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A Quantitative Approach Using An Axiomatic Design Framework To A Medication Distribution System

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A QUANTITATIVE APPROACH USING AN AXIOMATIC DESIGN FRAMEWORK
TO A MEDICATION DISTRIBUTION SYSTEM

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APPLYING AXIOMATIC DESIGN TO A MEDICATION DISTRIBUTION SYSTEM

By

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THESIS

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ABSTRACT

As the need to minimize medication errors drives many medical facilities to come up with robust solutions to the most common error that affects patient's safety, these hospitals would be wise to put a concerted effort into finding methodologies that can facilitate an optimized medical distribution system. If the hospitals' upper management is looking for an optimization method that is an ideal fit, it is just as important that the right tool be selected for the application at hand. In the present work, we propose the application of Axiomatic Design (AD), which is a process that focuses on the generation and selection of functional requirements to meet the customer needs for product and/or process design.

The appeal of the axiomatic approach is to provide both a formal design process and a set of technical coefficients for meeting the customer's needs. Thus, AD offers a strategy for the effective integration of people, design methods, design tools and design data. Therefore, we propose the AD methodology to medical applications with the main objective of allowing nurses the opportunity to provide cost effective delivery of medications to inpatients, thereby improving quality patient care. The AD methodology will be implemented through the use of focused stores, where medications can be readily stored and can be conveniently located near patients, as well as a mobile apparatus that can also store medications and is commonly used by hospitals, the medication cart. Moreover, a robust methodology called the focused store methodology will be introduced and developed for both the uncapacitated and capacitated case studies, which will set up an appropriate AD framework and design problem for a medication distribution case study.

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CHAPTER I

1.0 INTRODUCTION

In a health care professional's quest to provide continuous quality patient care, it is imperative that hospital management remains vigilant to find ways to pursue this commitment. One area that has been under constant scrutiny in the medical profession is the occurrence of medication errors. According to the National Coordination Council for Medication Error Reporting and Prevention (2012), a medication error is defined as... any preventable event that may cause or lead to inappropriate medication or patient harm while the medication is in the control of the health care professional, patient or consumer...[21, 22]. Medication errors have been identified as the most common type of error affecting the safety of patients and the most common single preventable cause of adverse effects [22]. The National Coordination Council for Medication Error Reporting and Prevention (2012) reported that an estimated 98,000 die every year from medical errors in U.S. hospitals and a significant number of those deaths are associated with medication errors [21]. Medication errors can occur at all stages of the medication process. The four major types of medication errors in hospitalized are prescription errors (e.g. a wrong drug, dose or form), transcription and/or interpretation errors (e.g. misinterpretation of abbreviations, handwritten prescriptions or spoken prescriptions), preparation and dispensing errors with correct prescription (e.g. errors in dispensing, calculation errors) and administration errors (e.g. a wrong dose or infusion rate, a wrong administration time, omission of dose or additional dose, incorrect handling of drugs during administration). Most of the medication errors occur at the administration stage (53% median, range: 9-90.7%) [21]. For the present thesis, the focus will be on finding ways to minimize drug distribution system errors.

There are several factors that contribute to drug distribution system errors. Brady *et al* (2009), highlighted contributing factors to medication errors, including information overload, lack of clinical decision supports with general inadequacy in the ‘checks and balances’ inherent in any drug administration process. Medication errors are also more prevalent with inappropriate reliance on manual documentation or information systems that do not communicate with each other. Omission errors due to the availability of non-stock drugs and through difficulty in locating stock drugs prescribed generically but supplied in brand name packaging are also a possibility. Incorrect or delayed transcriptions are another possible cause of medication errors. Different drug administration systems are also associated with higher rates of medication errors. New technologies such as computer-order entry systems, computerized medical records and bar-coded enabled systems have the potential for nurses to make medication errors without the proper supervision and guidance on how to use these products properly [22].

For the present thesis, a methodology will be presented to improve the medication distribution process, with specific attention on the administering of medications by nurses, beginning at the nurse’s station and ending at the patient area(s).

Engineering principles and tools will be utilized to assist in this effort. Engineering tools such as simulation modeling could play a vital role by allowing engineers to study the behavior of this medication distribution system. An invaluable advantage of simulation modeling is that it helps designers and engineers to avoid repeated attempts to build multiple prototypes when analyzing the design of new or existing complex systems. Simulation modeling has several inherent principles that the engineer must be attentive to:

- Model conceptualization requires system knowledge, engineering judgment and model building tools

- A good modeler requires abilities and they are developed through practice
- Modeling process is evolutionary
- Problem statement is the primary controlling element for problem solving

For this reason, we propose the application of the Axiomatic Design (AD) methodology. The AD methodology was developed by Dr. Nam Pyo Suh, a MIT professor who first proposed this theory in the 1970's. He defines it as a process that focuses on the generation and the selection of functional requirements to meet the customer needs for product and/or process design [1]. He also said that this concept could become an invaluable tool to many businesses because he believes that it “helps to overcome the shortcomings of the product design and the product development process that is based on a recursive ‘design/build/test’ cycle, which requires continuing modifications and changes as design flaws are discovered through testing” [2]. The appeal of the axiomatic approach is to provide both a formal design process and a set of technical coefficients for meeting the customer's needs. Thus, AD offers a strategy for the effective integration of people, design methods, design tools and design data [9].

In the present thesis, several key AD elements will be reviewed, such as:

1. Introduction to the key concepts of axiomatic design theory
2. Robustness of design by examining designs that involve concerns between the customer's needs and the definition of the functional requirements (FRs), and,
3. Principles and their implications for design

For an effective medical distribution system, there are several elements that must all be linked together as an ongoing process. This includes a robust supply chain process, strong leadership in inventory management, a multi-faceted purchasing process, and a prompt delivery system in place to provide the medications to the patients as needed. In addition to these components,

knowledgeable vendors that can deliver the medications on time, expert hospital management, who ensures the proper distribution of medications to the right nursing stations and an experienced nursing manager and nursing staff that promptly delivers the medications to the patients on a timely basis.

In the present thesis, we propose applying the AD methodology to a medical distribution system with the main objective of allowing nurses the opportunity to provide cost effective delivery of medications to inpatients, thereby improving quality patient care. Therefore, in the present approach, the primary objectives in using the Axiomatic Design methodology for the medication distribution design analysis are to:

1. Maximize the amount of patients that have a single common medication, and,
2. Compare the results of the uncapacitated vs. the capacitated case for the medication distribution problem

The first objective will be achieved through the use of focused stores, where medications can be readily stored and can be conveniently located near patients, as well as a mobile apparatus that can also store medications and is commonly used by hospitals, the medication cart.



Figure 1-1: Pictures of Medication Carts [4]

The medication cart is made by a number of companies such as Stanley Inner Space, Medline and Rubbermaid. Its ease of mobility to be positioned in areas of the nursing ward that the nurses deem appropriate allows them to continue to provide quality patient care. Most importantly, it gives the hospital staff the means to provide medications to inpatients in a timely fashion.

The first objective will be addressed by seeking opportunities to find the greatest number of patients that have a single common medication. This concept is called the commonality factor, which will be described in more detail in Chapter IV.

For the second objective, we will examine both the uncapacitated and capacitated scenarios for the medication distribution case study presented in Chapter IV. The uncapacitated case is when there are no restrictions on the amount of product that can be stocked and that is available. The capacitated case is when there are restrictions placed on the amount of product that can be stored and is available. Traditional rewarehousing/techniques of material allocation and additional investment for processing are not considered in this case. On the other hand, the capacitated case is when there are limitations as to the capacity or space that can store medications for the patients. This is mainly due to the lack of resources that are available to stock the products.

CHAPTER II

2.0 LITERATURE REVIEW

This chapter is a review of recent and applicable literature related to the AD methodology and the application of this concept to provide a good delivery process of the medications and information about the health condition of the patients. A broad overview will be provided on the supply chain management of delivering the medications to the patients in a timely fashion. Emphasis will be directed to the AD concepts that can be integrated into this logistical operation.

2.1 Axiomatic Design Framework

AD has been applied to a variety of products, systems, organizations and processes such as machines processes, space systems, software organizations and materials. Moreover, organizations have been designed using AD to improve their efficiency by removing unnecessary and sometimes undesirable human barriers and interactions [2].

The AD world is made up of four domains: (1) Customer Domain, (2) Functional Domain, (3) Physical Domain and (4) Process Domain.

The customer domain should be characterized by the customer attributes (CAs) that the customer desires in a product, process, system, organization or materials. In the functional domain, customer needs are satisfied in terms of functional requirements (FRs) [2, 15, 16].

To satisfy the specified FRs, decision parameters (DPs) are conceived in the physical domain

Finally, to produce the product specified in terms of DPs, a process is developed that is characterized by process variables (PVs) in the process domain. Many different fields including manufacturing systems, software, hardware, materials, and organizations can be described in terms of these four design domains [2, 5, 16].

Suh (1998), incorporated the AD theory into the theory of systems by his development of the FRs, DPs and PVs. Just like the AD theory, he believed that this systems theory had many applications in different kinds of systems, including machines, large systems, software systems, organizations, and systems consisting of a combination of hardware and software [16].

Moreover, Engelhardt (2000), merged the concepts of the FRs, DPs and PVs in his proposed problem solving approach for existing designs in conjunction with seven quality control tools, noise factor analysis and design experiments in order to complete a thorough investigation of possible problems within the design to form an approach for quality improvements and problem solving [17].

Kremer *et al* (2012), also incorporated these same concepts with the Theory of inventive problem solving technique (TRIZ) and optimization in its effort to seek an optimal locomotive ballast arrangement design system [6].

Once the perceived customer needs are identified and defined (i.e. the attributes the customer is looking for in a product) in the customer domain, these needs must be translated into FRs in the functional domain. This must be done within a ‘solution-neutral environment’. This means that the FRs must be defined without ever thinking about something that has already been designed or what the design solution should be.

Once the FRs are chosen, they must be defined into the physical domain through the design parameters (DPs) that can satisfy the FRs. The mapping process is typically a one-to-many process, that is, for a given FR, there can be many possible DPs. The right DP must be chosen by making sure that other FRs are not affected by the chosen DP and that the FR can be satisfied within its design range. Figure 2-2 illustrates this domain structure [2]:

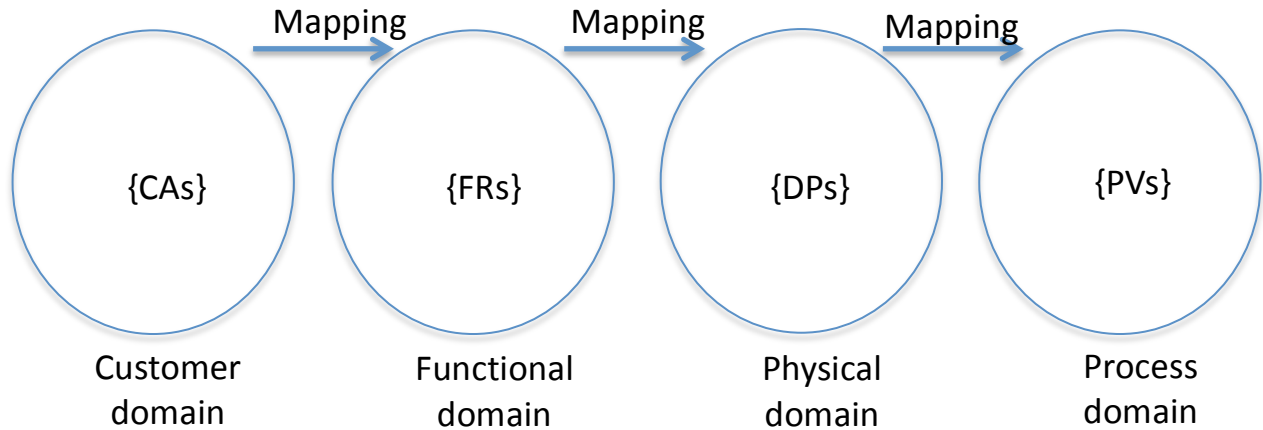


Figure 2-1: Four domains of the design world [2]

For defining a design in terms of a mapping process, this is illustrated in Figure 2-2. The domain on the left represents what we want to achieve, relative to the domain on the right, which represents the design solution, that is, how we propose to satisfy the requirements specified in the left domain [2, 5].

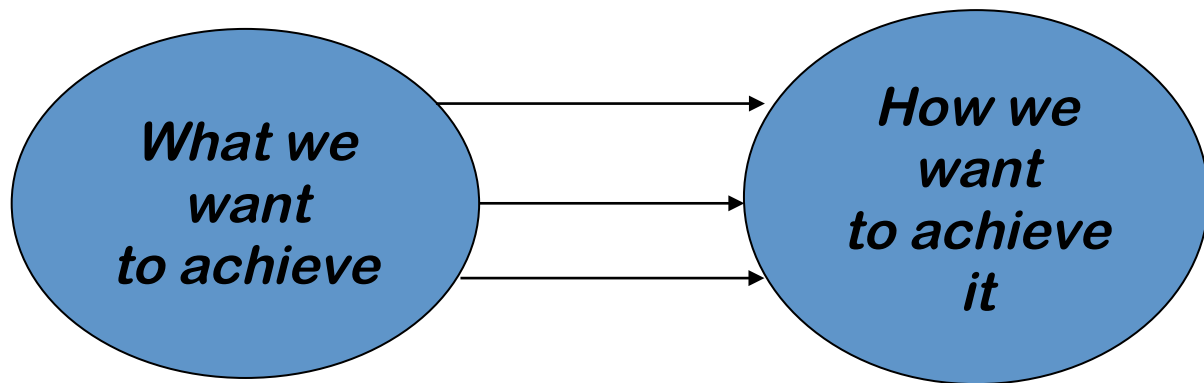


Figure 2-2: Definition of Major Objectives of Axiomatic Design [2]

Gutierrez and Crispin (2005), used the concepts presented in Figure 2.2 when analyzing the scheduling practices of a preprinting laminated tab divider manufacturer. The company's desire to have a quick response to customer demand and inquiry rapidly and efficiently leads to the 'What we want to achieve' phase since compliance with customer demands is vital for the organization to retain and increase its market share. To conform with the 'How we want to

achieve it' phase, this company relies on its ability to perform scheduling operating practices in both the Made-To-Order (MTO) and Make-To-Stock (MTS) environments.

These production-scheduling decisions achieve two major objectives: (1) full resource utilization and, (2) the quick response to product priorities based on product demand requirements. There are several phases in this decision-making process to achieve an optimal scheduling environment. The first phase is the rough-cut capacity assignment phase where a global capacity analysis based on current production schedule and new orders based on due dates and priorities are performed. The next step is a local capacity assignment phase where a relationship matrix is developed for those items that are on the production/customer order schedule and required in the upcoming week and/or current week. Then a clustering analysis for initial product/capacity allocations is conducted. This is where a hierarchical clustering algorithm is utilized to construct a logical number of clusters given the computationally difficult class of NP-complete problems. Finally, candidate items for the proposed clusters from the non-hierarchical clustering analysis are then selected on the order scheduling system using the order assignment factors such as priority, capacity required, and size of the demand transaction. Pair-wise interchanges for the same sized clusters and adjacent clusters are performed to improve assignments by trading off machine/cells and due dates. For the most efficient arrangement, the actual assignments are performed and the number of required scheduling times for each order are generated [11].

2.2 Axioms in the Axiomatic Design

The basic postulate of an AD theory is that there are fundamental axioms that define acceptable designs. Axioms have played a major role in developing mathematics, natural sciences and engineering, for example, Newton's laws of mechanics, Euclid's geometry, and the laws of

thermodynamics. These axioms also help to eliminate the possibility of making mistakes when products – both hardware and software – are developed [2].

The first axiom is called the Independence Axiom. To satisfy the conditions of this axiom, the independence of FRs must always be maintained [2, 5, 6, 7, 13]. It also implies that when there are several FRs, the design must be such that the FR can be satisfied without affecting any of the other as FRs [2]. The second axiom is known as the Information Axiom, which states that among those designs that satisfy the Independence Axiom, the design with the highest probability of functional success will be the best design [2, 5, 6, 7, 13].

2.3 The First Axiom: The Independence Axiom and the Design Process

The Independence Axiom states that the independence of the FRs must always be maintained [23]. The relationship between FRs is decided by the choice of DPs. It should be noted that FRs are independent from each other by definition. Therefore, we have to choose a correct set of DPs to be able to satisfy the FRs and maintain their independence [2].

