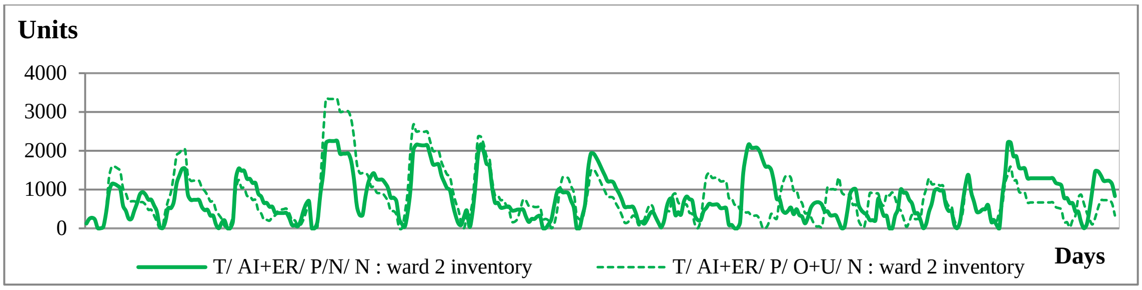
Lost demand: accumulated differences between the system with 2 wards and an ER and the system with 3 wards –no ordering effects:



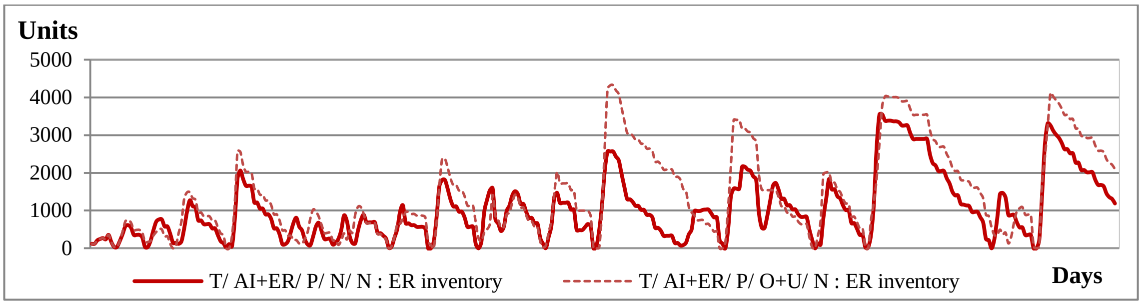
Ward 1 inventory level – over and under-ordering effects at the wards versus no ordering effects:



Ward 2 inventory level – over and under-ordering effects at the wards versus no ordering effects:

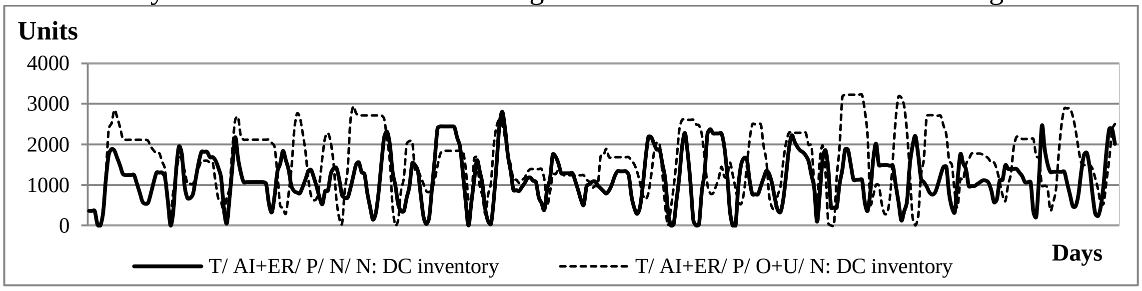


ER (ward 1) inventory level – over and under-ordering effects at the wards versus no ordering effects:



Observation: The duration of the cycles is very different.

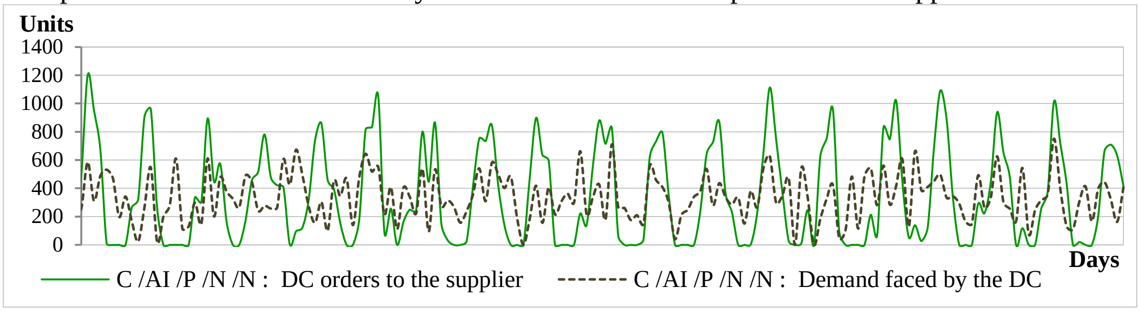
DC inventory level – over and under-ordering effects at the wards versus no ordering effects:



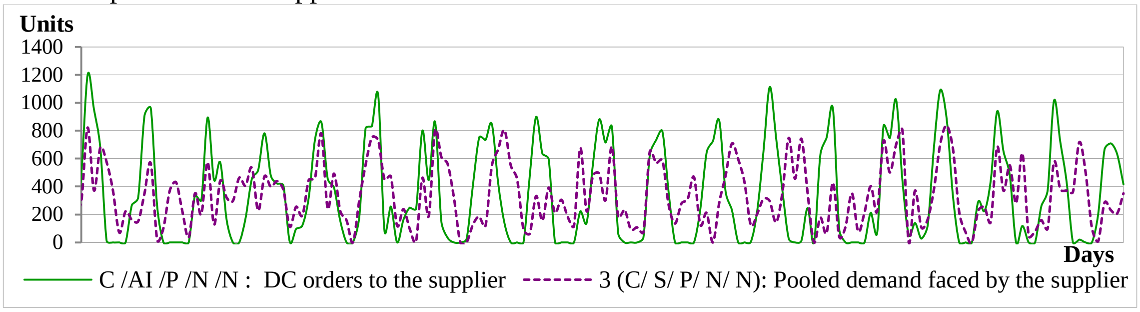
Appendix 4.23 – SC with one DC and three identical wards (and emergency deliveries from the DC): demand faced by the DC and passed to the supplier

<u>Daily demand of the wards generated using Process 2</u>

Comparison of the demand faced by the DC with the demand passed to the supplier:

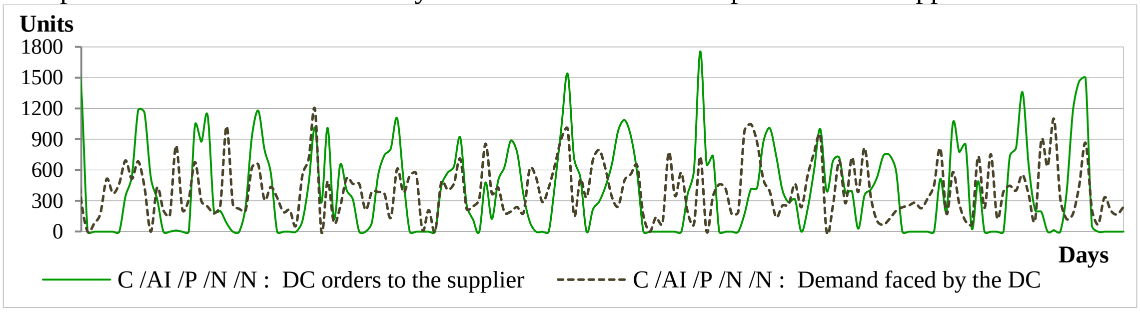


Demand passed to the supplier:

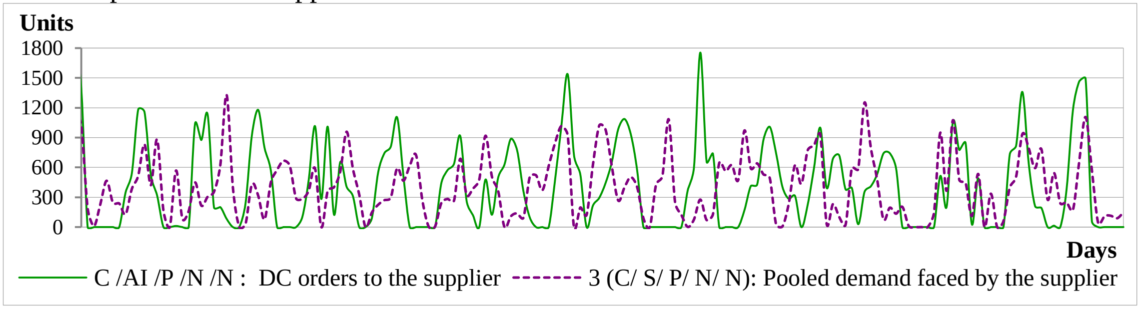


<u>Daily demand of the wards generated using Process 3</u>

Comparison of the demand faced by the DC with the demand passed to the supplier:

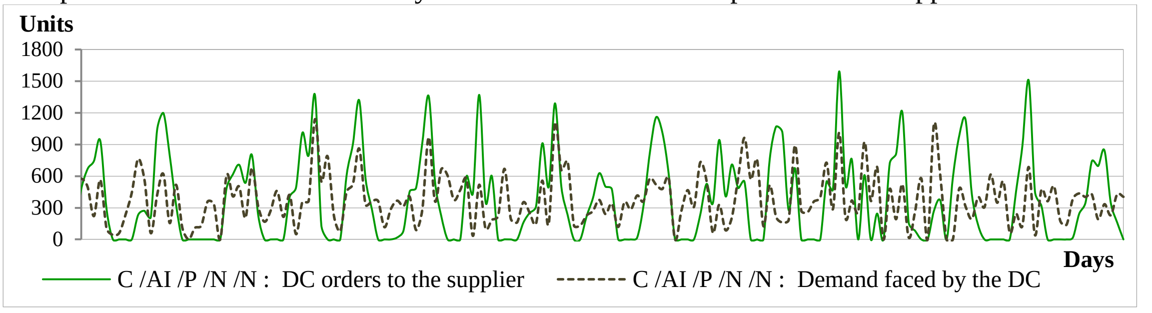


Demand passed to the supplier:

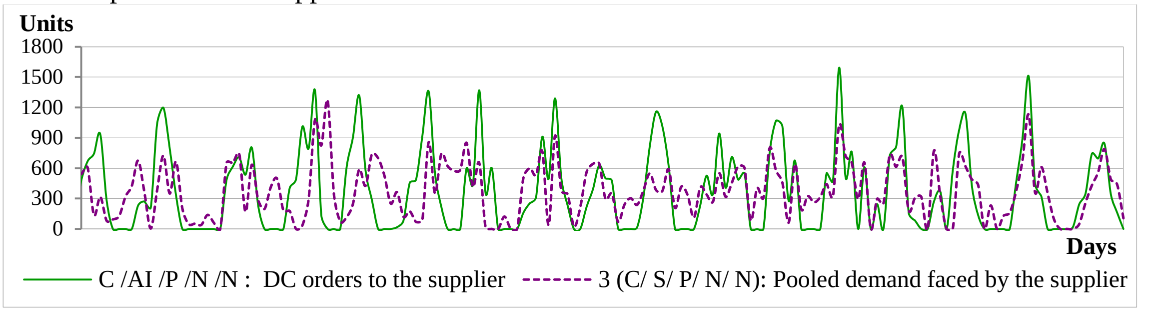


Daily demand of the wards generated using Process 4

Comparison of the demand faced by the DC with the demand passed to the supplier:



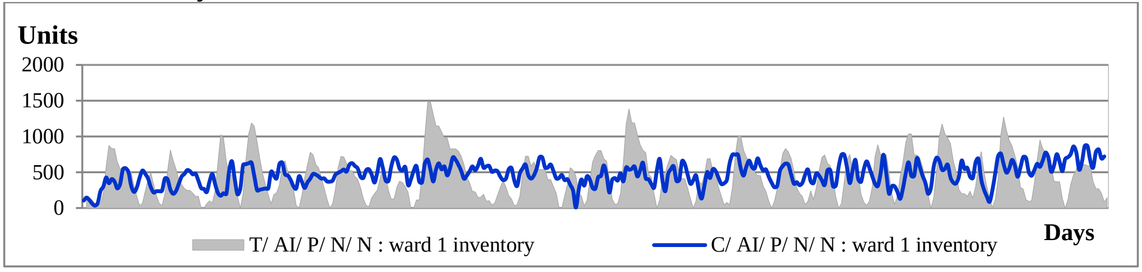
Demand passed to the supplier:



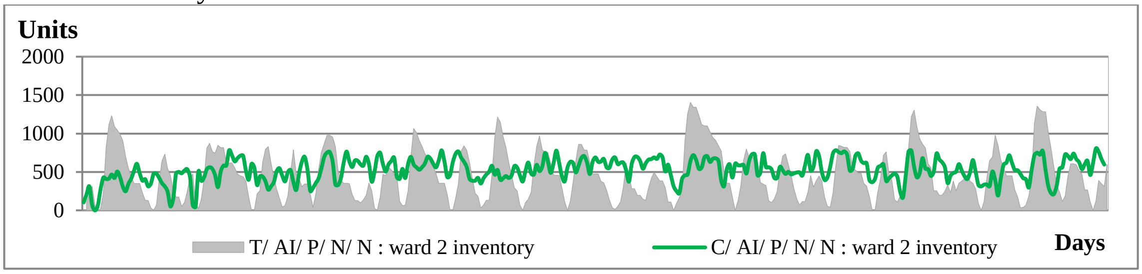
Appendix 4.24 – SC with one DC and three identical wards (and emergency deliveries from the DC): comparison of traditional and centralised inventory control systems – inventory level evolution at the various SC echelons

