Replenishment Prioritization of Highly Perishable Goods: A Case Study on Nuclear Medicine

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Abstract

Serving customers in a nuclear medicine supply chain requires frequent and responsive replenishments. Nuclear medicine is a special category of perishable goods that is subject to rapid, but predictable radioactive decay. This study examines the viability of differentiating service through segmenting customers in Tyco Healthcare's (THC's) nuclear medicine supply chain. More specifically, the network of pharmacies that THC serves is divided into two groups—THC-affiliate pharmacies and independent pharmacies—and their demand characteristics are examined.

This study rejects the hypothesis that THC should differentiate service by pharmacy affiliation after comparing the demand characteristics of the THC and independent pharmacies. Alternatively, the study tests the hypothesis that product segmentation is a viable option by comparing the demand characteristics of THC's products. This study does not reject the alternative hypothesis and presents proposed policy for coordinated replenishment. To facilitate the comparative analyses, THC's nuclear medicine supply chain is first described. Finally, recommendations on how to improve supply chain performance follow the hypothesis testing.

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Biographical Note

Young-bai Michael Yea is a 2000 graduate of the United States Military Academy at West Point. Before joining the MLOG program, Yea served as a field artillery officer in the United States Army for five and a half years. During the years of active duty, which culminated in a yearlong tour in Iraq, Yea served as Fire Direction Officer, Platoon Leader, Fire Support Officer, and Assistant Operations Officer. Planning and executing logistics missions were a large part of his responsibility and passion, the experience largely responsible for seeking a career in logistics and supply chain management.

Hui (Judy) Zou is currently a student of the Master of Logistics program at MIT. Before joining the MLOG program, Zou joined Delmar International Inc in Canada as a leader. At Delmar, Zou assisted company to develop and implement customer cost-effective logistics solution. Before then, she worked as a manager in the shipping industry in China. Zou completed a Master of Business Administration from Macau University of Science and Technology in 2001. In 1993, she graduated from Foreign Language University of PLA.

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1 Introduction

At the end of World War II, the nuclear reactor facilities developed for the Manhattan Project began producing radioactive isotopes for medical application, mostly in diagnostic procedures. Today, about 13 million nuclear medicine procedures are performed each year (Cherry 4). These procedures are performed in hospitals, some of which have their own particle accelerators to produce radiopharmaceuticals onsite, but most providers receive nuclear medicine from regional radiopharmacies located within a 100-mile radius. This proximity is primarily due to the short half-lives[1] of radioactive isotopes which require immediate and rapid distribution upon production. As a result of growing demand, companies in the $2 billion US nuclear medicine market manufacture and distribute radiopharmaceuticals to either regional radiopharmacies or directly to hospitals (Bourassa 15).

This study examines Tyco Healthcare (THC), one such manufacturer and distributor of nuclear medicine. As the sponsor of this study, THC is interested in learning whether it should differentiate the service between its *Mallinckrodt*[2] radiopharmacies and the independent, non-affiliated radiopharmacies. As discussed above, the short half-life, analogous to the perishable property of some commodities, of a radionuclide requires that THC replenish its customer radiopharmacies frequently and responsively. Therefore, transportation costs are significant cost driver of the nuclear medicine supply chain. To put this in perspective, THC's nuclear medicine group spends approximately 30% of the Imaging Division's annual transportation budget even through

[1] The half-life of a radionuclide is the time required for it to decay to 50% of its initial activity level.
[2] The 37 THC radiopharmacies are referred to as Mallinckrodt, named after their founder.

radiopharmaceutical sales represent a disproportionately smaller amount of the Division's annual revenues (Tyco 2007). Therefore, THC is interested in controlling costs without significantly affecting customer service. THC believes that its relationship with the Mallinckrodt pharmacies can be leveraged to provide a level of service different from that provided to non-THC pharmacies.

This study rejects the hypothesis that THC should differentiate service by radiopharmacy affiliation after comparing the demand characteristics of the Mallinckrodt and independent radiopharmacies. Alternatively, the study tests the hypothesis that product segmentation is a viable option by comparing the demand characteristics of THC's nine products. This study does not reject the alternative hypothesis and proposes a policy for coordinated replenishment. To facilitate the comparative analyses, THC's nuclear medicine supply chain is first described. Finally, recommendations for improving supply chain performance follow the hypothesis testing.