Once the FRs have been established, the next step is to conceptualize the design solutions. This is a mapping process from ‘what’ in the functional domain to ‘how’ in the physical domain.

During this process, we must consider the different ways of fulfilling each of the FRs by identifying plausible DPs. Sometimes it is convenient to consider a specific DP to satisfy a specific FR, repeating the process until the design is completed.

When there are many FRs, the design task can become difficult since the Independence Axiom may be violated. Measures must be taken to ensure that these difficulties are addressed early in the process [2, 6, 7].

To create an engineered system that is acceptable, the FRs and constraints related to that could arise must be identified and designed for from the very beginning of the design process. To

satisfy these and other FRs of the system, DPs and PVs must be chosen. Any physical embodiment of products and systems is acceptable as long as the FRs are satisfied with any given set of constraints. Unless FRs are correctly defined at the beginning of the design process, it becomes difficult to incorporate human factors when the design is completed. It is equally difficult to modify an existing system to issues that may arise [2].

The design equation relating these FRs and DPs together is [9, 13]:

$$FR = [A]\{DP\} \quad (2.1)$$

where $[A]$ is called the *Design Matrix* that relates FRs to DPs and characterizes the product design. For a design that has three FRs and three DPs, the design matrix is the following:

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (2.2)$$

Equation (1) is a design equation for the design of a product; in differential form it is written as:

$$dFR = [A]\{dDP\}$$

where the elements of the design matrix are given by:

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j}$$

For a linear design, A s are constants; for a nonlinear design, A s are functions of the DPs. There are two special cases of the design matrix:

- (1) The diagonal matrix, where all $A_{ij} = 0$ except for those where $i = j$.

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \quad (2.3)$$

- (2) The triangular matrix as shown below:

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (2.4)$$

For the design of processes involving mapping from the $\{DP\}$ vector in the physical domain to the $\{PV\}$ vector in the process domain, the design equation may be written as:

$$\{DP\} = [B]\{PV\} \quad (2.5)$$

where $[B]$ is the design matrix that defines the characteristics of the process design and is similar in form to $[A]$.

Albano and Suh (1994), utilized many of the concepts previously discussed in his application of AD in concurrent engineering. He felt that the DPs specified in the physical domain are functional requirements that must be satisfied in the process domain. He also believed that the zigzag mapping and decomposition activities must be coordinated across the functional, physical and process domain. Finally, he mentioned that representing the product and process designs in terms of matrix mapping supports a number of operations that can increase the efficiency of integrating the contributions of multiple design disciplines [9].

To satisfy the independence axiom, the design matrix must be either diagonal or triangular. If the design matrix $[A]$ is diagonal, then each of the FRs can be satisfied independently by its respective DP. Such a design is called an *uncoupled* design. When the matrix is triangular, the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. Such a design is called a *decoupled* design. Any other form of the design matrix is called a full matrix and results in a *coupled* design [2, 4, 15].

2.4 Corollaries and Theorems

Many corollaries and theorems have been derived. A few theorems will be stated here to show the useful nature of these theorems in design.

Theorem 1 (Coupling due to insufficient number of DPs): *When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.*

Theorem 2 (Decoupling of coupled design): *When a design is coupled due to the greater number of FRs and DPs, it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other, if a subset of the design matrix containing $n \times n$ elements constitutes a triangular matrix.*

Theorem 3 (Redundant design): *When there are more DPs than FRs, the design is either a redundant design or a coupled design.*

Theorem 4 (Ideal design): *In an ideal design, the number of DPs is equal to the number of FRs, and the FRs are always kept independent from each other.*

When the design is a redundant design, which may be intentional or unintentional, it may be systematically reduced to an uncoupled design or a decoupled design [2].

2.5 Decomposition, Zigzagging and Hierarchy

Figure 2-3 illustrates the decomposition of the FRs and DPs through zigzagging between the functional and physical domains. We start out in the ‘what’ domain and go to the ‘how’ domain. In the physical (how) domain we can conceptualize a design and determine a DP that will correspond to the FR that must be satisfied. Once a DP is chosen, we zigzag to the functional domain to create FR1 and FR2 at the next level that collectively satisfy the highest-level FR. FR1 and FR2 are the FRs for the highest-level DP. Then we select DP1 and DP2 to satisfy FR1 and FR2, respectively. This process of decomposition is continued until all of the branches reach the final state, where they do not need to be decomposed any further. The final state is indicated by thick boxes, which are called ‘leaves’ [9, 16].

Turhan *et al* (2011), utilized the decomposition technique as part of a decision-making tool incorporating supply chain balanced scorecard performance measured for supply chain reengineering for a paint company [14].

Yenisey (2007), merged the decomposition procedure in his approach to create a design process in his quest to create quality E-commercial websites [19].

Ullah (2005), also incorporated the idea of decomposing the FRs and DPs in his axiomatic design-like formulation using linguistic design formulations (LDFs) in order to develop an effective method for determining the optimal design embodiments under the following assumptions: (1) the design approach involves the axiomatic design theory, and (2) the design-relevant information refers to a designer's intuition, expressible as qualitative computer information, known as f-granular information [18].

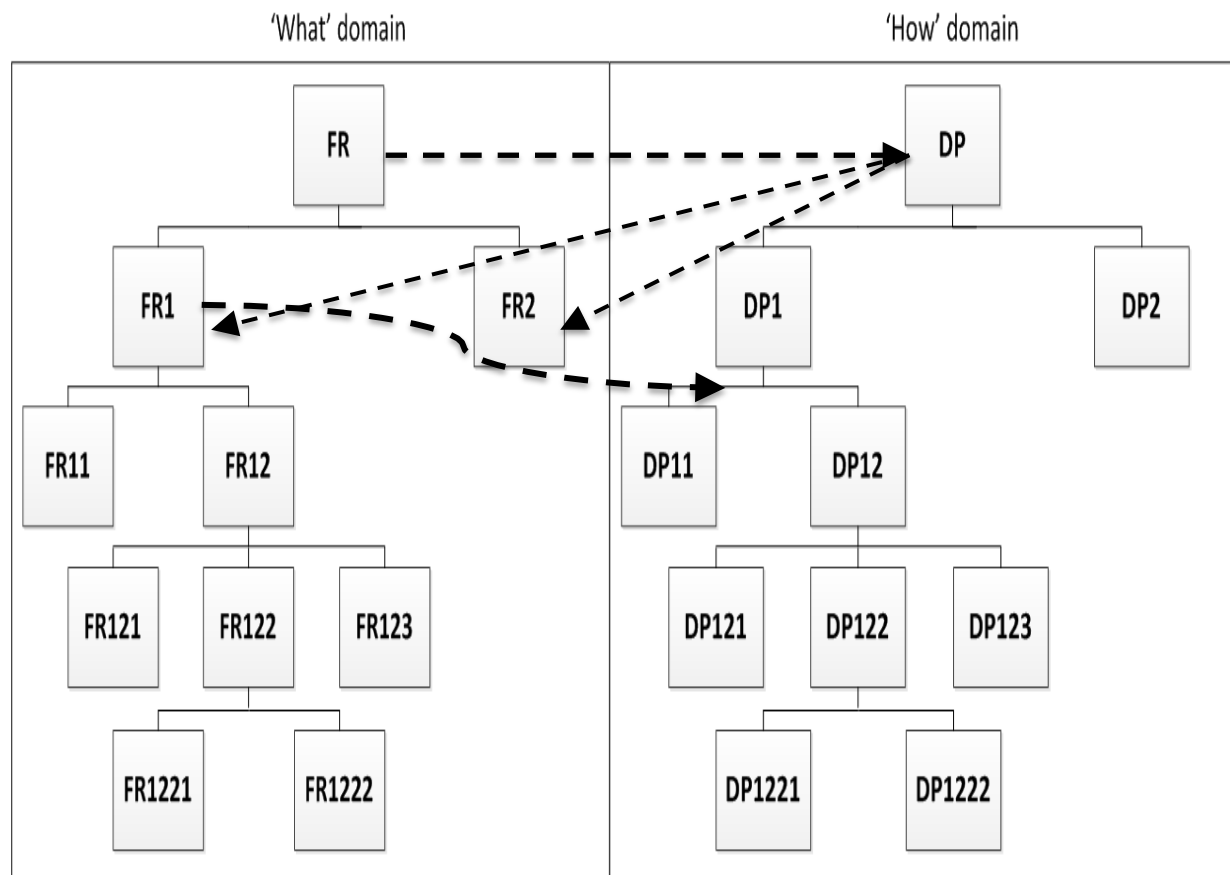


Figure 2-3: Comparison of Traditional Functional Decomposition Model vs. Axiomatic Decomposition “Zigzagging” in functional and physical domains to create FR and DP hierarchies [2]

Figure 2–3 also illustrates a case with five abstraction levels. The top FR and DP are fairly abstracted. The design details are developed as the design is decomposed [2, 6, 7, 14].

For each level of decomposition we must specify the design equation: $(FR) = [A](DP)$. This is to be sure that the right sign decision was made.

Suppose that the designer came up with the decoupled design represented by the following design equation:

$$\begin{pmatrix} FR_1 \\ FR_2 \end{pmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{pmatrix} DP_1 \\ DP_2 \end{pmatrix} \quad (2.6)$$

Since design details have not been developed at this stage of the design process, the triangular matrix represents the design *intent*. All subsequent lower-level design decisions must be consistent with this high-level design decision. At each level of decomposition, the design decisions must be made consistent with all higher-level design decisions.

A designer must develop detailed designs that do not violate the original design intent. When he finds that existing technologies cannot be used, new inventions and innovations must be created. Whenever possible, we must model and analyze the proposed design. In some cases, the design matrix, which is formulated in terms of X and 0 , must be further developed by replacing the X 's with the equations or numbers. We will then have a set of equations that relate FRs the DPs [2].

2.6 The Second Axiom: The Information Axiom

There may be many acceptable designs that satisfied the Independent Axiom. For a given set of FRs, there may be many acceptable design solutions. The Information Axiom can be useful in selecting the best among those designs. The Information Axiom provides the theoretical basis for design optimization and robust design. It states that a design with the minimum information content is the best design.

Information content I_i for a given FR_i is defined in terms of the probability P_i of satisfying FR_i .

$$I_i = \log_2 \frac{1}{P_i} = -\log_2 P_i \quad (2.7)$$

The information content is expressed in bits of information. The logarithmic function is chosen so that the information content will be additive, which is useful when many FRs must be satisfied simultaneously.

In the general case of m FRs, the information content for the entire system I_{sys} is:

$$I_{sys} = -\log_2 P_{(m)} \quad (2.8)$$

where $P_{(m)}$ is the joint probability that all m FRs are satisfied.

When all FRs are statistically independent as is the case for an uncoupled design,

$$P_{(m)} = \prod_{i=1}^m P_i$$

then I_{sys} may be expressed as:

$$I_{sys} = \sum_{i=1}^m I_i = -\sum_{i=1}^m \log_2 P_i \quad (2.9)$$

When all FRs are not statistically independent, as is the case for a decoupled design,

$$P_{(m)} = \prod_{i=1}^m P_i | \{j\} \quad \text{for } \{j\} = \{1, \dots, i-1\} \quad (2.10)$$

where $P_i | \{j\}$ is the conditional probability of satisfying FR_{*i*} given that all other relevant (correlated) {FR_{*j*}}_{*j*=1,...,*i*-1} are also satisfied. In this case, I_{sys} may be expressed as:

$$I_{sys} = \sum_{i=1}^m \log_2 P_i | \{j\} \quad \text{for } \{j\} = \{1, \dots, i-1\} \quad (2.11)$$

The Information Axiom states that the design with the smallest I is the best design, since it requires the least amount of information to achieve the design goals. When all probabilities are equal to 1.0, the information content is zero, and, conversely, the information required is infinite when one or more probabilities are equal to zero. That is, if the probability is small, we must supply more information to satisfy the FRs [2, 13, 16].

Weng and Jenq (2012), incorporated many of the concepts concerning the information axiom to

improve the design of machine tools and equipment used for agile manufacturing units as well as contribute to the evaluation model in the decision-making process to maximize the evaluation indices [7].

The FR must be satisfied within the specified range, which we define as a *design range*, we accept the design. The probability of success is governed by the intersection of the design range defined by the designer to satisfy the FRs and the ability of the system to produce the product within the specified range [2]. The probability of success can be computed by specifying the *design range* for the FR and by determining the *system range* (DP range) that the proposed design can provide to satisfy the FR. Figure 2-4 illustrates these two ranges. The vertical axis represents the probability density and the horizontal axis represents either the FR or DP, depending on the mapping domains involved; for product design, the horizontal axis is a FR and for process design, it is a DP [2, 8].

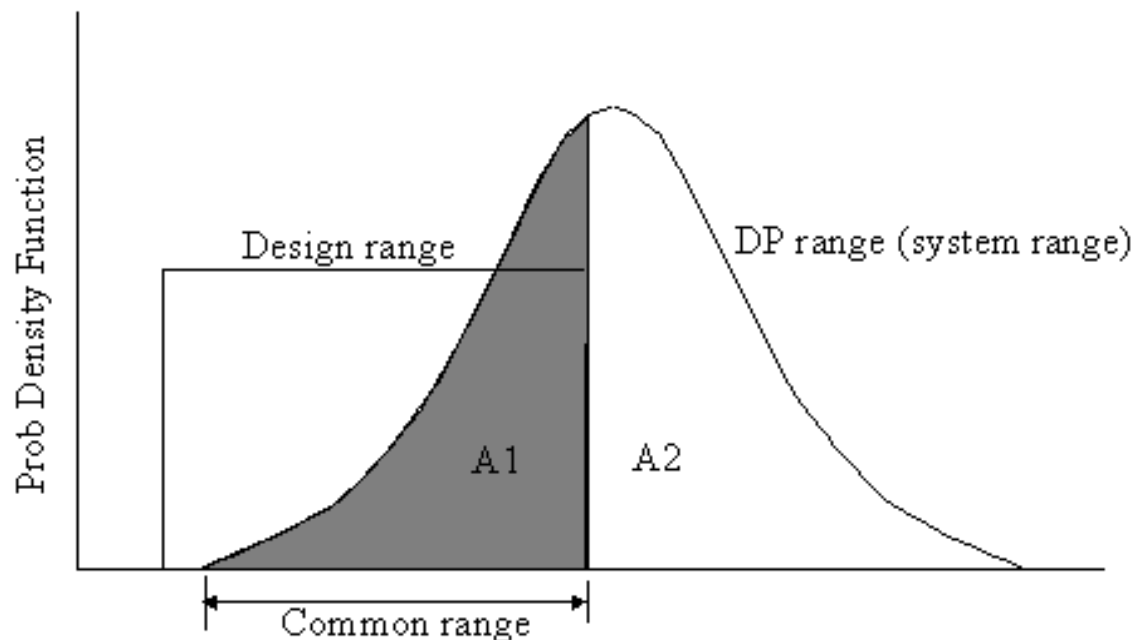


Figure 2-4: Design range, system range, common range and system PDF for a FR [8]

Clearly, those instances of the *system range* which contribute to the distribution shown in the shaded area, A1, are acceptable designs (successes), while those that fall outside this range, in area A2, are unacceptable (failures). Thus, the probability of success, P, in this case would be:

$$P = A1/(A1 + A2) \quad (2.12)$$

If the DPs are distributed uniformly over the *system range* (uniform distribution instead of normal), then a simpler formula to use would be [8]:

$$\text{Probability of success } (P) = \frac{\text{common range}}{\text{system range}} \quad (2.13)$$

To achieve a robust design, the system range should lie inside the design range, thus reducing the information content to zero. This can be achieved if the variance of the system and the bias are small. The bias can be eliminated if the design satisfies the Independence Axiom [2].

Celik *et al* (2009), utilized the ideas contained in the Information Axiom, in particular the concepts associated with the design range, system range, common range and system probability density function for a FR when he was developing a systematic evaluation model on docking facilities of shipyards to provide a decision aid for technical ship managers and to perform this responsibility in an efficient manner [10].

2.7 Axiomatic Design Process

Understanding the customers' needs is paramount for successfully converting their suggestions into a tangible concept that can be utilized to improve a product, organization, system or material. Their recommendations are often stated in non-engineering terms (e.g. a stereo system that sounds good). Also, several of the requirements may be implicit. It is the engineering designer's task to identify and adapt these requirements to somewhat more engineering specific requirements (the Signal to Noise ratio of the stereo must exceed 100 decibels). Thus, the customers' needs are converted into a set of FRs that will be satisfied by the design. The actual

design artifacts that satisfy each of the FRs lie in the design domain (a particular combination of pre-amplifier and power amplifier that yield the required signal amplification) [8].