Daily demand of the wards generated using Process 1

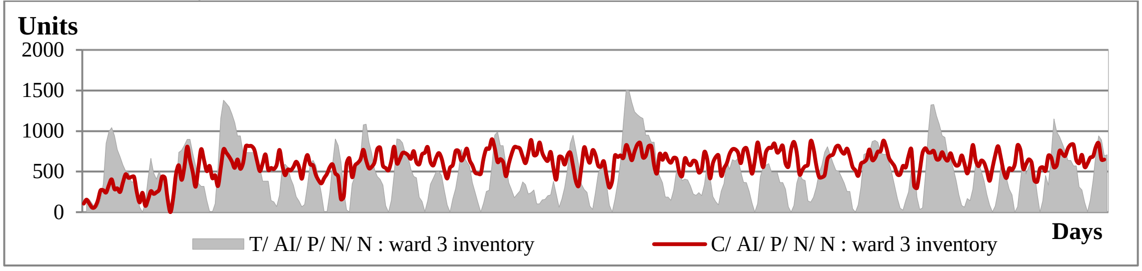
Ward 1 inventory level:



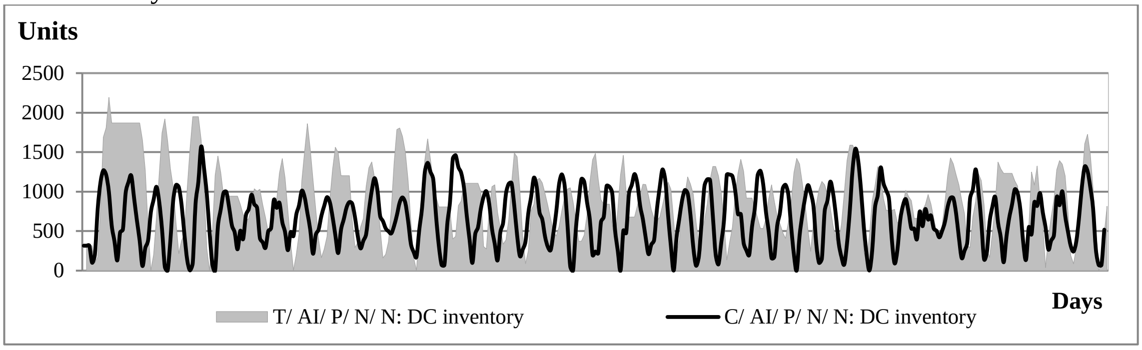
Ward 2 inventory level:



Ward 3 inventory level:

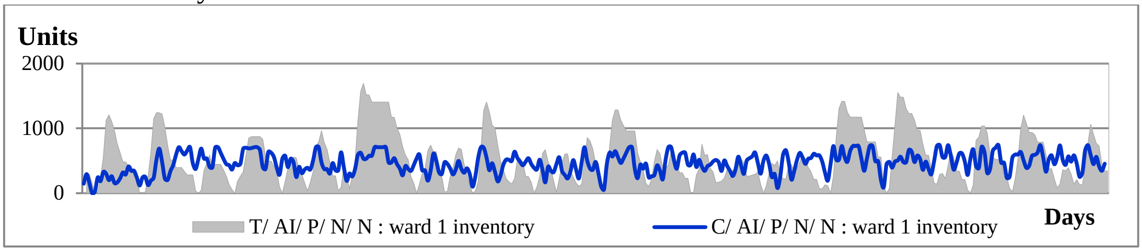


DC inventory level:

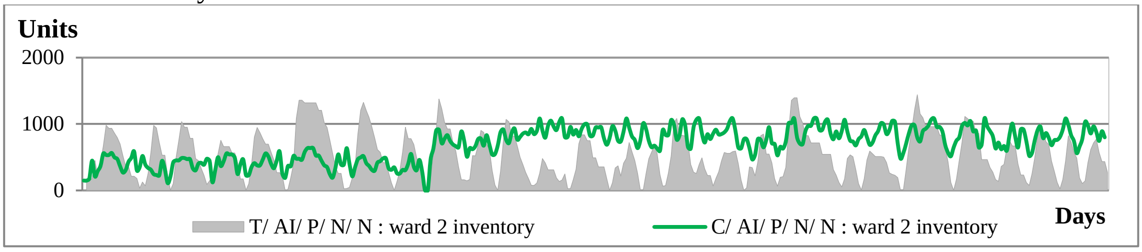


Daily demand of the wards generated using Process 2

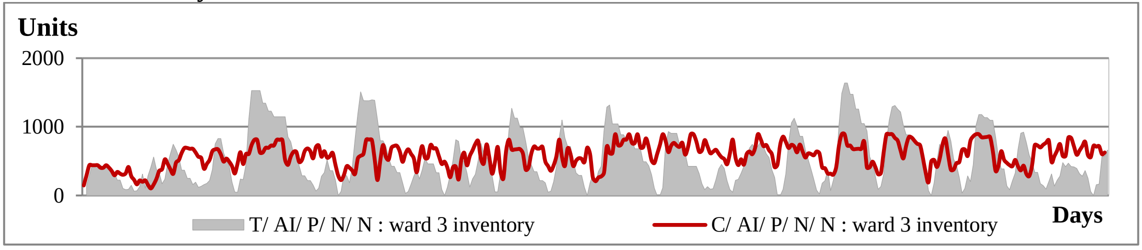
Ward 1 inventory level:



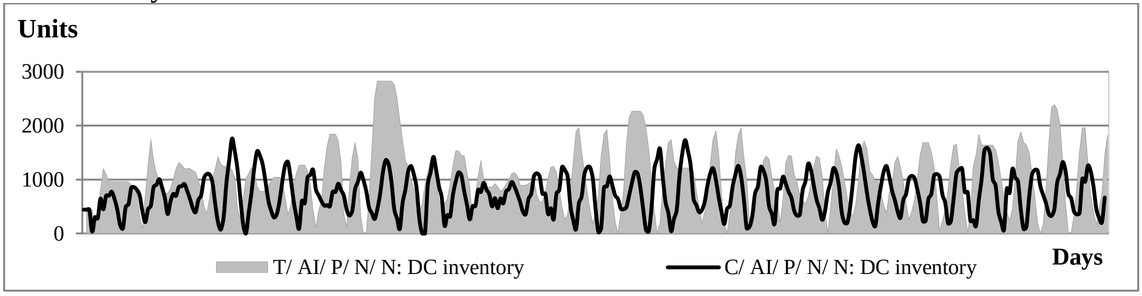
Ward 2 inventory level:



Ward 3 inventory level:

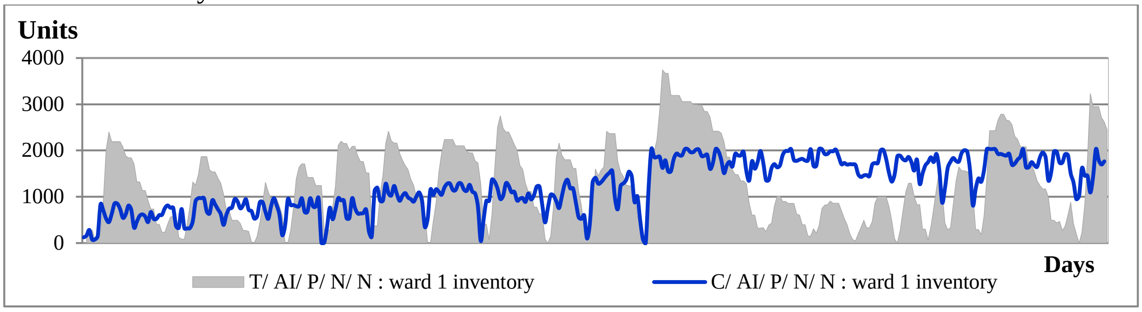


DC inventory level:

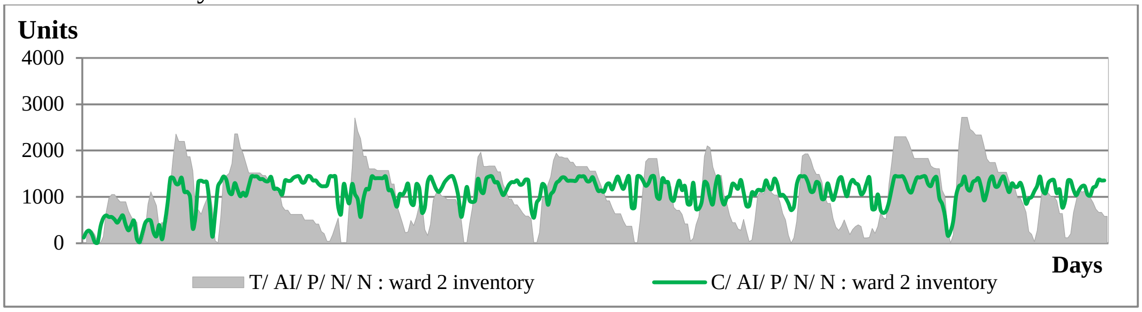


Daily demand of the wards generated using Process 3

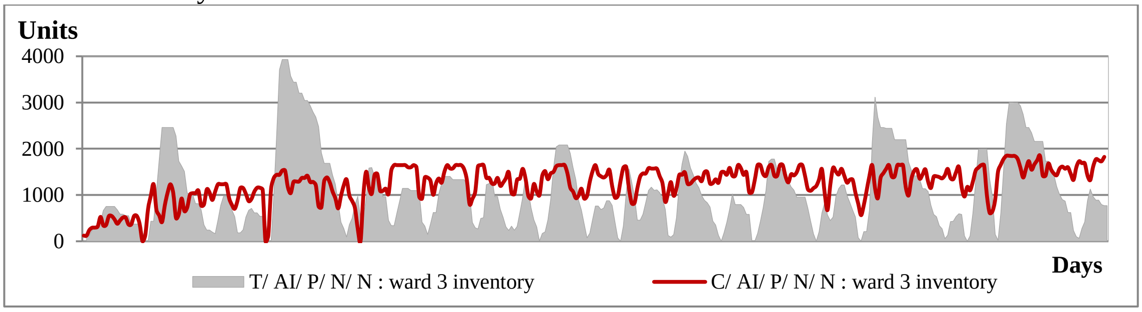
Ward 1 inventory level:



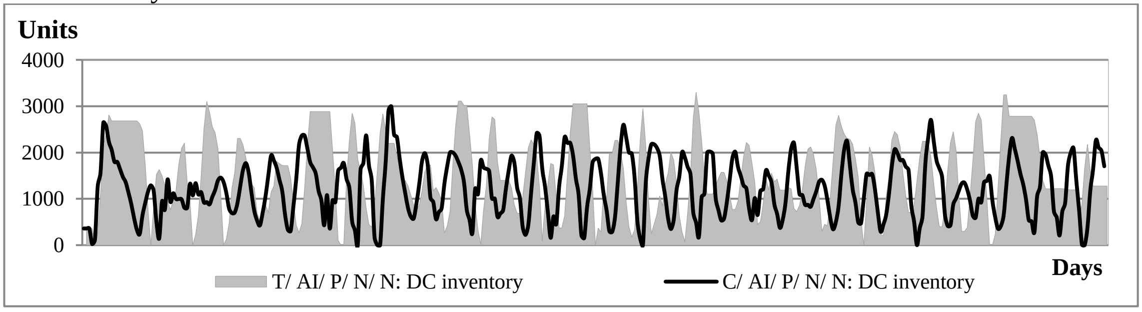
Ward 2 inventory level:



Ward 3 inventory level:

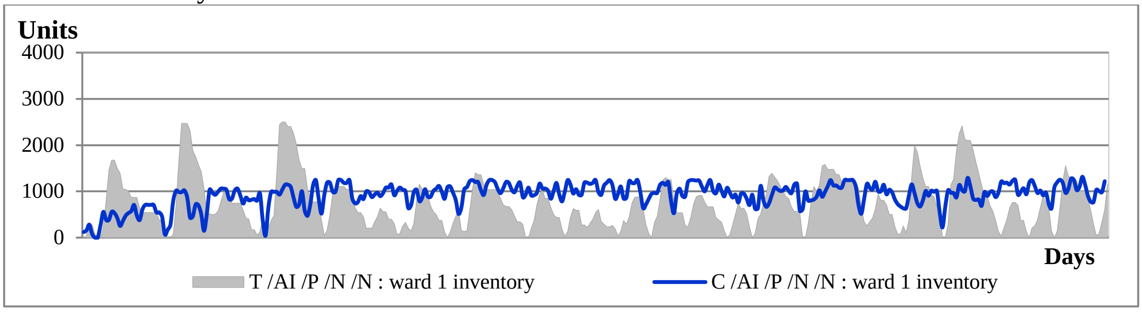


DC inventory level:

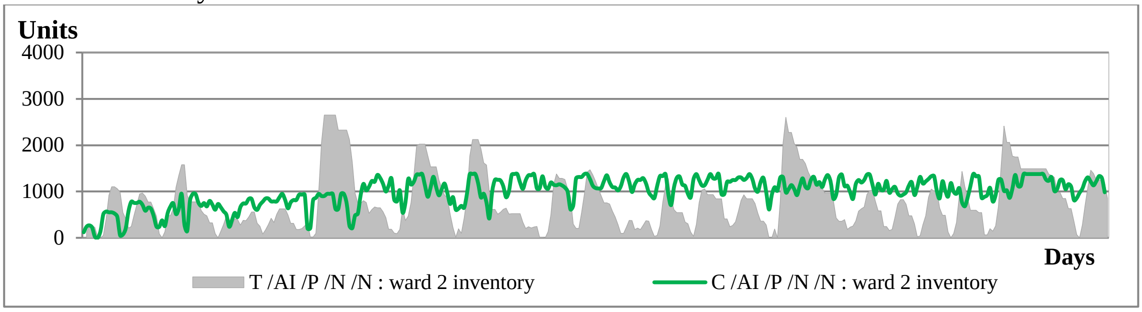


Daily demand of the wards generated using Process 4

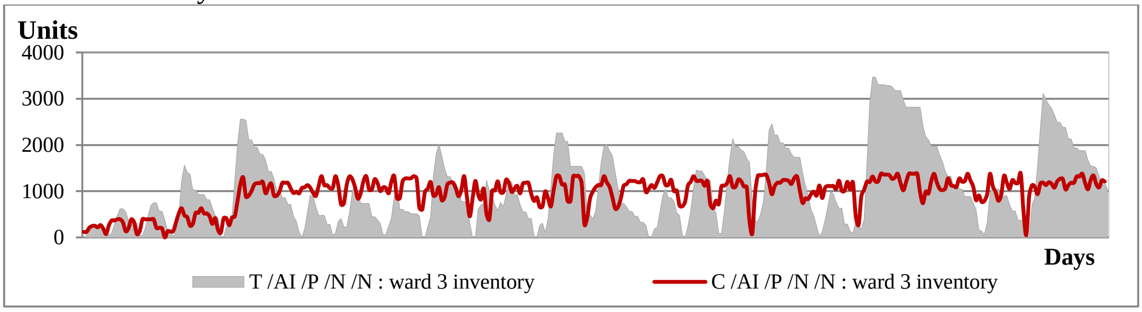
Ward 1 inventory level:



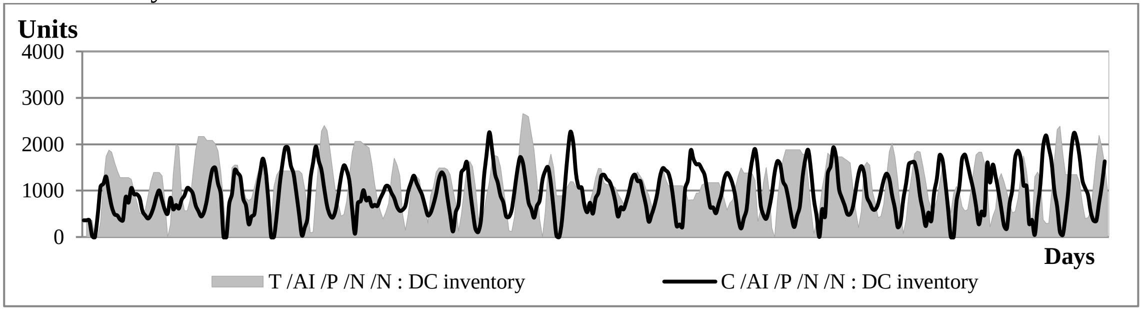
Ward 2 inventory level:



Ward 3 inventory level:



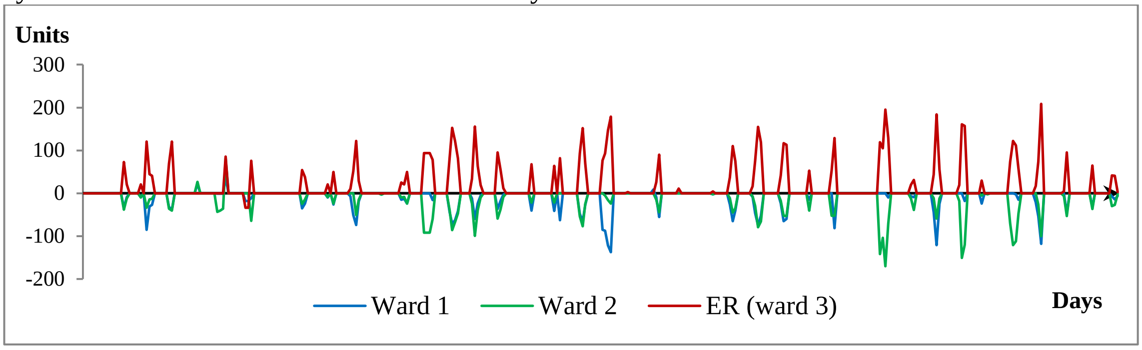
DC inventory level:



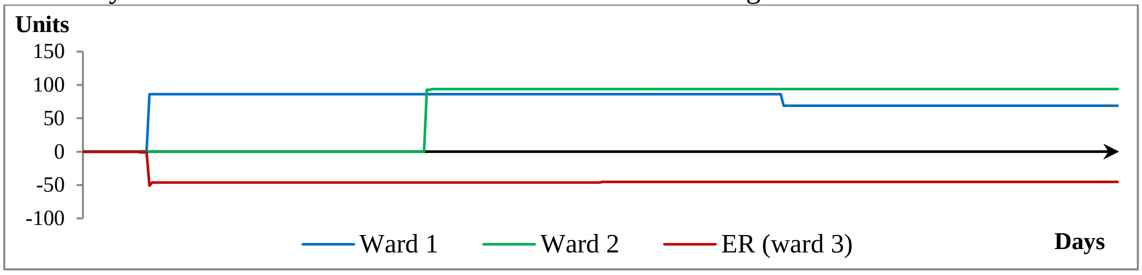
Appendix 4.25 – Centralised quasi-arborescent with three identical wards (and emergency deliveries from the DC) – comparison of inventory allocation rules