1.1 Nuclear Medicine

Nuclear medicine serves both diagnosis and therapy. First, intravenous injection of trace amounts of compounds labeled with radioactivity, called radionuclides, facilitates collection of diagnostic information in a wide range of disease states. Second, radiopharmaceuticals used in therapy against various diseases including cancer.

The basic nuclear medicine study involves injecting a compound consisted of a gamma-ray-emitting or positron-emitting radionuclide called "hot kit", and a non-radioactive substance called "cold kit", which directs the radionuclide into a specific body part (Chandra 32-34). The radiation from this radio-labeled compound enables an external imaging system to detect it and to produce an image of the radionuclide distributed in the body. Nuclear medicine provides more sensitive measures of a wide range of biologic processes than do other medical imaging procedures, such as MRI, x-ray, and CT (Cherry 8-9). Notwithstanding this superior performance to other imaging methods, the difficulty and cost of producing radionuclides and strict regulations on handling, transporting, and disposing radioactive material have kept hospitals from producing their own radiopharmaceuticals. Therefore, hospitals rely on suppliers like THC.

While the number of radiopharmaceuticals is ever increasing with advancement in technology, one property of radiopharmaceutical has not changed. The majority of radiopharmaceuticals have relatively short half-lives to minimize the patient's exposure to the radioactive material inside the body. Because of the radioactive decay, radiopharmacies, which receive bulk radiopharmaceuticals and subsequently extract patient doses from them, require that the transit time between production and replenishment be kept as short as possible. This requirement poses a significant challenge to a centrally-located radiopharmaceutical manufacturer like THC. In addition, careful supply chain planning is necessary to ensure that perishable pharmaceuticals are delivered in a cost-effective manner.

1.2 Motivation

As a point of departure, THC's motivation has been confirming or denying whether differentiating service by pharmacy affiliation, either Mallinckrodt or independent, can lead to reducing logistics costs. THC believes that its different revenue structures and varying degrees of system integration serve as points of demarcation for differentiating service; it believes that customer segmentation is appropriate for allocating transportation and other scarce resources. The findings from this study will initiate THC's planning with regard to service differentiation. Moreover, this research in the nuclear medicine supply chain can provide additional insights into the ongoing research dealing with replenishment of other perishable pharmaceuticals such as avian flu vaccines and antibiotics. Finally, there are opportunities to improve efficiency of the nuclear medicine supply chain, and such improvement can serve the interests of all the stakeholders, especially the end-users who benefit from therapeutic and imaging applications of nuclear medicine.

1.3 Literature Review

The purpose of literature review is three-fold: first, to investigate the properties of radiopharmaceuticals to assess their effect on the supply chain; second, to review research conducted in perishable goods replenishment in other industries; third, to summarize previous studies conducted on the radiopharmaceutical supply chain and assess their relevance to this study.

1.3.1 Radiopharmaceutical Properties

Chandra (2004) discusses three primary methods of producing radionuclides: irradiation of stable nuclides in a reactor, irradiation of stable nuclides in an accelerator or cyclotron, and fission of heavier nuclides. The radiopharmaceuticals covered in this study are produced using the first two methods. Chandra explains that initiating a nuclear reaction to produce radionuclides is probabilistic and that the production yield rate varies from one radionuclide to another. In addition, systematic and random errors affect the production yield. If the distribution of radionuclide yields is determined to be significant during data analysis, it may be useful to investigate whether it has any effect on THC's radiopharmaceutical replenishment decisions. In addition, Chandra also lists three types of the radionuclide generator. The first generator system is the most commonly used today and is used by THC. The second generator system is useful for geographically remote places where frequent deliveries of radiopharmaceuticals are infeasible. The third generator is under development and is receiving attention because of its special advantages for positron emission tomography, a nuclear medicine imaging technique which produces a three-dimensional image or map of functional processes in the body. If found economically and technically feasible by the manufacturer, the use of different types of the radionuclide generator may improve the supply chain's efficiency; however, such a discussion is outside the scope of this research.