In the present study, the nurse manager would be the customer with the main objective of “Ensure quality patient care by getting the medications to the patients on time.” Converting this into an engineering statement would yield the following result, “Minimize the delivery costs of medications to the patients.” This statement would be the problem definition.

Figure 2-5 provides a step-by-step process when developing an application of axiomatic design. Following its path, the FRs, DPs and the PVs should be determined. The FRs are needed to identify the customer requirements; the DPs are the means to satisfy the FRs and the PVs are the manpower, tools or material handling to accommodate the DPs. At this point, the constraints should be developed in order to determine the acceptable bounds for the case study. This information should be combined and arranged in terms of the maximization and/or minimization of the candidate DPs and PVs. Then, the main issue for each product will be decomposed into basic-level problems [6]. There should be one FR to one DP (i.e. a coupled design will be obtained). It is required that the parameter design matches the FR. It is mandatory to explain the AD procedure for definition and design information that is necessary to match the FRs with the parameter design and improve the satisfaction of the original need to the evaluation of the information content.

Uang *et al* (2011), used this step-by-step approach in conjunction with the Theory of Inventive Problem Solving (TRIZ) to establish a systematic product design model for a handheld Global Positioning System (GPS) product. The model’s efficiency was analyzed and evaluated to determine its effectiveness [20].

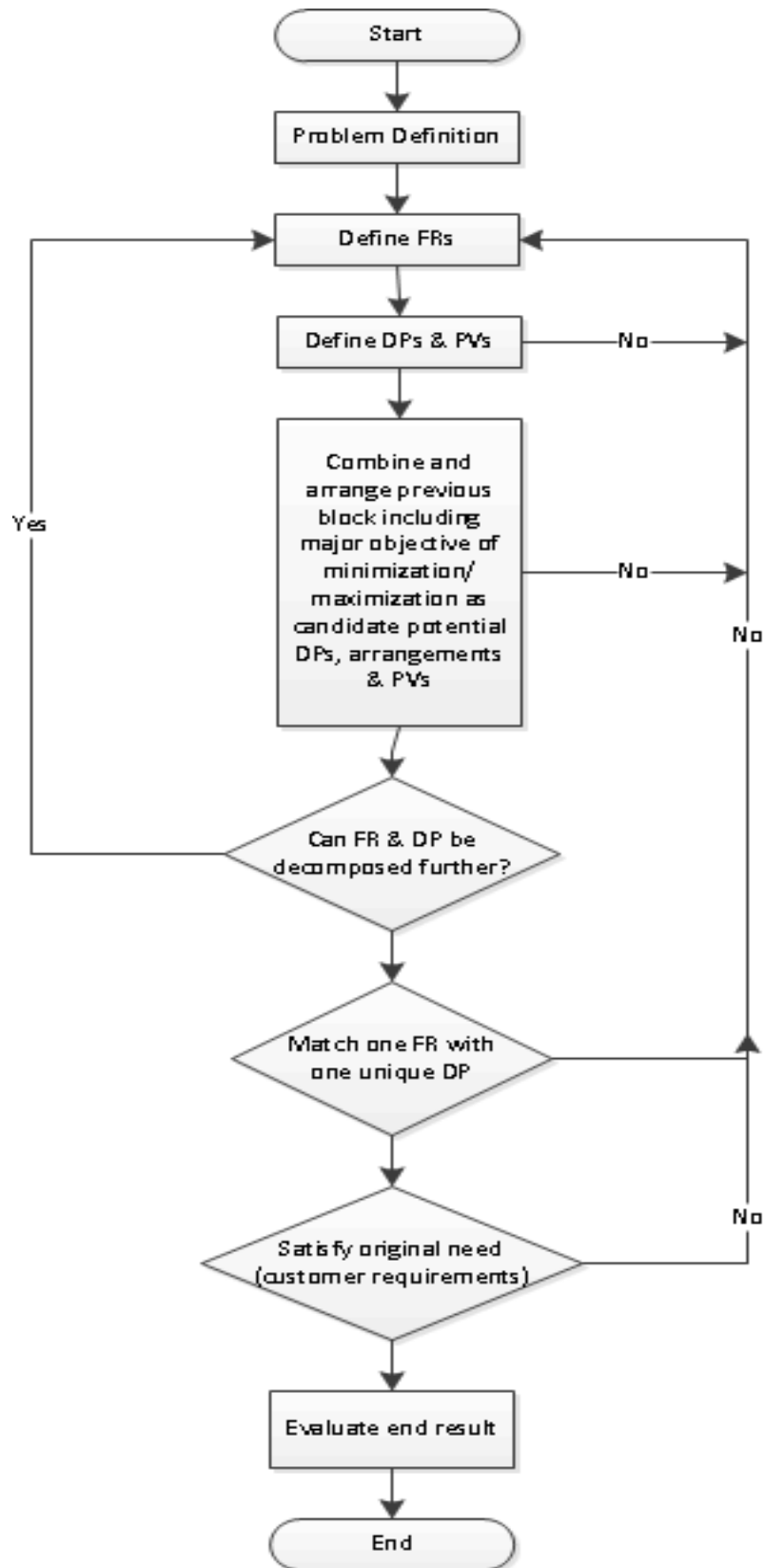


Figure 2-5: Axiomatic Design Procedure [5]

CHAPTER III

3.0 INTRODUCTION

Section 3.1 discusses several important concepts that are pertinent to the medication distribution design problem. Section 3.1.1 starts this chapter with an introduction to multi-echelon inventory systems, which lays the groundwork when performing a sensitivity analysis for different parameters of an ideal medication distribution system. The focused store (i.e. storage media that can store medications within the vicinity of patients) methodology proposed in Section 3.1.2 is presented as a decision support tool and will serve as a tie-in between the theory of multi-echelon inventory systems as well as the development of a mathematical model (in the next chapter) for both an uncapacitated and capacitated medication distribution case study. It requires the assumption of a planning horizon. In Section 3.2, the different medication stocking definitions and processes are introduced in section 3.2.1 while in section 3.2.2 an axiomatic design framework for the medication distribution problem is presented. Section 3.3 follows with general costs concepts pertinent to the medication distribution problem.

3.1 Concepts

3.1.1 Multi-Echelon Inventory Systems

The multi-echelon inventory system is characterized by three administrative components: the organizational structure, policies governing purchases and inventories, and dynamic operating actions and decisions.

The echelons define the organizational structure where the inventory exists. The policies governing purchases and inventories are the set of rules established for daily activity such as levels of working process inventory, replenishments, vendor product supply, decentralized stores inventory, and levels of reorder point.

Dynamic operating actions and decisions refer to the production orders required to satisfy customer demands as well as the multi-bin/medication order system signals required to adjust inventory fluctuations at the focused stores based on the level of medication distribution activity. Given the current level of activity at the vendor's headquarters where the customer's medication orders are being loaded to the current weekly production master schedule without any time fence considerations, it is assumed one-week time fence as a period of influence for decision-making efforts. The organization of the multi-echelon inventory system is shown below:

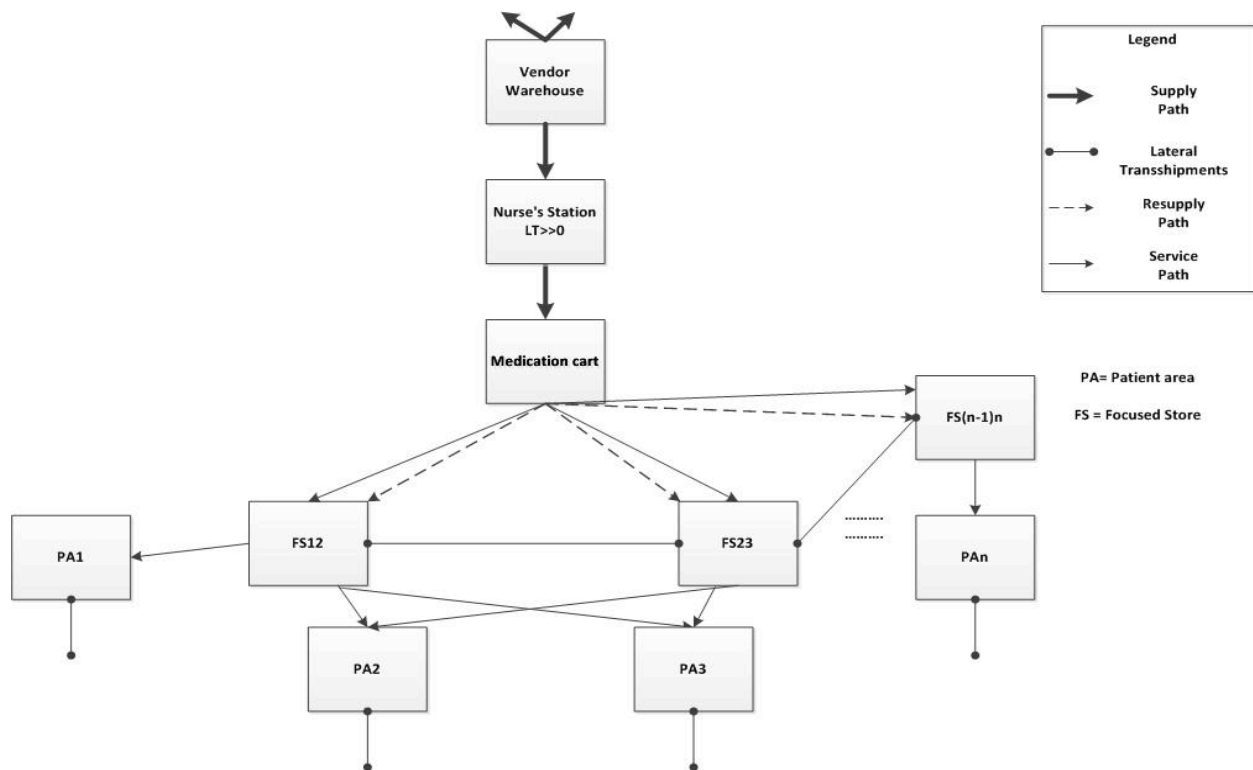


Figure 3-1: Multi-Echelon Inventory System

Figure 3-1 consists of a source (i.e. the vendor warehouse) from where the medications originated from could be transported to the nurse's station. The nurse's station is the primary storage area for the medications and serves as the designated pickup point where the nurses can transfer the medications to the medication cart. The nurse can use this medication cart to deliver medications to the patients. There are n patient areas (n is the number of patients) where the

patients are located (i.e. PA1, PA2, PA3,..., PAn), and $n-1$ focused stores (FS12, FS23,..., FS $(n-1) n$) that can store the medications within the vicinity of the patients and the stationary focused stores and can be resupplied as needed. In this particular setup, the patients can be served by either the medication cart or FS12, which is placed between PA1 and PA2. Similarly, the medication cart or FS23 serves PA2 and PA3 and FS $(n-1) n$ is for PA $(n-1)$ and PAn.

One of the most important points in this schematic is the emphasis on the paths that are illustrated. The supply path (represented as the dark arrow \Rightarrow) is a supply chain route primarily between the vendor warehouse and the nurse's station. The lateral transshipments (displayed as two dots joined by a line $\bullet \text{---} \bullet$) are replenishing events between each of the medication carts where the nurses can conveniently resupply one stationary focused store from another focused store. The service paths (depicted by the light arrow \rightarrow) represent a trail where medications can be given to patients individually. Again, these medications are taken directly from the stationary focused store to the particular patient. Finally, the resupply paths (shown as the dashed light arrow $- - \rightarrow$) are restocking opportunities for hospital staff to deliver medications from the medication cart to each of the stationary focused stores.

The methodology is designed to respond to demands placed on stocking points based on the requirements at the finished goods level, subassembly level and the stocking points at different points in time based on material consumption. It also includes the modeling of demand processes for intermittent customer demand patterns. Demands depend on the needs at the higher echelon levels, for different times, quantities, and priorities and can be routed to different stocking points within the system.

The decision to stock a medication at the focused store depends on its commonality relative to the storage locations. In this regard, the metric for measuring commonality is defined by the

number of patients consuming the medication. The decision regarding where a medication may be stocked in the focused stores is based on cost-tradeoffs. Thus, a shared focused store offers the advantage of reduced safety stock due to risk pooling. However, this advantage may be offset by additional handling costs.

Finally, Figure 3-1 sets the stage for several possible scenarios that would be investigated for the medication distribution design problem:

1. Commonality factor (CF) = 1, (a fully centralized system, which tends to support the uncapacitated case; medications would be located at the nurse's station)
2. CF = 2, (depicting either a fully centralized system or a fully decentralized system)
3. CF = 3 and higher, (depicting a fully decentralized system which tends to support the capacitated case; medications would be located in the focused stores at or near the patient rooms)

Both the uncapacitated and capacitated case will be explained in further detail in Chapter IV.

3.1.2 Focused Stores Methodology

The proposed methodology is defined in five major phases of data analysis and is shown in Figure 3-2. These major phases in simplified terms can be defined as:

- | | |
|------------|-------------------------------|
| Phase I: | Uncapacitated location |
| Phase II: | Uncapacitated allocation |
| Phase III: | Bin sizing (Medication order) |
| Phase IV: | Capacitated location |
| Phase V: | Slotting |

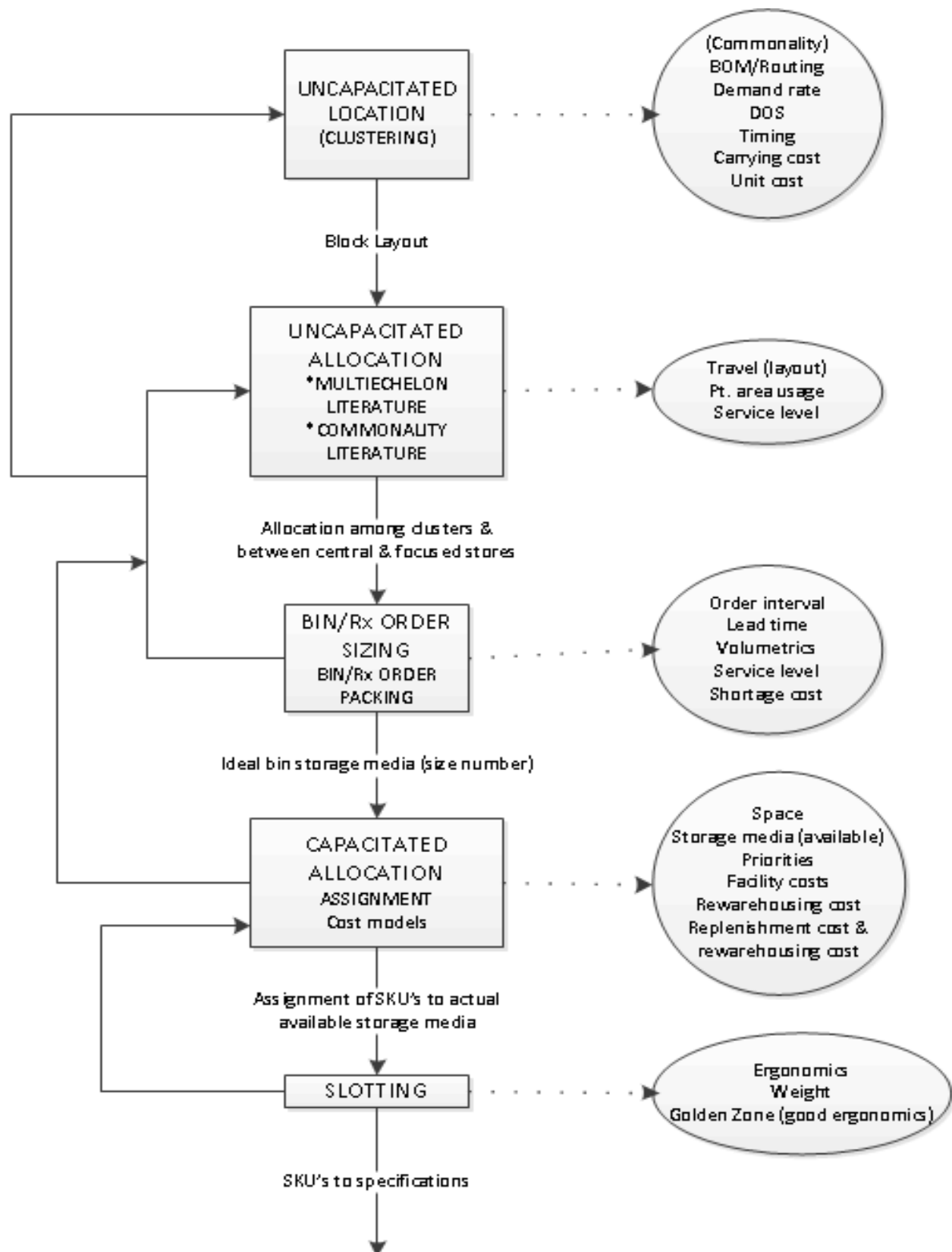


Figure 3-2: Major phases of Focused Store methodology

Phase I provides the clustering analysis to group sets of medication-based commonality, Duration of Stay (DOS), and medication-allocation timing. Phase II identifies the medication allocation, which is amongst the medication clustering and between the central warehouse and the focused stores. At this juncture, any conditions of cluster overloading and lateral transshipments should be solved before proceeding to Phase III. Bin sizing/medication order analysis should account for conditions such as volumetrics and service levels and is required to identify “ideal” size and type of storage media. Under conditions of unfeasibility of sizing/order parameters, the analysis requires that Phase II be performed again until sizing/order selected parameters from Phase III becomes feasible. Phase IV determines the assignment of medications to actual available storage media that reflect conditions of space, priorities, and facility and warehousing costs. The decision to proceed to Phase V should be made only when it is feasible to assign medication types. Otherwise, the analysis will require recalculation of Phase II and III. Phase V defines medication types to specifications considering ergonomic conditions. Thus, it is required that Phase IV be recalculated for re-allocation of space among ergonomic and non-ergonomic medication distribution conditions.