<u>Daily demand of the wards generated using Process 2</u>

Quantities supplied to the wards (*Ward orders fulfilment*): Accumulated differences between the system with one ER and two wards and the system with three identical wards:

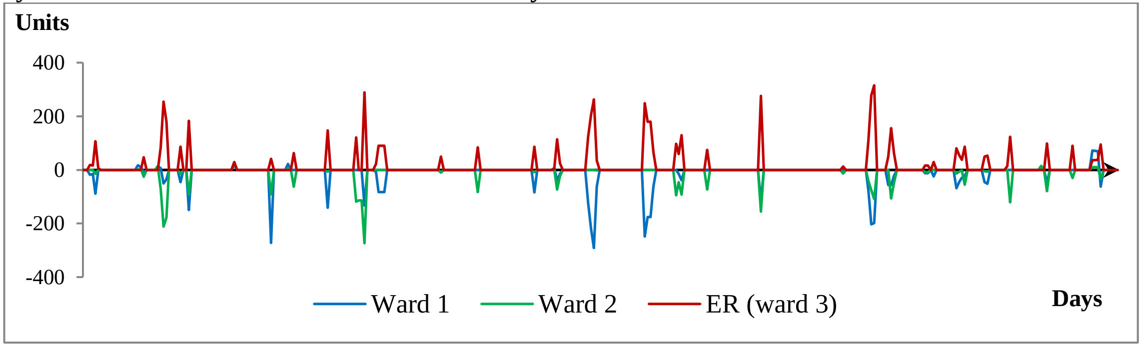


Lost demand: accumulated differences between the system with 2 identical wards and an ER and the system with 3 identical wards – over and under-ordering effects at the wards:

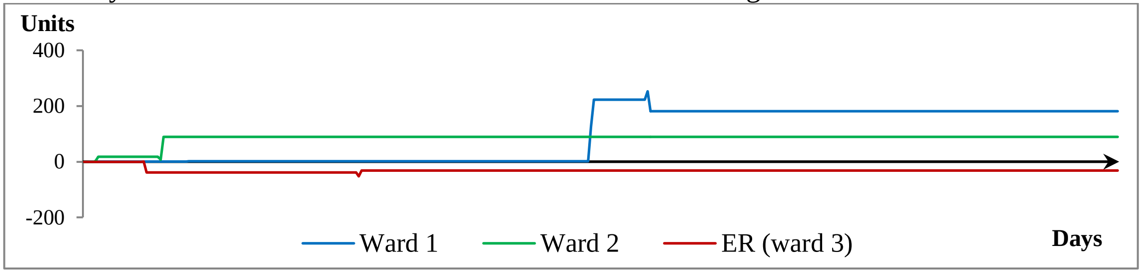


<u>Daily demand of the wards generated using Process 3</u>

Quantities supplied to the wards (*Ward orders fulfilment*): Accumulated differences between the system with one ER and two wards and the system with three identical wards:

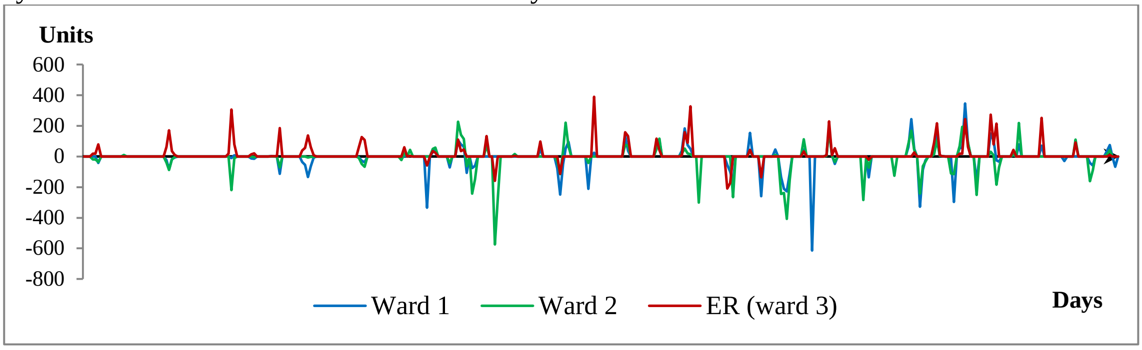


Lost demand: accumulated differences between the system with 2 identical wards and an ER and the system with 3 identical wards – over and under-ordering effects at the wards:



Daily demand of the wards generated using Process 4

Quantities supplied to the wards (*Ward orders fulfilment*): Accumulated differences between the system with one ER and two wards and the system with three identical wards:



Lost demand: accumulated differences between the system with 2 identical wards and an ER and the system with 3 identical wards – over and under-ordering effects at the wards:

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