Cherry (2003) discusses the current nuclear medicine practice and provides information on production of each radionuclide in THC's product line. Cherry's coverage on pros and cons of each radionuclide is useful in determining its relative demand. Cherry further develops Chandra's coverage of radionuclide production methods by discussing the relative merit of each method. For example, cyclotrons generally produce radionuclides with smaller quantities of radioactivity than do nuclear reactors; therefore, the cyclotron products tend to be more expensive than the reactor products. Such information may enable the grouping of the numerous products that belong to THC's nine radiopharmaceutical families. The most significant subject, however, is Cherry's discussion on the most popular radiopharmaceutical, the Technitium-99 (Tc-99) generator. Cherry describes and illustrates the elution process in six hour increments after the first elution, which should ideally take place around 24 hours after production (extraction of Tc-99 is called the elution process). This activity is important to understanding the nuclear medicine replenishment process at THC since the first elution yields the greatest amount of useful radionuclides. Therefore, it is plausible that most radiopharmacies require that the generators arrive within 24 hours of production to ensure the maximum number of useful elutions.

1.3.2 Perishable Goods in Other Markets

If Chandra and Cherry treat matters specific to nuclear medicine, Ferguson (2007) deals with matters directly related to the perishable goods supply chain. Ferguson posits that a variation of the economic order quantity (EOQ) model can be a more effective means of dealing with inventory planning of perishable goods than does the classic EOQ model. Ferguson's variation estimates the holding cost curve parameters by considering product lifetime, holding costs, markdown policy, and spoilage. The parameters, which are constants, are then applied to the EOQ model as follows:

$$EOQ = \left(\frac{1}{h} \left(1 + \frac{1}{\gamma} \right) A D^{\gamma} \right)^{\left(\frac{1}{1+\gamma} \right)} \qquad \text{Equation 1.1}$$

Where A is fixed ordering cost, D a constant demand rate, and h holding cost per unit which increases with the time t in the following relationship: $H(t) = ht^{\gamma}$ --

γ and h are constants and are greater than zero.[3]

In case of nuclear medicine, the increase in holding cost per unit over time can be best approximated by the radioactive decay of the radionuclide. As the radionuclide decays, the number of useful doses proportionately decreases, lowering the value of the radiopharmaceutical. This variation of the EOQ model has practical implications to nuclear medicine replenishment planning, and its application is discussed in Section 4.

Ferguson's finding can enable THC to compare the actual orders placed by radiopharmacies and economically efficient orders, and identify inefficient customer behaviors at the radiopharmacy level. In addition, replenishment frequency can be obtained to adjust order quantity to account for additional radioactive decay due to increased duration between replenishments.

Another perishable goods inventory model derived by Kanchanasuntorn (2004) is useful in investigating inventory control of the fixed-life perishable products. The objective of Kanchanasuntorn's model is to reduce the total cost by incorporating fixed lifetime perishability and lost sales. The maximum inventory level at warehouse (S) and the reorder point at warehouse (s) can be computed using the model. The steps are as follow:

Step 1. Compute the z- value of the standard normal distribution for the probability of no stockout at outlet i, (Z_i) from Equation 1.2:

$$F(Zi) = \frac{\pi_i}{(\pi_i + c + \sum_{j=1}^{k} \alpha^{j-1} h_i^{'} + a^{k-1}\theta)} \qquad \text{Equation 1.2}$$

Where i : retail outlet, i =1,2,3.....,n

[3]Appendix I contains a complete derivation of this model.

π_i : shortage cost of lost sales per unit at retail outlet i

c : purchase cost per unit

k : product lifetime with zero lead-time

h_i : holding cost per unit per period at the warehouse

a : the discount rate

θ : outdating cost per unit

Step 2. Compute the difference between maximum inventory lever level and reorder point and the renewal function Δ and R(Δ) from Equation 1.3 and Equation 1.4:

$$\Delta = 1.3 * u^{0.494} * (K / h)^{0.506} * (1 + \sigma_L^2 / u^2)^{0.116}$$ Equation 1.3

$$R(\Delta) = (\Delta / u) + \left[\left(\sigma^2 - u^2\right) / 2u^2\right]$$ Equation 1.4

Step 3: Using a one-dimensional search in Cost function, Equation 1.5, to determine z-value of the standard normal distribution for the probability of no stockout at warehouse, Z and the least cost:

$$C(\Delta, Z, Z_i) = \frac{A}{T} + c * E(U) + \theta * \frac{E(O)}{T} + h * E(I) + \sum_{i=1}^{n} \left[h_i * E(I_i) + \pi_i * E(B_i)\right]$$ Equation 1.5.