The objective of Phase I is to define clusters of different medications that are associated based on similarities of seven dimensions: Demand, volumetrics, commonality, Duration of Stay (DOS), timing, carrying cost and unit cost. One major constraint that should be addressed is the customer intermittent demand, where the vendor does not have control. Demands are not all similar; they may be for different finished goods, different quantities, contain different priorities, and have different backorders and shipment policies. The ability of modeling production conditions is difficult and complex. Therefore, a proposed forecasting method is applied to generate material production requirements at the component level, considering bill of materials

and production routings to characterize the medication-patient area relationship. Another aspect that is considered is the DOS, which refers to time buckets required for material consumption in the patient area. Longer DOS corresponds to higher space requirements in the focused stores and higher material handling requirements if the material is not located next to patient area. The shorter or the average DOS represents lower requirements in terms of time buckets within the production plan and lowering carrying cost for inventory cost. Timing is an important dimension for medication clusterization given the inventory constraints of space and volume in the patient areas. Unit cost of material is also considered during the clusterization analysis.

The material allocation among the medication carts and the focused stores is the objective of Phase II. It is considered material allocation across different patient areas under conditions of high commonality; there is more than one focused store that is needed to store the same medications. Furthermore, it is required to analyze multi-echelon inventory systems at the service levels, patient area usage and nursing ward layouts for material handling across the patient areas. Conditions of transshipments among the same echelons for material commonality and clustering overlapping are considered and revised between Phases I and II.

The conditions of lumpiness in the demand variation are considered at this point to validate the operating conditions of the multi-bin sizing/medication order inventory system as a viable tool for specific demand conditions. Push systems will be advised as a potential implementation tool to control materials when this system is not valid under lumpiness conditions of demand.

The objective of Phase III is to determine the “ideal” bin/medication order storage media that is necessary for the current production schedules for each stocking point. It is considered in the analysis conditions of order interval, lead time, volumetrics, service level and shortage cost. To validate the solution given in Phase III, the current storage conditions and storage media

available are considered in Phase IV.

The assignment of medication type to the actual available storage media is the objective of Phase IV. In this phase of the algorithm, it is defined as the cost model to incorporate cost information of the nursing ward layout and replenishment. Moreover, it is incorporated information of space, storage media available and priorities. Given that the current conditions of operating Phase III are recalculated, if recalculation of the ideal storage media is also required, this is needed to identify the required storage media for Phase IV.

The objective of Phase V is to define the medication distribution specifications given conditions of weight and ergonomics. The purpose of this is to identify adequate conditions of material storage and retrieval from the storage media located next to the patient areas. Given the constraints of space, if the solution of Phase V requires recalculation, then Phase IV must also be recalculated among ergonomic and non-ergonomic conditions.

3.2 Mathematical Modeling for Medication Distribution Design Problem: the case of finite production rate

3.2.1 Medication stocking definitions and processes

Unit load is a term that is well known to persons involved with material handling, particularly with warehouse activities. The most common example is an arrangement of cartons that is stacked in layers and on a pallet. They would be moved from the vendor warehouse to the nursing stations, which will serve as the primary storage area for the medications as well as the pickup point for the medications to be distributed. The medications can also be stored either at the nurse's station or at the stationary focused stores.

3.2.2 Axiomatic Design Framework for the Medicine Distribution System

The FR for this medication distribution system is defined as the minimization of the costs associated with delivery of medications to inpatients. The constraint considered in this case is the storage capacity of the medication cart. These needs are mapped onto the top-level FR with the associated DP and then are decomposed into lower-level FRs and DPs as shown in the following table:

Table 3-1: FRs with the Corresponding DPs for the Medicine Distribution System Case Study

Objective	Solution
Functional Requirements	Design Parameters
FR1 Minimize delivery costs of medications to patient	Utilization of medication cart (cart) and/or Focused Stores (FSs)
FR1.1 Ready access to all medications for each nurse	Locate cart near patients and/or FSs in vicinity of patient areas
FR1.2 Restock cart or FS periodically with medications	Nurse's station and/or FS near patient rooms that is stocked with medications
FR1.3 Secure cart/FS to prevent theft of medications	Unique combination code for each nurse
FR1.4 Ready access to medication information to each nurse	Computer containing medication information or patient medication cards

If the independence axiom is applied to the table above, it should lead to the establishment of a coupled design for this analysis. The application of the FRs and DPs shown in Table 3-1 should lead to the identification of an input constraint that corresponds to this design. The information axiom should be applied to allow further evaluation of the alternative design process.

Presuming a specific storage location in the proposed multi-echelon network, the next task is to develop a quantitative model that can be used to determine the location/allocation for the different medicine types, which will be described in the next chapter. This is given that the cart will be frequently moved to different areas of the nurse's ward that are within the vicinity of

patient rooms. It is also expected that there is adequate space for medications in the cart or focused store, which renders an uncapacitated location/allocation problem [5].

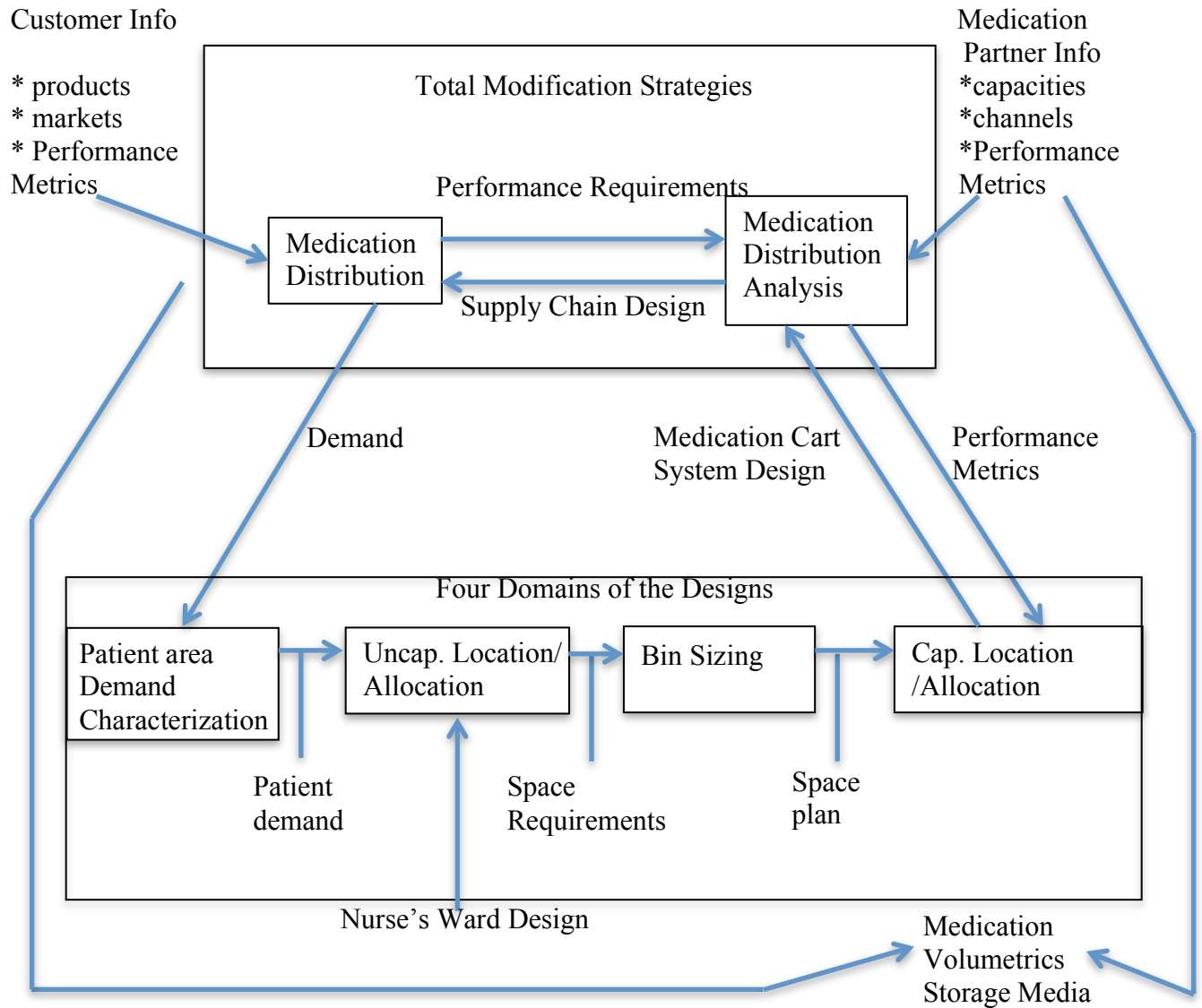


Figure 3-3: Applying the four domains of the AD methodology for a general design problem for medication supply for patients at the hospital level [5]

3.3 Costs concepts

The idea of the Commonality Factor (CF) is to group the maximum number of patients (i.e. patient 1 up to patient n where n represents the total number of patients) to receive a single common medication. Thus, the higher the CF the more patients can receive the same medication. The CF will be part of a procedure designed to minimize the costs associated with the delivery process and will be measured as an independent variable.

There are three types of costs that could be measured as dependent variables to the CF:

- 1) Material Handling Cost (HC): The handling cost is defined as the cost of transporting the medications over a specified distance. For example, the distance from the nurse's station to all of the patient areas. It will be calculated using the following formula:

$$HC = U \times MCD \quad (3.1)$$

where

U = cost of medication cart usage

MCD = moving cost of the medication cart per unit distance

- 2) Inventory Holding Cost (H) – Hs are the costs associated with storing medications at the nurse's station, the focused store (FS) or the medication cart (MC). Storing medications in the MC will incur a holding cost penalty since it is not considered a storage area. The main storage area for the medications is the nurse's station with the FS as the secondary storage area. Once the vendor delivers the medications to the nurse's station, they could be stocked and stored at the nurse's station or transported via the MC and distributed to the stationary FS for storage. The formula for H is:

$$H = \frac{1}{2} QiC \quad (3.2)$$

where

Q = how many units are purchased at a time/quantity ordered

i = interest rate

C = cost of each medication

3. Variable Facility Cost (VC) – This is the cost of moving medications over a distance.

The calculation that is used is:

$$VC = MMC \times TFM \quad (3.3)$$

where

MMC = Medication Cart Movement Cost (refer to Parametric Analysis slide)

TFM = Total Footage Moved

Whether it is the daily or yearly costs, in order to determine the total cost of a medication distribution system it is important to note that there are two components to this cost. There is the: (1) total transportation costs, and, (2) medication distribution costs. It is summarized in the formula below:

$$TMDC = T.C.T. + MDC \quad (3.4)$$

where

$TMDC$ = Total Medication Distribution Costs

$T.C.T.$ = Total Transportation Costs

MDC = Medication Distribution Costs

First, there is the cost of transportation from the vendor to the hospital can be represented by:

$$TCT = C.T. + DC + \text{Holding Cost} \quad (3.5)$$

where

$C.T.$ = Cost of Transportation

DC = Distance Cost from vendor warehouse to hospital

Thus, the second component to the Total Medication Distribution Costs (TMDC) is the cost of operating a medication distribution system between the nursing station and each patient can be determined by the following formula:

$$TMDC = SC + Holding\ Cost\ (POU) + Stockout\ Costs + HC \quad (3.6)$$

where

SC = Setup Costs

POU = Point Of Use

HC = Material Handling Cost

For the present thesis, only the TMDC will be calculated since we are only concerned with transportation costs of medications from the nurse's station to the patient areas.

The setup costs will be the costs of setting up a patient room. Equation 3.6 will be part of the analysis since the case study only goes from the nurse's station to the patient area(s).

Figure 3-1 provides a conceptual view of the general design problem for delivering medications to patients in a way that is compatible with an integrated supply chain strategy. All design tasks are contained in these four domains. In setting up the medication logistical system for a hospital, customer attributes may be the attributes desired by all patients; the FRs may be flexibility, efficiency and controllability; the DPs could be the layouts and design of the supply chain elements themselves as composed of physical elements; and the PVs might be the people and material handling and so on. The successful management of hospital resources planning with incoming medications is dependent on the knowledge of nursing management.

Assuming a network analysis, the optimization network model of a FS system is graphically represented in Figure 3-3 [12]. It also includes the assumptions made in the model.

It starts with a vendor source (denoted as ‘Source’), which delivers medications to the ‘Nursing Station’, which serves as the primary storage area for the medications. For the distribution of the medications, they will be placed in storage bins contained in MC1 and MC2 (referred to as ‘Rack 1’, ‘Rack 2’ and ‘Rack 3’):

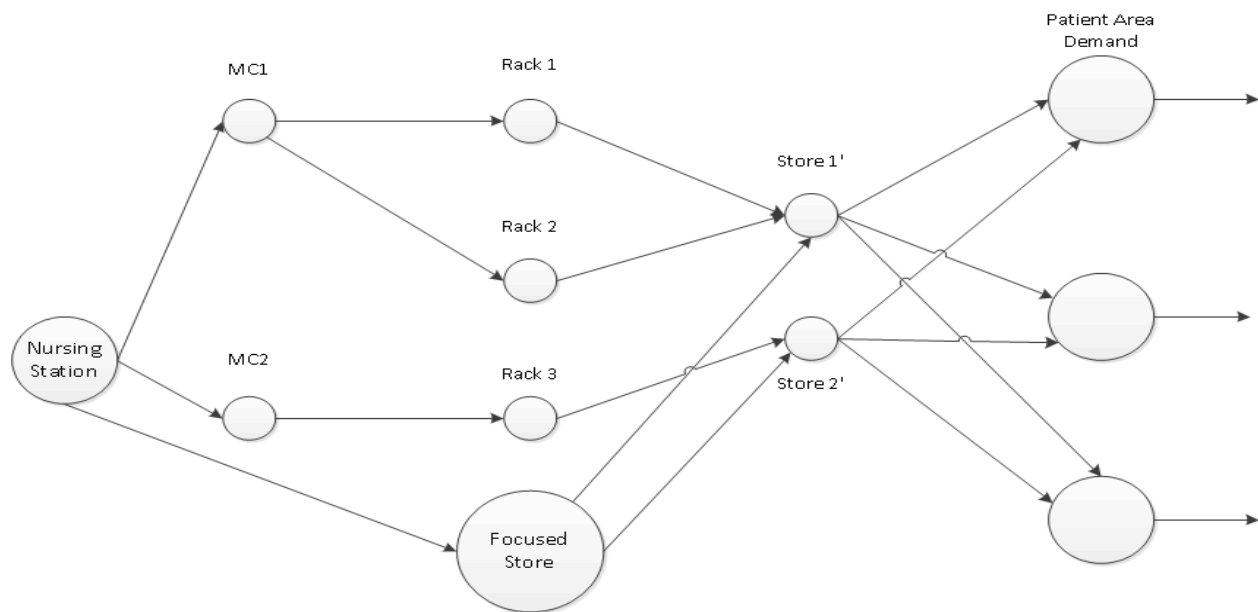


Figure 3-4: Sample optimization network model of a Focused Storage (FS) system [12]

Utilizing these MCs, there are two options that the nurses have to deliver these medications to the patients (shown as ‘Patient Area Demand’). The first option is for the medications to be taken from the nursing station and delivered to the patients. The second option would be for the medications to be moved to the focused stores (depicted as ‘Store 1’ and ‘Store 2’ in the model) and the medications can be taken to the patients from them.