Where A : ordering cost at the warehouse

T : ordering cycle time at the warehouse

E(B_i): expected number of units short

E(U): expected number of units required per period

E(O): expected outdating cost per period

E(I) : expected inventory level

Step 4: Determine he maximum inventory level at warehouse (S) and the reorder point at warehouse (s) from Equation 1.6 and Equation 1.7:

$$s = u_L + \sigma_L Z \qquad \text{Equation 1.6}$$

$$S = s + \Delta \qquad \text{Equation 1.7}$$

Where u_L : lead time demand at the warehouse

σ_L : standard deviation of forecast error (or demand variation if forecast error is not available) over the lead time at the warehouse

To test this model, a numerical study was conducted by Kanchanasuntorn. The experimental outcomes show a significant improvement in the proposed model over the original case.

Kanchanasuntorn's model is informative as it includes stockout policy for each retail outlet and associated marginal profits. It can be applied to perishable products in high demand and with short life times, improving the inventory control of perishable goods.

The last study poses and answers the following question: how to apply the optimal ordering policy for perishable commodities to different types of customer? Ishii (1996) has derived a perishable goods inventory model by examining the ordering policies of two types of customer. The two types of customer are high priority customers who are sensitive to freshness of the products and low priority customers who are not as sensitive to freshness. Their study factors in the discriminating sales prices, the lifetime of commodity, and the capacity constraint of the warehouses at the two types of customers. However, Ishii does not expand the scope of model to include numerical validation; therefore, the model does not provide as meaningful information as do the other models described in this section.

1.3.3 Past Research

On one hand, this thesis is an extension of the joint research conducted by Bourassa (2006) and Yang (2006). Their research focused on evaluating advantages and disadvantages of THC's four transportation alternatives that support radiopharmaceutical replenishments from the manufacturing plant to 37 THC-affiliated pharmacies and 690 independent pharmacies in the US. Furthermore, their research identified system constraints, service requirements, and costs involved in shipping radiopharmaceuticals. Finally, their research recommended a transportation alternative, or transportation strategy, that served as the impetus for THC's effort to improve its logistics operations.

This study is an extension in the sense that it examines operations across the same supply chain; however, it examines why comparable in-house pharmacies and independent pharmacies are indiscriminately served and whether differentiating service can result in significant cost savings. By THC's own estimation, such practice is a byproduct of tribal knowledge, due in no small part to the complex nature of radioactive property and system constraints such as strict federal regulations on storage and transportation of radiopharmaceuticals (Tyco 2007). Therefore, this thesis has potential to not only widen the scope of the previous research but also to discover underlying and persistent drivers of cost and inefficient behavior.

1.4 Approach

This study is conducted by performing data collection and analysis to test the two hypotheses, leading to proposed replenishment policy. In the first stage, fieldwork facilitates the understanding of the THC's nuclear medicine supply chain and identifies the policies and procedures that affect the supply chain's efficiency and effectiveness. Section 2 outlines the information collected by interviewing THC personnel from distribution, transportation, marketing, and other business units as well as radio pharmacists. In addition, internal reports supplied by THC dealing with operational procedures, transportation contracts, and activities in the upstream parts of the supply assist in mapping the replenishment activity. The second stage involves careful study of the data furnished by THC to examine what manner of differentiation, if any, is appropriate for THC's nuclear medicine supply chain. Section 3 compares the THC radiopharmacies and non-THC pharmacies using four criteria--order volume, order type, order pattern, and geographical distribution of demand--to evaluate the merit of the service differentiation argument. An alternative hypothesis is also tested by applying the same criteria. Section 4 introduces and describes a modeling technique used to coordinate nuclear medicine replenishment. This stage also provides recommendations for improving the nuclear medicine supply chain.

2 Nuclear Medicine Supply Chain

This section is comprised of two parts that describe THC's nuclear medicine supply chain. The first part provides a general overview of the nuclear medicine supply chain. The second part describes in detail each component of the supply chain: raw material procurement, production, distribution, marketing and sales, and customer service.

2.1 Supply Chain Overview

THC has a single supply chain that serves 37 regional THC radio-pharmacies and 690 independent radio-pharmacies (Tyco 2007). These radiopharmacies in turn serve hospitals and clinics that administer nuclear medicine procedures. THC has one central manufacturing facility in Maryland Heights (MH), Missouri that produces nine families of nuclear medicine: chromium (Cr-51), gallium (Ga-67), indium (In-111), iodine (I-123 and I-131), technetium (Tc-99), phosphate (P-32), thallium (Tl-201), and xenon (Xe-133). The product designation is comprised of the name of the element in the periodic table to which a given nuclide belongs and the mass number of the nuclide. Each product family includes many products with different concentrations and doses of the particular radionuclide and whose final cold kit pairings determine the nature of application. The radioactivity of a product is measured in curies (CI), equivalent to 3.7×10^{10} nuclear decays per second or Becquerel, the SI standard unit. This study uses CI and millicurie (mCI; equivalent to 1/1000 curie) to measure radioactivity, consistent with the units of measure used by THC. Although THC typically supplies both hot kits and cold kits to its customer radiopharmacies, it also supplies just the cold kits, particularly those considered proprietary, to the pharmacies that purchase the hot kits from elsewhere (THC 2007). This study focuses on the replenishment activity of the hot kits as it is the subject of interest in perishable goods replenishment. Since radiopharmaceuticals are subject to radioactive decay, which renders them useless in a matter of hours, days, or weeks, radiopharmacies prepare radiopharmaceuticals for patient use and deliver them to hospitals and clinics before the first morning appointments, usually within a few hours of receiving that day's shipment from the MH plant.

2.2 Supply Chain Components

There are five supply chain components—raw material procurement, production, distribution, marketing and sales, and customer service—that affect THC's replenishment operations.

2.2.1 Raw Material Procurement

THC purchases raw material from international and domestic US suppliers. A THC facility in Petten, Netherlands supplies most of Mo-99, parent source of the Tc-99 generator, along with a supplier in South Africa. A Canadian supplier is solely responsible for I-123. In addition, international and domestic suppliers provide the rest of radioactive isotopes and non-radioactive metals, which are used in the cyclotron-based production. International shipments arrive in Chicago and are delivered to the MH plant by a combination of regional air and ground carriers. Inbound logistics requires careful coordination and maneuvering across a number of gateways and customs associated with handling hazardous material. Mo-99, for example, spends about 28 hours in transit from the time it leaves the Petten facility to the time it arrives at the MH plant, going through international airports in Brussels, Belgium and Chicago, Illinois and regional airports in the US before arriving in St Louis (THC 2007). In addition to scheduled raw material purchases, THC sometimes makes ad-hoc purchases from alternate suppliers. As explained in Section 1, nuclear reaction is probabilistic; therefore, there are occasional production failures and lower-than-expected production yields. At those times, it is not unusual for THC to purchase raw material or finished goods from its competitors and visa versa.