CHAPTER IV

4.0 SENSITIVITY ANALYSIS OVER DIFFERENT PARAMETERS TO DETERMINE LOCATION/ALLOCATION OF MEDICINE TYPES IN A SPECIFIC STORAGE LOCATION

In the present chapter, section 4.1 sets up our case studies by providing a real world example. A specific methodology for the medication distribution design problem is presented in (Section 4.2) by detailing how medications will be distributed to six patients utilizing a schematic nursing layout and describing how this distribution is affected depending on different commonality factors scenarios. Section 4.3 continues this chapter with model formulation assumptions that will be used in Section 4.4, which introduces the mathematical model that will be utilized for the medication distribution case study to attempt to minimize hospital facility and inventory costs. Next, we examine both cases, beginning with an analysis of the uncapacitated case in Section 4.5. Section 4.5.1 focuses on the portfolio effects (safety-stock reduction due to the variance reduction in risk pooling) and facilities effects (variable costs of storage and handling). Section 4.5.2 considers the portfolio effects. Section 4.5.3 provides us with several design rules of thumb based on analysis that is pertinent only to the uncapacitated case. Section 4.5.4 provides a closer examination of the portfolio rule. Section 4.6 provides an analysis of the capacitated case by describing the simulation model used to mimic capacitated conditions. The final section, section 4.7 examines the results of the uncapacitated case (section 4.7.1) and the capacitated case (section 4.7.2).

4.1 Case study

In City X, there are five areas hospitals that range from a 110-bed hospital to a 327-bed hospital. Each hospital consists of a Medical/Surgical unit, Telemetry unit, Emergency Department,

Orthopedic/Neurosurgery unit, Neonatal Intensive Care unit, and an Intensive Care Unit (ICU). For the present thesis, focus will be placed on the ICU. The ICU is a specialized section of the hospital that can provide comprehensive and continuous care for inpatients who are critically ill and who can benefit from treatment [26]. A typical ICU layout is shown below:

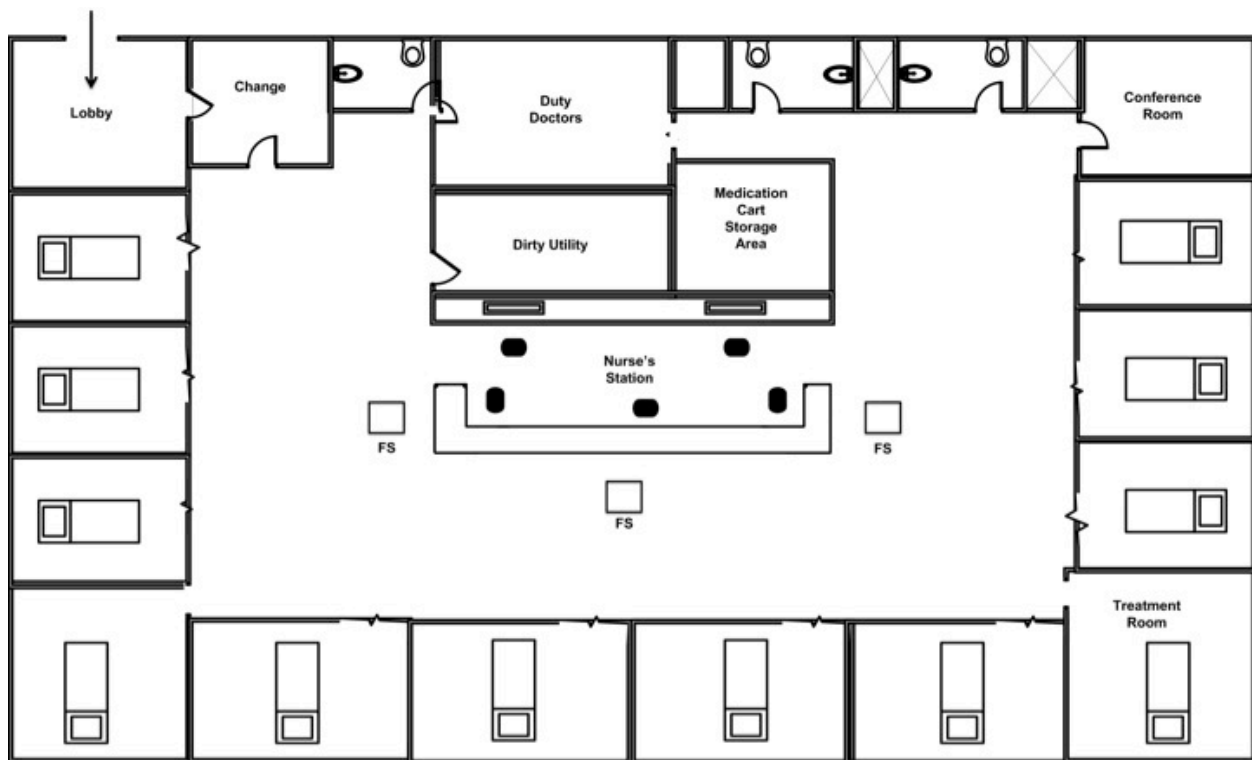


Figure 4-1: Typical Intensive Care Unit layout

In all of the hospitals that were chosen for this study, the ICU consists of 12 beds with a normal patient to nurse ratio of 6:1; range 4:1 to 8:1 [25]. This implies that under normal conditions one nurse can provide up to 6 patients with a single medication (i.e. $CF = 6$). There are two medication carts available that are stored in a designated area near the nurse's station (i.e. Medication Cart Storage Area). The medications, which are stored at the nurse's station, are loaded onto the medication cart and distributed either to the patients or the focused stores (shown as a rectangle labeled 'FS'). The three focused stores shown in the diagram are all within the vicinity of the patient areas and serve as easy access points for medications when the nurses

deem it necessary to obtain medications from them instead of the nurse's station. Two nurses (one working the 7am to 7pm shift and the other working 7pm to 7am) provide each inpatient with their medications once every 8 hours. Thus, the sample study consists of a total of 10 nurses providing medications to a total of 120 patients up to three times per day.

4.2 Methodology

In section 3.2.2, the AD method was presented in Figure 3-3, which is very similar to the drawing shown in Figure 4-2. Figure 3-3 provides a generalistic view of the medication distribution system. Figure 4-2 is focused more at the storage level and will play a key role when utilized with the CF, as explained later in this section.

Figure 4-2 [12] displays the effectiveness of commonality on optimizing a medication distribution system. This figure breaks down the network design described in Figure 3-3 for a commonality factor (CF) up to 3, concentrating solely on the distribution of medications to three patient areas that each has a FS. If it is determined that $CF = 1$, the nurse would deliver the particular medications that each patient needs. If $CF = 2$, the nurse could move the cart to FS2 and then travel a short distance and deliver the same medication type to both PA1 and PA2. In a $CF = 3$ scenario, the nurses could push the cart to FS3 and deliver the particular medication type could then be delivered to all three patient areas.

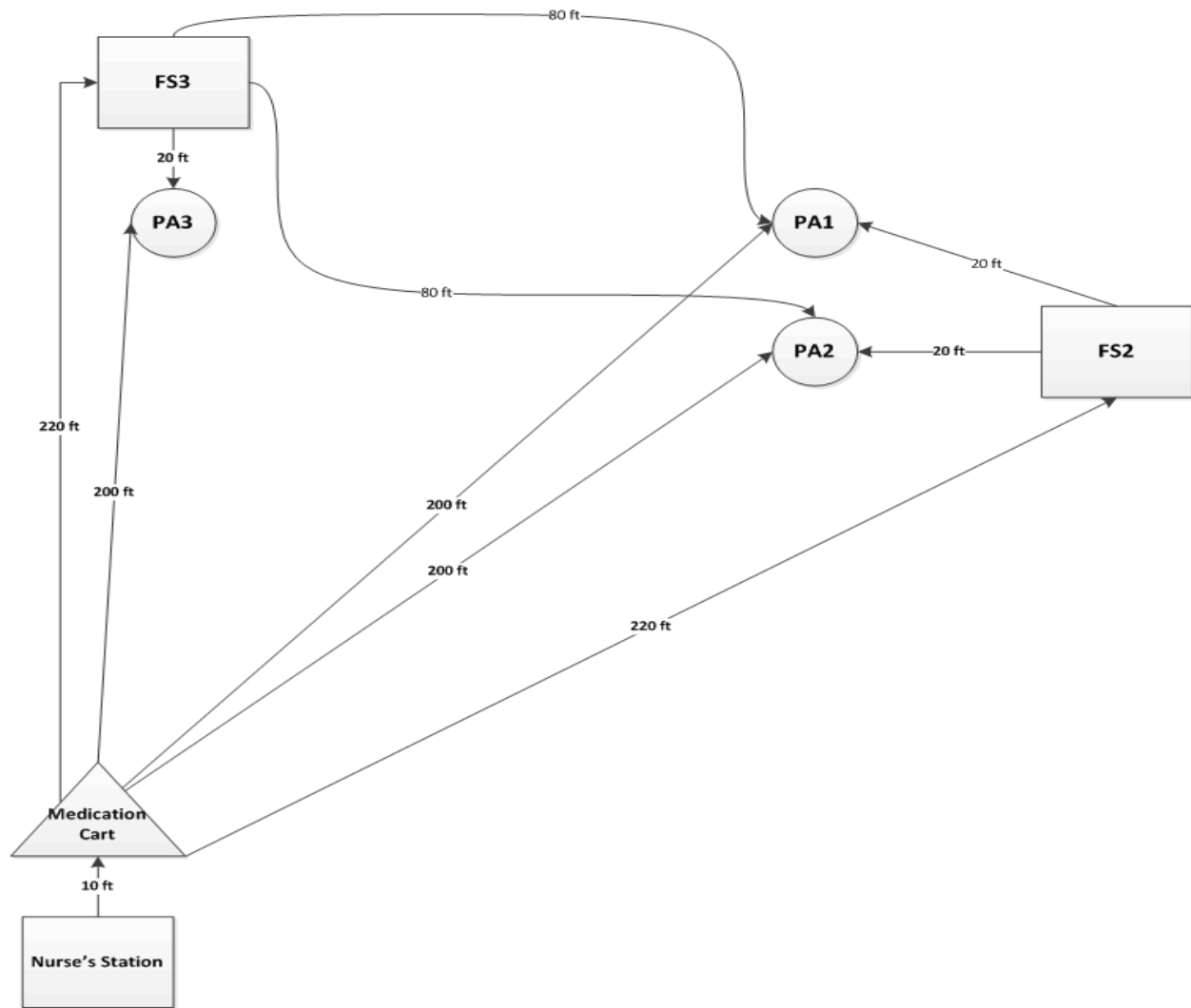


Figure 4-2: Proposed distribution of medications from nurse's station to patient areas [12]

4.3 Model Formulation Assumptions

The model formulation is based on the following assumptions for both uncapacitated and capacitated cases:

- All beds in the nurse's ward will always be occupied with inpatients
- One nurse can administer medications up to a maximum of six patients
- If the patient has more than one medication type that the nurse must administer then the nurse must provide that particular medication and go retrieve subsequent medications (from the nurse's station or focused store)

- There are a maximum of five medication types that are available
- Safety stock is taken into consideration (non-linear constraint)
- Needed medications for patients can always be resupplied from the nurse's station (NS)
- The NS has infinite storage capacity and is always readily stocked with medications (i.e. reordering of medications is assumed and there is no medication shortage)
- Medication carts and focused stores can satisfy more than one patient area component demand, but only one store for patient area per component demand is allowed
- Distance from the NS to any patient will be 200 feet and the distance from the NS to any focused store is 220 feet
- Common zones exist, will be located halfway between two patients and will also be halfway (100 feet) between these two patients and the NS
- All medication types will have a maximum stock of 60 pills and a safety stock of 20 pills but a stock level of 40 pills will also exist
- The bin size of the MC is normally 10 pills but if the stock level of any medication type is 20 pills or less then the bin size of the MC is 5 pills
- For the capacitated case only,
 - A minimum 25% loss in capacity will be assumed
 - Focused stores exist and will serve as storage locations
- The interest rate i will be 14%

4.4 Mathematical Model for the Medicine Distribution System

The solution of the problem is based on a constrained nonlinear model. The objective is to minimize a cost function that includes:

1. Facility costs, including fixed, variable, and units of medicine movement costs, and,

2. Inventory holding cost (H) based on the average inventory level

The constraints will guarantee (1) unique allocation of medications to patient areas, (2) identification of selected medications, (3) satisfaction of minimum space requirements to hold medications in the focused store or the nurse's station (NS), and (4) satisfaction of storage capacity of the focused stores and at the NS.

The deletion of the fourth set of constraints will render the uncapacitated case.

The main variables of the model are defined as follows:

$$a_{jkp} = \begin{cases} 1, & \text{if focused store } j \text{ serves patient } k \text{ for medication } p * \\ 0, & \text{otherwise} \end{cases}$$

* if $j=0$, the storage point is the source

Based on these definitions, the complete mathematical model is given as:

Minimize

$$\begin{aligned} & \sum_{j \in F} \sum_{k \in C} \sum_{p \in P} HC_{jkp} \cdot DM_{jkp} \cdot a_{jkp} \\ & + \sum_{k \in C} \sum_{j \in F} \sum_{p \in P} (MMC_{ikp} \cdot TFM_{ikp}) \\ & + \sum_{j \in F} \sum_{p \in P} Val_p \cdot H \cdot (SS_{jp} + (\frac{1}{2})Q_{jp}) \end{aligned}$$

Subject to

$$\sum_{j \in F} a_{jkp} = 1 \quad \forall \quad k \in C, p \in P \quad (4.1)$$

$$\left. \begin{aligned} Mean_{jp} &= \sum_{k \in C} DM_{kp} a_{jkp} \\ Var_{jp} &= \sum_{k \in C} DV_{kp} a_{jkp} \\ SS_{jp} &= k_p \sigma_{jp} \end{aligned} \right\} \quad \forall \quad j \in F, p \in P \quad (4.2a)$$

$$\sigma_{jp} = \sqrt{R_p + L_p} \sqrt{Var_{jp}} \quad \forall \quad j \in F, p \in P \quad (4.2b)$$

$$Q_{jp} \geq (R_p + L_p) Mean_{jp} + SS_{jp} \quad \forall \quad j \in F, p \in P \quad (4.2c)$$

$$\sum_{p \in P} 2 \cdot Vol_p \cdot Q_{jp} \leq Cap_j \quad \forall \quad j \in F \neq 0 \quad (4.3)$$

$$a_{jkp} \in \{0,1\} \quad \forall \quad j \in F, k \in C, p \in P \quad (4.4)$$

The sets C, F, and P are used in the model are defined as follows:

C = set of patient locations (i.e., use points)

F = set of potential storage points (e.g., focused stores)

P = set of medications j

The parameters used in the model are defined as follows:

Cap _{j} = maximum capacity of focused store j (volume per bin)

DM _{kp} = demand mean for medication p at patient area k (units/day)

DV _{kp} = demand variance for medication p at patient area k (units²/day)

HC _{jkp} = handling cost to move medication p from storage point j to patient area k (\$ per unit)

H = inventory holding cost rate (\$/\$ per day)

k _{p} = safety factor for medication p (found by table lookup, based on required service level, or probability of no stockout over a replenishment interval)

L _{p} = lead time from source to storage point for medication p (days)

MMC _{ikp} = movement cost to transport medication p to patient k using medication cart i (\$ per day)

R _{p} = inventory review cycle for medication p (days)

Val _{p} = value of medication p (\$/unit)

Vol _{p} = volume of medication p (e.g., tote size, cubic feet, etc.)

We observe that set (4.3a) in the model does not represent "true" constraints. Instead, they define dependent variables that are used in the development of the minimum lot size constraint (4.3c) and the capacity constraint (4.4). These dependent variables are defined as follows:

Mean_{jp} = demand mean of medication p at focused store j (units/day)

SS_{jp} = safety stock of medication p at focused store j (units)

Q_{jp} = order quantity of medication p at focused store j (units)

Var_{jp} = demand variance of medication p at focused store j (units²/day)

Equation 4.1 states that the total sum of all of the available focused stores j with medication p available for patient k is one for all patients k contained in the nurse's ward C and all medications p contained in total inventory P .

The next set of equations (4.2a) all show the calculations used to determine the mean, variance and safety stock of focused store j containing medication p . The mean is determined by calculating the sum of the demand means of all medications p that patient k requires multiplied by the available focused stores j containing medication p for patient k . Similarly, the demand variance is calculated in the same manner as the demand mean where the sum of all demand variances of medication p for patient k multiplied by the number of available focused stores. The third set in equation 4.2a describes the calculation of the safety stock for focused store j for medication p . The safety factor of the medication p and the standard deviation of the focused store j for medication p (which is calculated by using equation 4.2b) must be known for it to be calculated. Equation 4.2c shows that the order quantity of focused store j with medication p is greater than or equal to the safety stock of focused store j for medication p combined with the additive total of the inventory review cycle for medication p and the lead time from source to storage point for medication p multiplied by the demand mean of medication p at focused store j .

The set of equations in Equation 4.2a, 4.2b and 4.2c are all for all focused stores j contained in the total number of focused stores F and all medications p contained in total inventory P .

This is followed by Equation 4.3, which shows that the maximum capacity of focused store j is greater than or equal to the sum of twice the volume of medication p multiplied by the order quantity of focused store j with medication p . This is for all focused stores j contained in the total number of focused stores F being used (i.e. $\neq 0$).

Equation 4.4 says that the available focused stores j with medication p available for patient k must be one (i.e. used to serve patient k with medication p) or zero (otherwise). This is for all focused stores j contained in the total number of focused stores F , for all patients k contained in the nurse's ward C and all medications p contained in total inventory P .

- Material handling cost (H) – The handling cost per unit distance is identical for the CZ and the FS. However, since the FS is located closer to the patient area, H is lower for the FS than the CZ. Table 4-1 gives some representative costs per foot of travel distance per unit load for the medication cart:

Table 4-1: Parametric Analysis for the base case of a single patient

Parameter	Base Case	Range
Patient Area (PA) Share of Demand	1:1	1:1 - 3:1
Lead time (days)	0	0 – 90
Review Interval (days)	1	1 – 30
Item Value	\$2.50	\$0.25 - 50
Medicine Movement Cost (cost/foot) (NS->CZ/NS->FS/NS->PA)	\$0.0040/ \$0.0049/ \$0.0113	---
Cost of Capital (Annual rate)	14%	14%

- Variable facilities cost (VC) – VC is near zero for the CZ if space is readily available in the central stores. For the FSSs, the VC depends on the storage medium. Table 4-2 gives representative costs (\$/location/day) for typical storage media used for storage of medications:

Table 4-2: Variable Facility Costs

Storage Medium	Storage Cost (\$/day)
Nursing Station	\$0.02
Focused Store (FS)	\$0.075
Medication Cart (MC)	\$1.00

Several parameters do not differ between the focused stores and the medication cart:

1. Total patient demand
2. Variance (at patient area level)
3. Review interval
4. Lead-time interval
5. Cost of capital
6. Medication unit value
7. Medication volumetrics

4.5 Analysis of the Uncapacitated Case

The uncapacitated case involves modeling a problem without capacity constraints to quantify the storage requirements for a mix of items and to determine an initial location/allocation assignment. The approach will be to compare total holding costs and total material handling costs of stocks of medications and describe the costs per patient area as functions of the

commonality factor (CF). This method provides insights into the conditions under which the safety stock (SS) should be pooled or dispersed. It is important to note that centralization of the SS does not preclude focused storage of the cycle stock at the patient area level. However, if the SS is centralized then direct point-of-use delivery from supplier to nursing station is precluded. Based on experience with implementation of focused storage in industry, the margin of error in the input cost data is estimated to be roughly $\pm 15\%$. Thus, if the total cost of a centralized and decentralized system is within $\pm 15\%$, the decision maker is indifferent.

4.5.1 Portfolio and Facility Effects

Table 4-4 shows the two main categories of costs, inventory holding costs and facilities costs:

Table 4-3: Cost Categories

Holding Costs	Facilities Costs
Safety Stock Holding Costs	Variable Facility Costs
Cycle Stock Holding Costs	Handling Costs

However, for the medication distribution design problem, only the facilities costs (i.e. Variable Facility Costs and Handling Costs) will be of value in conducting a cost analysis. The Safety Stock Holding Costs and the Cycle Stock Holding Costs will not be significant variables to account for this hospital logistics network.

Portfolio effect is the savings in inventory holding cost resulting from risk pooling (variance reduction) when stocks are centralized and the demand is concentrated on one stock point. In the case of commonality, there are centralization benefits from a smoothing effect of demand variability. When the demand is below average in one patient area, the demand in another patient area may be above average such that the variability of demand at the nurse's station is lower.

The variable Var (variance of demand at the FSs or CZs) will depend on the CF (i.e. number of patients that demand a given medication). Safety stock (SS) is defined as follows (refer to the mathematical model in the previous chapter):

$$SS = k\sqrt{R+L}\sqrt{Var}$$

Let the parameter CF be the number of patient areas that demand a single medication. If each patient area is served by its own local focused store, then the SS level is independent of CF. If the patient areas are served by a single CZ, then the SS level (per patient area) at the CZ is proportional to the factor:

$$\frac{1}{\sqrt{CF}} \quad (4.7)$$

The following equation fragment shows the SS contribution to total cost and how the SS-related cost varies with CF for a centralized system:

$$\left(VC \cdot 2 \cdot Vol + Val \cdot H \cdot \frac{3}{2}\right) \left(k\sqrt{R+L}\right) \left(\sqrt{Var}\right) \left(\frac{1}{\sqrt{CF}}\right) \quad (4.8)$$

where

CF = commonality factor (number of patient areas using the medication)

VC = variable facility cost (Table 4-1)

Vol = Medication volumetrics

Val = Medication unit value

H = Inventory holding cost rate (\$/\$/day)

Var = Variance of demand

k = Safety factor (number of standard deviations of the normal distribution)

L = Lead-time interval from supplier

R = Review interval for periodic review of stock level

Note that the medication unit value, volumetrics, facility variable cost, holding cost factor, and safety factor all affect the total cost in the same multiplicative fashion. Lead-time, review interval and variance affect the total cost by the square root relationship as well as the number of patient areas by the inverse square root relationship. These relationships provide insights into the parametric analysis.

Consider the base case scenario in Table 4-1. The coefficient of variation is:

$$CV = (\text{Standard Deviation of Demand}) / (\text{Mean Demand}).$$

The $CV = 0.5$ in the base case was derived from a mean demand of 30 units/day and a standard deviation of 15 units/day.

Table 4-4 shows system costs for the base case and a single patient area (i.e. $CF = 1$) in the uncapacitated static model. It also summarizes the cost elements for the two extreme cases. If the cost per patient area is plotted versus the commonality factor, the total cost of centralization will always be higher for the case of one patient area:

Table 4-4: Absolute and Relative Costs of the FS and the CZ for $CF = 1$

Cost Component	Absolute		Relative (%)	
	FS	CZ	FS	CZ
Variable Facility Cost	0.3	0.3	42.74	35.29
Handling Cost	0.402	0.55	57.26	64.71
Total	0.702	0.85	100	100

It will be assumed that all of the stock will be centrally located at the nurse's station and delivered from this source to the FS via a MC. The nurse's station will be replenished from the outside supplier on a dock-to-stock basis and the stationary FS is replenished from the MC on a Kanban pull basis.

Table 4-5 shows that both costs are more cost effective with the utilization of the common zone to get medications to the patients than with the focused store for the case of three patient areas and decentralized stocks of medication. For centralized stocks, the handling costs are relatively high and the variable facility costs are relatively low compared to decentralized medication stocks. This difference in variable facility costs relates to the types of storage media (Table 4-1):

Table 4-5: Summary of the Absolute and Relative Costs for $CF = 3$

Cost Component	Absolute		Relative (%)	
	FS	CZ	FS	CZ
Variable Facility Cost	0.9	0.3	42.74	41.32
Handling Cost	1.206	0.426	57.26	58.68
Total	2.106	0.726	100	100

Figure 4-3 illustrates the effect of commonality on all costs. The condition of linearity was assumed between two or more patients. Note that total costs are equal for the case of two patient areas and that costs are all in the indifference region in the range of $1 < CF < 7$:

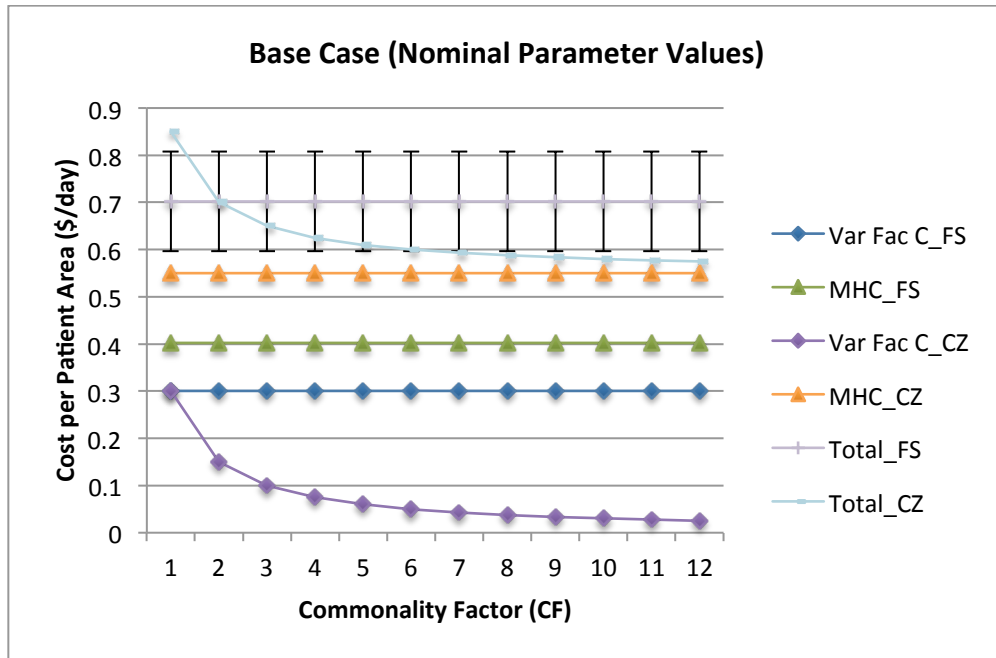


Figure 4-3: Base Case Cost Relationships

The parametric analysis first addresses factors that affect the total cost multiplicatively. Figure 4-4 shows that a low value item is an excellent candidate for focused store, regardless of the commonality. In this case, the handling cost is relatively high in comparison to the variable facility cost. Since the FS is closer to the patient area than the CZ, the FS option is less expensive. Conversely, Figure 4-5 shows that for a high-value item, centralized stores are preferred for any degree of commonality. Figures 4-4 and 4-5 suggest the need for further parametric analysis over a wide range of unit values:

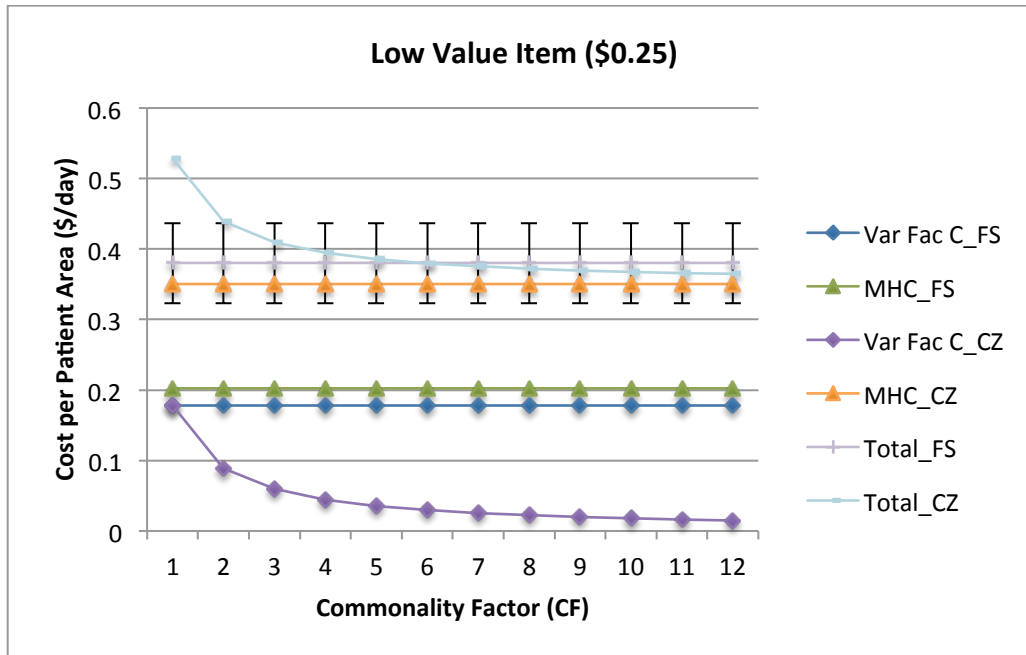


Figure 4-4: Low Value Item Cost Relationships

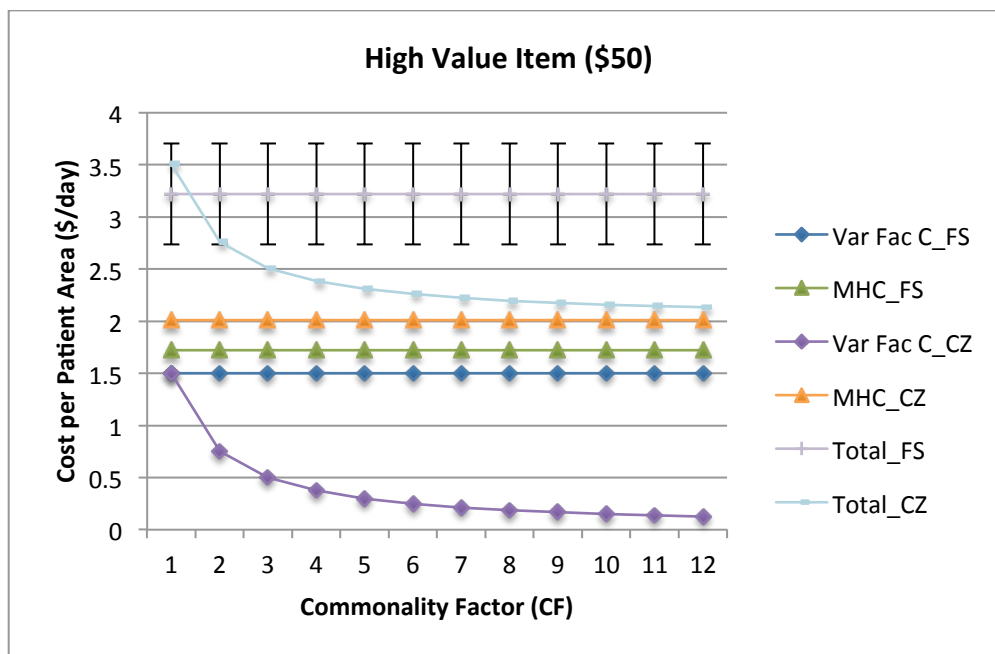


Figure 4-5: High Value Item Cost Relationships

Figure 4-5 plots unit value vs. the value of CF at which centralization becomes marginally preferred (total cost curve coinciding with the lower 15% bound). For example, a unit value of \$50 the total cost curve crosses the lower 15% bound at CF = 2. The base case value of \$2.50

per unit is near the knee of the cost curve. The cost curve is relatively flat at CF of 2 to 3 for unit values over \$4. The conclusion from this relationship might be that for unit values of \$4, central storage of safety stocks is preferred for any degree of commonality ($CF > 1$). In other words, items of value over \$4 are not good candidates for direct point-of-use delivery to the patient area. Instead, the safety stock should be centralized at the nurse's station.

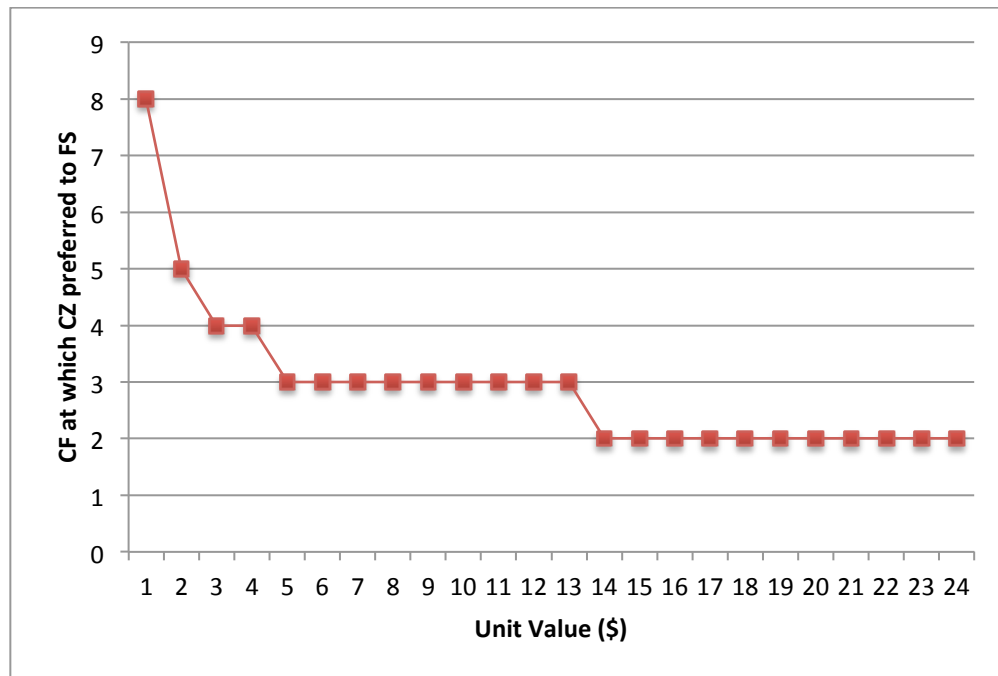


Figure 4-6: Decision sensitivity to Unit Value

Charts such as Figures 4-3, 4-4, 4-5 and 4-6 reveal the domains in which focused storage is preferred. There is a high degree of similarity for all factors that impact total cost multiplicatively.

The following four parameters are consistent, in that low values favor focused stores and high values favor centralized stores:

- Unit Value
- Coefficient of variation
- Interest rate

- Service level

These figures show that the handling cost can be a sensitive parameter. Consequently, it is important to accurately estimate the handling and transportation costs. These figures also show that lead-time has little effect on the decision to utilize the focused stores. This effect is explained by the fact that total cost is a function of the square root of lead-time.

4.5.2 Design Rules-of-Thumb based on analysis of the Uncapacitated Model

A primary objective of the characterization is to identify rules-of-thumb to implement commonality analysis in design toolsets. An analysis of the uncapacitated model yields rules related to safety stock holding cost and vendor package size.

4.5.3 Portfolio rule

This rule is intended to evaluate the potential portfolio effect as the number of using patient areas increases. For CF=1, calculate the (1) ratio of actual safety stock holding cost with respect to the total cost of the Common Zone (CZ), and (2) difference of total cost between common zone and focused store with respect to the common zone total cost. If (1) is greater than (2), then there is a significant opportunity to gain portfolio effects by centralizing stocks at commonality factors greater or equal to 2. This result can be summarized in terms of the following rule:

Let

%SS = Safety stock cost as percentage of total cost for a completely centralized system

TC(C) = Total cost for centralized stores

TC(F) = Total cost for focused stores

If

$$\%SS > \left[\frac{TC(C) - TC(F)}{TC(C)} \right] * 100 \quad (4.9)$$

This is followed by the pooling of the SSs for common medications in a centralized store. A test of the rule shows that it provides valid results in 94% of possible cases examined, based on the parametric ranges specified in Table 4-1. Rule failures tend to be at lower degrees of commonality (e.g. $CF \leq 6$). The errors tend to be in favor of centralized stores. Therefore, this rule is robust in the sense that if it recommends focused stores, the user has a high degree of confidence in adopting focused stores. Another favorable feature of the rule is that the penalty costs of the incorrect assignments are less than 10%.

4.6 Analysis of the Capacitated Case

The purpose of the capacitated analysis is to characterize the focused storage problem of location and allocation for a mix of medications in a multi-echelon inventory system under storage constraints. A mixed integer-programming model is used to analyze the multi-medication case. The modeling toolset for this research was the Arena™ Simulation Program (Version 14.0) and Microsoft Excel™ running on an Intel Core i7/596 MB laptop computer with 4GB of memory. The first step was to model a problem without capacity constraints to quantify the storage requirements for a mix of medications and to determine an initial location/allocation assignment. The basic approach for the capacitated analysis was to find the uncapacitated solution that we obtain from the simulation results. This provided a reliable baseline of data from which further studies could be based off of.

In the determination an effective medication distribution system, Table 4-6 shows the medication information for the different case scenarios analyzed for the sensitivity analysis:

Table 4-6: Medication Costs

Medication	Item Value (\$/unit)
P1	2.50
P2	48.50
P3	5.40
P4	21.15
P5	10.45

There were six models that were developed to mimic each of the six different commonality scenarios: $CF = 1$, $CF = 2$, $CF = 3$, $CF = 4$, $CF = 5$ and $CF = 6$. Nonetheless, each program followed a similar path as shown in Figure 4-7 (uncapacitated) and Figure 4-8 (capacitated). In each program, the assigned entity (i.e. for the simulation program is the medications) went through the first part of the simulation, which was the nurse's station, which is the primary storage point for all of the medications:

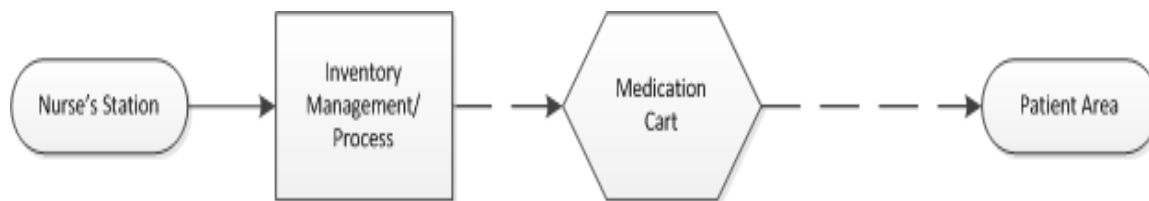


Figure 4-7: Schematic of the simulation model for the Uncapacitated Case

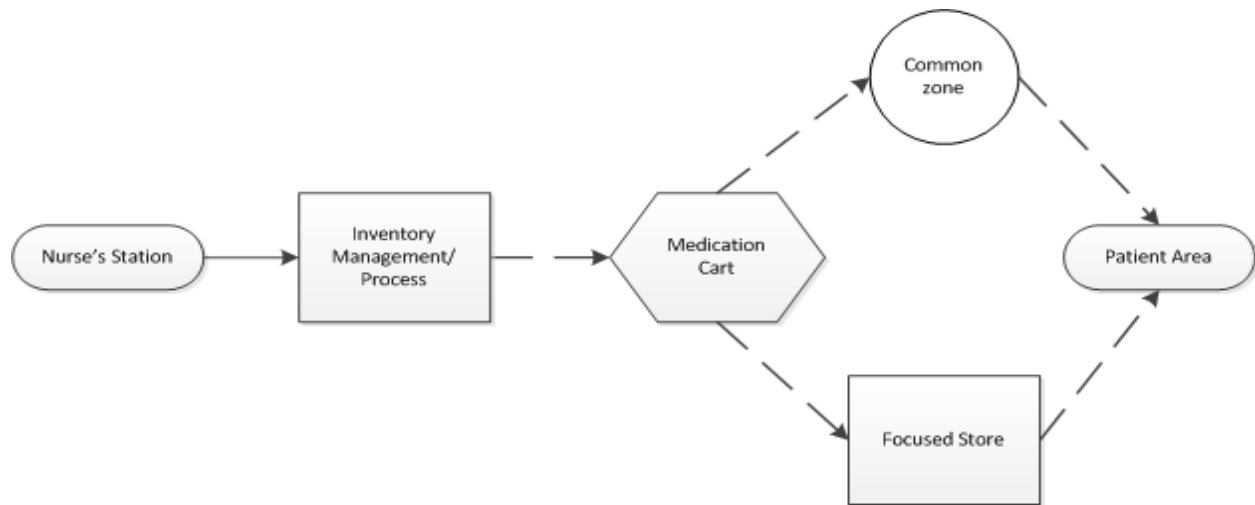


Figure 4-8: Schematic of the simulation model for the Capacitated Case

The entity then entered the next part of the program, the inventory component, in which the demand is created by the simulation model for each particular medication was tallied and compared against the available medication inventory to ensure there is adequate stock. If there is enough stock available of the needed medication(s) for the nurse to deliver them to the patient(s), then the bin size of the medication cart is 10, which means up to 10 medication pills of any type can be delivered to the patients at a time. However, when a predetermined safety stock is reached, the needed medications are merely retrieved from the nursing station, thus with no lead-time required. In this situation, the bin size is 5 (i.e. 5 pills of any type can be delivered to the patient(s) at a time). Additionally, a record was kept of how many times per day the bin size of 5 and the bin size of 10 was used. Once the medications were restocked (at the focused stores and/or patient areas) the inventory was adjusted to reflect the updated inventory level. The unit cost for each type of medication was taken into account. This logic was utilized in the six scenarios developed using the Arena program (Figures 4-11, 4-12 and 4-13 are screenshots from the Arena program for $CF = 1$, $CF = 2$ and $CF = 3$).

Minimum and maximum inventory levels were established to determine when restocking of the appropriate medication types should take place for each commonality factor, as shown in Tables 4-7 and 4-8 for the cases up to a Commonality Factor (CF) of 3:

Table 4-7: Maximum and minimum inventory of the corresponding medication type for the
CF = 1 and CF = 3 scenario

Medication Type	Maximum Inventory (pills/box)	Minimum Inventory (pills/box)
P1	60	20
P2	40	20
P3	40	20
P4	60	20
P5	60	20

Table 4-8: Patient pairings with maximum and minimum inventory for each medication type for
the CF = 2 scenario

	Medication Type with Maximum and Minimum Inventory (pills/box)				
Patient Pairing	1	2	3	4	5
PA1-PA2	0	40/20	0	60/20	0
PA2-PA3	0	0	40/20	0	60/20
PA1-PA3	60/20	0	0	0	0

Finally, the entity arrived at the end component of the simulation, where a sequence simulating the distribution of the medications from the nurse's station to the medication carts (MCs) and eventually making its way to the patient areas or the focused stores via the MCs or was created. The common zone (depicted as a oval that is near the patient areas in Figures 4-8 and 4-9) is not

an actual physical location but an area designated by the nurses to temporarily store medications should the situation arise to ensure the patients are provided their medications in a timely but cost effective basis. Referring to Figure 4-8, this movement by the nurses is denoted by the light dashed arrow $\text{---}\rightarrow$. Both the material handling costs and the inventory holding costs for each medication type were tabulated.

The simulations were each replicated once over 365 days to obtain reliable results.

The next step was to systematically impose binding constraints by reducing the storage capacities of the common zones and/or the medication cart(s), thereby limiting the medications that can be provided to the patient areas, until a stock point below the capacity required by a solution was reached. This placed more of a focus on the focused stores to provide the needed medications to the patients to prevent a shortage of medications. For a given iteration, alternatives for an affected medication type are forced into the model to determine the costs of these alternatives. These costs were compared and examined to demonstrate the model validity. The forced solution method was applied to validate the solutions obtained from the storage constrained optimization model.

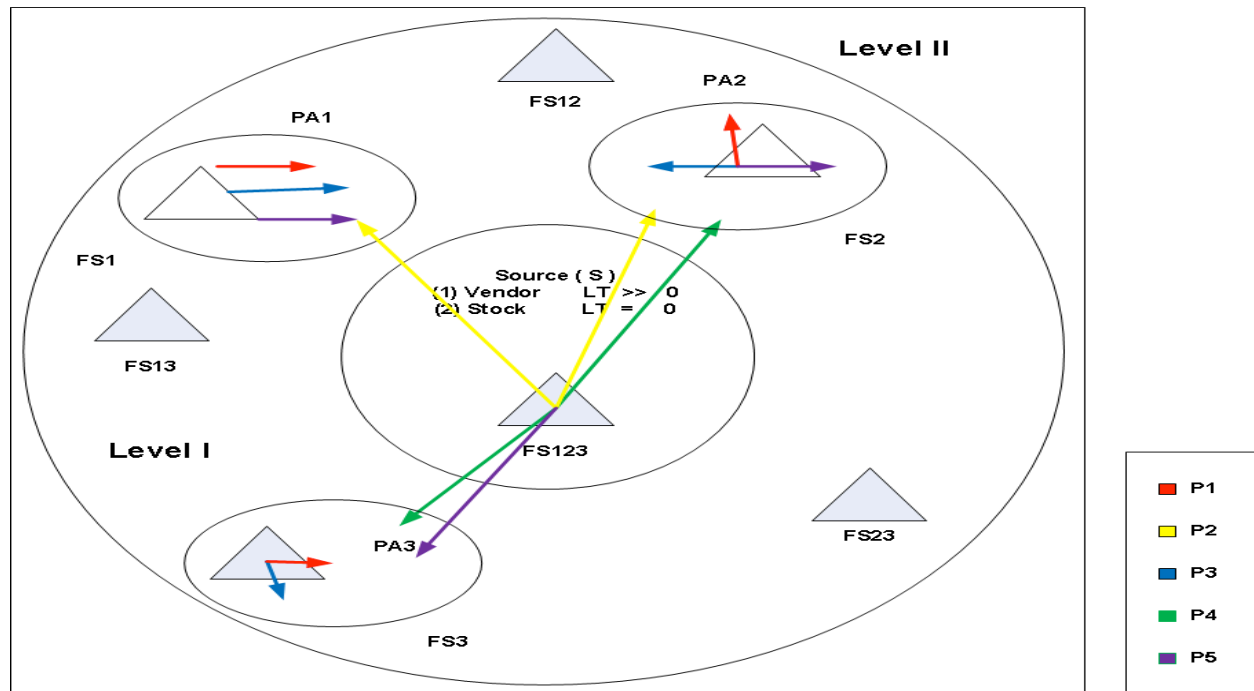


Figure 4-9: Schematic of Uncapacitated Case

4.7 Analysis of the Results

4.7.1 Uncapacitated Case

Figure 4-9 demonstrates a scenario indicative of a possible solution result of the simulation model for the uncapacitated case for the case of three patients.

The nursing station, referred to as the ‘Source’, is the starting point. The nurse’s station is the primary storage area for the medications and serves as the pickup point where the medications are loaded onto the medication cart and the appropriate medications are delivered to each patient common area (i.e. PA1, PA2 and PA3). If any of the medication types must be reordered, then the lead-time is greater than 0. The medication types are referred to as P1, P2, P3, P4 and P5. Medication types P2, P4 and P5 are distributed to the common areas of all three patients by the medication cart with P2 is being supplied to the common areas of PA1 and PA2, P4 going to the common areas of PA2 and PA3 and only P5 going to the common area of PA3.

We also note that from the focused store (FS) 1, the patient in PA1 is receiving medication types P1, P3 and P5. From FS2, the patient in PA2 is receiving also P1, P3 and P5. Finally, from FS3, we see that the patient in PA3 is getting P1 and P3.

In this scenario, Level I is indicative of the lowest level in the multi-echelon system. This is where the nurse is providing each patient with medications from the medication cabinet near each patient or from the nurse's station. Level II is the next tier in the multi-echelon level, which would involve all of the patients being provided medications by the nurses from either or both the medication cabinets and the nurse's station.

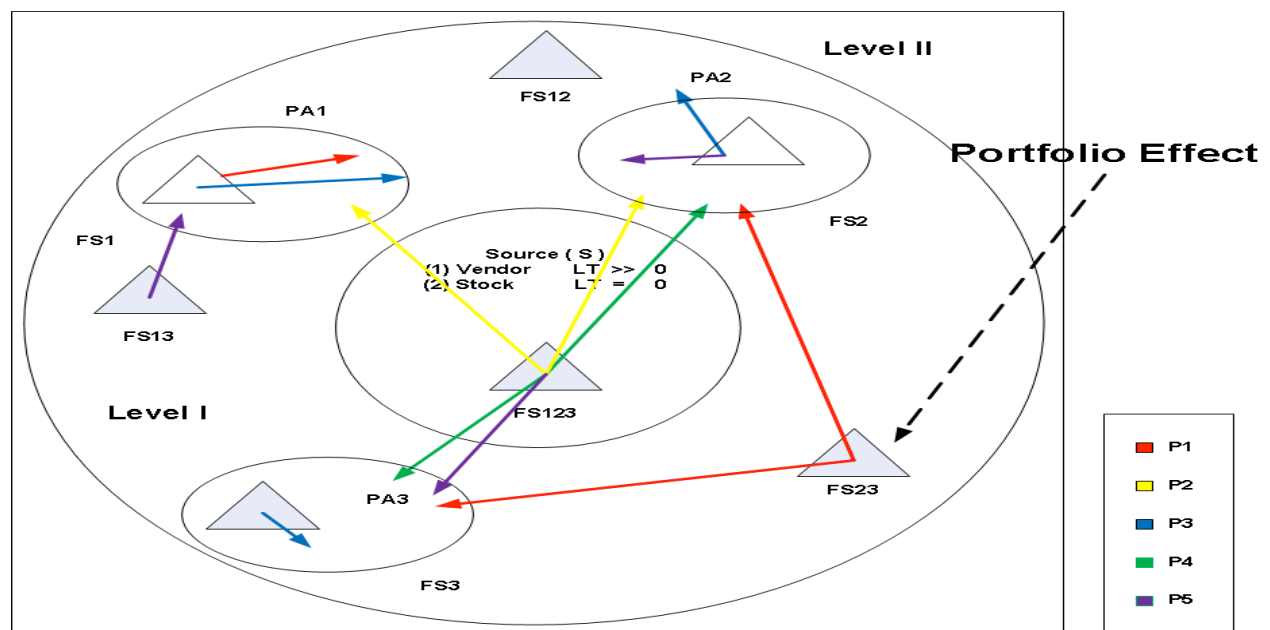


Figure 4-10: Schematic of Capacitated Case

4.7.2 Capacitated Case

Binding constraints were systematically imposed by reducing the storage capacities of the common zones and/or the medication cart(s), thereby limiting the medications that can be provided to the patient areas, until a stock point below the capacity required by a solution was reached. This affects the ability of the nurses to provide the needed medications to the patients on a timely basis. Referring to Figure 4-10, medication types P1, P3 and P5 are still supplying

the common areas for the case of three patients but the similarities end there. FS1 can only provide medication types P1 and P3 to the common area of PA1. FS13 must resupply FS1 with medication type P5. What is also telling is that PA2 is only getting the medication types P3 and P5 from FS2 and medication type P3 is only being provided to the common area of PA3. To compensate, FS23 displays a portfolio effect by supplying medication type P1 to the FS2 and FS3 so that this medication can be given to the common areas of PA2 and PA3.

In this scenario, Level I is the lowest level of the multi-echelon system where the each of the focused stores is providing medications (i.e. by the nurse) to each patient. Level II is the next tier in the multi-echelon level, which would involve all of the patients being provided medications by the nurses from either/both of the focused stores and the nurse's station.

4.7.3 Comparison with computational results from Arena simulation run

Figures 4-11, 4-12 and 4-13 show screenshots of the simulation models that were developed and run using the Arena program for the following Commonality Factor (CF) scenarios: CF = 1, CF = 2 and CF = 3. Note that models were also run for a CF scenario of 4, 5 and 6:

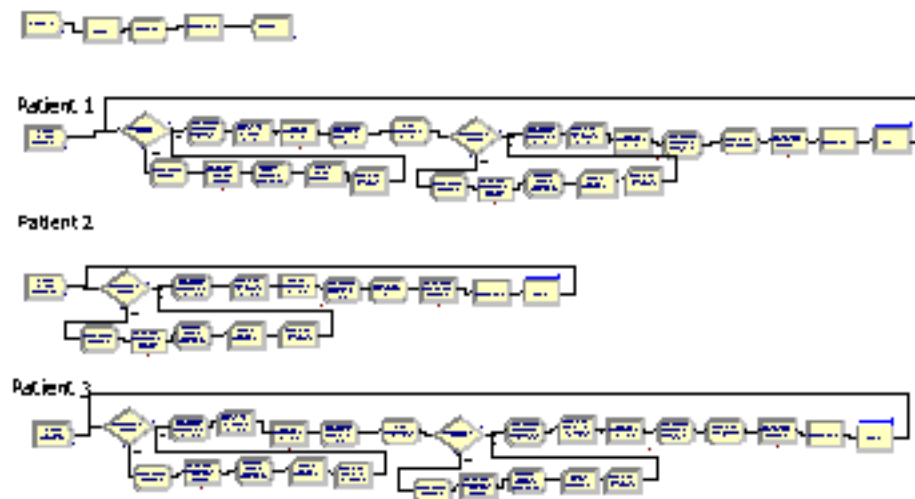


Figure 4-11: Arena simulation model for CF = 1 scenario

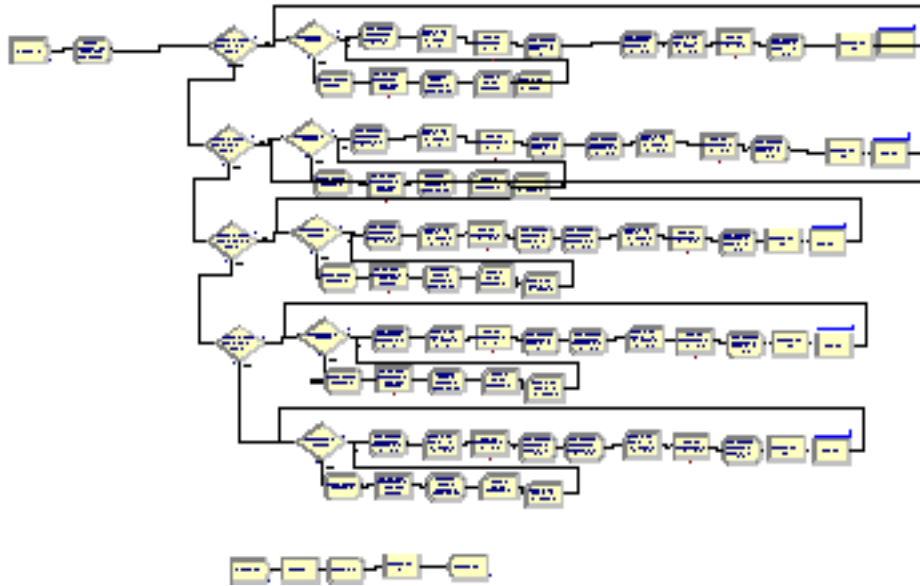


Figure 4-12: Arena simulation model for CF = 2 scenario

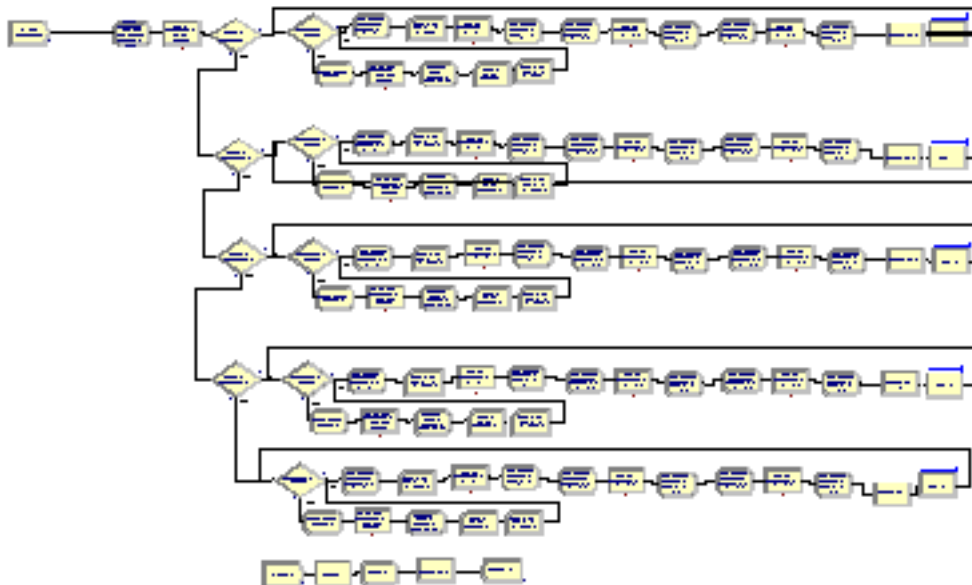


Figure 4-13: Arena simulation model for CF = 3 scenario

Table 4-9 displays the results of the Variable Facility Costs (VC), Material Handling Costs (HC), the inventory holding cost (H) and the bin sizes of 5 and 10 for Patient 1, Medication Type 1 only, for the six commonality factor scenarios. A steady increase in HC is evident as the commonality increases. This is consistent with the idea that as the number of patients receiving

the same medication increases the HC will reflect a corresponding increase in cost. The results of all six simulations also showed that H remained steady at \$7 for all of the commonality scenarios. Where the savings for the hospitals is most apparent is in the VC. There is a cost savings of 4.5% from CF = 1 to CF = 2 (i.e. \$326.06 to \$297.99). There is a dramatic jump from CF = 2 to CF = 3 where a 29.1% reduction occurs (i.e. \$297.99 to \$163.57). From CF = 3 to CF = 4 there is an 18.7% drop but the savings is less pronounced from CF = 4 to CF = 5 (8.4%) and from CF = 5 to CF = 6 (9.1%). The cost savings are evident as the transportation of the medications transitions from the nurse's station to the patient area (CF = 1) to focused store (CF = 2) and then to the common area (CF = 3) as the commonality of single medications among patients increases. These results also lend support to Figure 4-3, which shows the steady line for H and the increasing HC as the commonality increases. The steepness of the curve is pronounced as you go from CF = 1 to CF = 2 and then increases from CF = 2 to CF = 3. After CF = 3 the curve is not as steep.

Finally, the bin sizes among the different commonality factors seem to indicate a general trend of the commonality increasing as the use of the bin sizes 5 and 10 both decrease. As the CF increases, the decreasing use of bin size 5 is a good indicator of the reduced need to restock medications. Moreover, the use of bin size 10 decreasing seems to indicate there is less frequency of trips that the nurses must take to administer the medications as the commonality increases. There is a dramatic decrease from CF = 1 to CF = 2 in the bin size of 10 and another CF = 2 to CF = 3 but not as steep. Once you reach CF = 4, the bin size levels off for both cases. A similar pattern is shown in the bin size of 5 as the bin size of 10 but not as pronounced:

Table 4-9: Comparisons between several variables from Arena simulation run for the
Commonality Factors 1, 2, 3, 4, 5 and 6 for Patient 1, Medication Type 1

Commonality Factor	Medicine Movement Costs (MMC) (\$/day)	Inventory Holding Costs (H) (\$/day)	Material Handling Costs (HC) (\$/day)	Total Medication Distribution Costs (TMDC) (\$/day)	Bin Sizes (per day)	
					5	10
1	326.06	7	177.24	383.06	1.68	26.69
2	297.99	7	322.37	354.99	0.85	14.10
3	163.57	7	533.93	220.57	0.77	8.83
4	111.96	7	679.56	168.96	0.18	1.10
5	94.59	7	864.42	151.59	0.16	1.10
6	78.89	7	985.84	135.89	0.13	1.10

CHAPTER V

5.0 CONCLUSIONS AND RECOMMENDATIONS

The major contribution of the present work is the application of the Axiomatic Design methodology to the medication distribution design case study, which provides nurses with the ability to deliver medications to inpatients on a cost-effective basis.

The main problem considered in the present study was reduced into hierarchical, lower-level problems to assist in identifying the potential underlying issues that may arise when searching for a solution to the primary issue. This was accomplished by decomposing the primary issue for the focused store case study in terms of functional requirement with the corresponding decision parameter. This was then decomposed into basic, lower-level FRs and DPs. Constraints were placed in this study to maintain appropriate bounds on the accepted solution.

The next step of the AD process would be to identify the process variables for the decision parameters, ensure the original need for this project was satisfied and finally to evaluate the information content that is collected from observations of the results.

The focused store methodology was introduced and was an integral part of the development of the mathematical model for this case study. It is hoped that the analysis of this model will provide nursing managers with a results-oriented approach to give them options for an effective medical distribution system in their never-ending endeavor towards providing quality patient care.

Another significant development that the analysis of the mathematical model revealed was the development of both the capacitated and the uncapacitated case. The following observations were noted for the uncapacitated case:

1. The portfolio effect increases proportionally to $\frac{1}{\sqrt{CF}}$
2. For unit values greater than \$4 and more than two patient areas, it would be necessary to centralize the SS
3. For unit values of less than \$4 and typical cost structures, commonality may be neglected up to $CF > 7$
4. For low interest rate (<14% per year) and low coefficient of variation (<0.5), focused stores are preferred for any value of $CF < 13$
5. In all of the uncapacitated scenarios, there was a noted indifference that was typically seen for the CFs that were between 3 to 6
6. The portfolio rule performed very well and should be very useful to practitioners in designing focused stores. The rules tend to favor centralization and are thus conservative. On the other hand, the rules tend to side towards decentralization in cases where the penalty costs of an incorrect decision are small

As far as the analysis for the capacitated case, it suggested these general observations:

1. The portfolio effect on the material handling cost is the major factor for deciding location and allocation
2. Binding capacity at one location has modest effect on total cost but can have substantial effects on location/allocation decisions
3. The material handling cost is the major decision factor when portfolio effect benefits are diminished due to binding storage capacities
4. The capacity constraints tended to increase the handling costs

It is recommended that this research be extended to cover other areas in the study of medical distribution design systems including: (1) the development of multi-period models, and, (2) the incorporation of more complex simulation tools.

Finally, it is hoped that the AD methodology will become a viable option that companies should consider when developing new products or improving on the ones they already have.

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GLOSSARY

Axiomatic Design - a process that focuses on the generation of functional requirements and the selection of functional requirements to meet the customer needs for product and/or process design.

Axioms - truths that cannot be derived but for which there are no counterexamples or exceptions.

Capacitated - when there are limitations as to the capacity or space that can store medications for the patients. This is mainly due to the lack of resources that are available to stock the products.

Commonality Factor – number of patient areas that demand a single product.

Constraints - the bounds on acceptable solutions.

Decision Parameters - the key physical variables in the physical domain that characterizes the design that satisfies the specified functional requirements.

Functional Requirements - the minimum set of independent requirements that completely characterize the functional needs.

Independence Axiom - To satisfy the conditions of this axiom, the independence of FRs must always be maintained. It also implies that when there are several FRs, the design must be such that the FR can be satisfied without affecting any of the other as FRs [2]. The second axiom is known as the Information Axiom, which states that among those designs that satisfy the Independence Axiom, the design with the highest probability of functional success will be the best design [2, 5, 6, 7].

Input constraints – constraints that are specific to the overall design goals (i.e. all designs that are proposed must satisfy these goals).

Portfolio effect - the savings in inventory holding cost resulting from risk pooling (variance reduction) when stocks are centralized and the demand is concentrated on one stock point.

Process Variables - the key variables in the process domain, which characterizes the process that can generate the specified decision parameters.

Solution-neutral environment - This means that the functional requirements must be defined without ever thinking about something that has already been designed or what the design solution should be.

Stock out costs - Economic consequences of not being able to meet an internal or external demand from the current inventory. Such costs consist of internal costs (delays, labor time wastage, lost production, etc.) and external costs (loss of profit from lost sales, and loss of future profit due to loss of goodwill). Also called shortages costs.

System constraints – constraints that are specific to a given design; they are the result of design decisions made.

Uncapacitated case – where one can assume that the storage space/design (i.e. focused stores) are sufficiently large enough to accommodate any amount of inventory

CURRICULUM VITAE

Pepito Raguini Jr. was born in Corpus Christi, TX, and is the first son of Pepito Sr. and Proserfina Raguini. He holds a Bachelors' of Science degree in Mechanical Engineering from the University of Texas at El Paso. He has had the privilege of being a Teaching Assistant under Dr. Gutierrez as well as a Co-Op Industrial Engineer for Norfolk Southern. He also has had prior military service and has great love of god and country. He loves his family very dearly.

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