2.2.2 Production

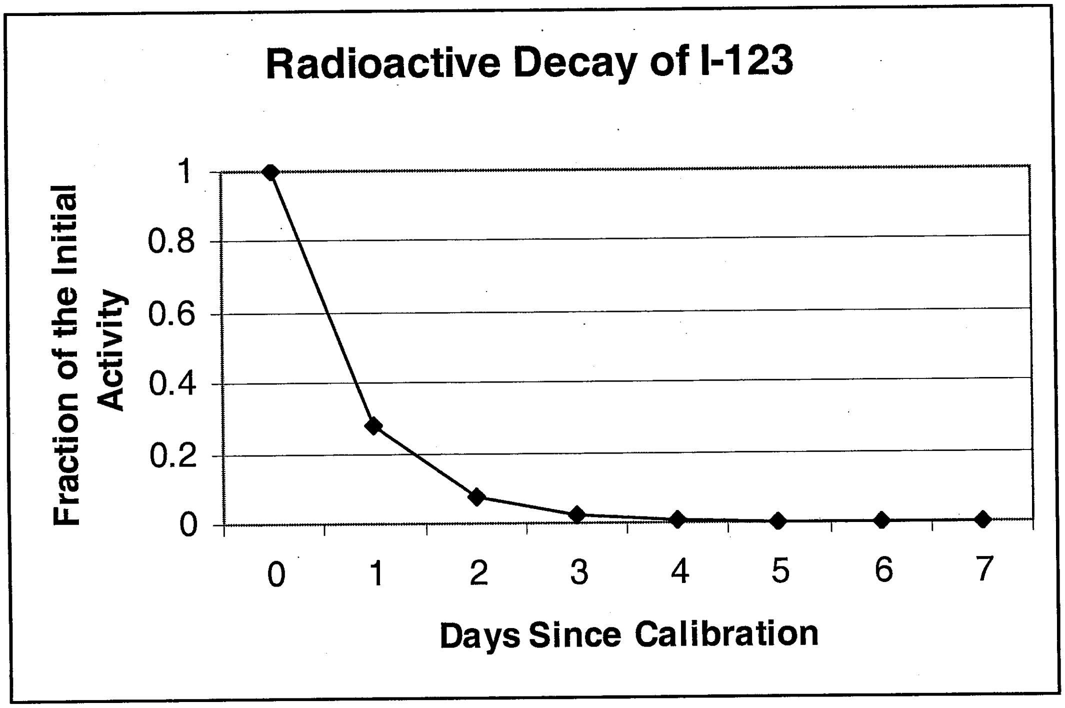
THC produces radiopharmaceuticals using the two methods first described in 1.3.1. First, the MH plant manufactures three product families, Tl-201, Ga-67, and In-111, through the use of its five cyclotron reactors. In this process, a charged subatomic particle is bombarded with a non-radioactive target substance to produce a number of radioactive and non-radioactive materials. The desired radionuclides are collected by separating them from the byproducts of the nuclear reaction and are then diluted to yield different concentrations. The products are then packaged in preparation for immediate shipment or, for some of the products, stocked in distribution for future shipment. In 2005, THC installed its fifth generator at the plant. The newly installed cyclotron provides 65 percent of the current capacity, and has alleviated the strain placed on the older cyclotrons. The second method of production involves dilution and packaging of radioactive isotopes purchased in bulk from various suppliers. Table 2.1 lists THC's nine radiopharmaceutical product lines and their production schedules as well as the radioactive decay rates. The production schedules of Ga-67 and In-111 are synchronized with that of Tl-201. The production schedules of the remaining products are closely tied to the inbound shipment schedule of raw material.

Table 2.1 THC Radiopharmaceutical (Hot) Product Families

Radionuclide	Daily Decay Factor	Production Schedule
Tl-201	0.80	Everyday Except Friday
Ga-67	0.81	Tuesday, Friday
In-111	0.78	Tuesday, Friday
Mo-99/Tc-99	0.78	Saturday, Sunday, Tuesday, Thursday
I-123	0.28	Sunday, Monday, Tuesday, Wednesday
I-131	0.92	Monday, Wednesday, Thursday
Cr-51	0.97	Bi-Monthly, 2^{nd} Week
Xe-133	0.88	Tuesday
Ph-32	0.95	Bi-Weekly/Tuesday, Wednesday

Each value in the second column, Daily Decay Factor, represents the fraction of radioactivity present after one day. For example, only 28 percent of initial, or calibrated, radioactivity of I-123 is present after one day, requiring immediate production and distribution after receiving a raw material shipment from the supplier. Figure 2.1 depicts the radioactivity level of I-123 as a fraction of the calibrated level.

Figure 2.1 Radioactive Decay of I-123



The graph also shows that the useful life of I-123 is about one day, equal to THC's target service time; therefore, the product is calibrated for use in a future point to account for the intervening time between production and replenishment.

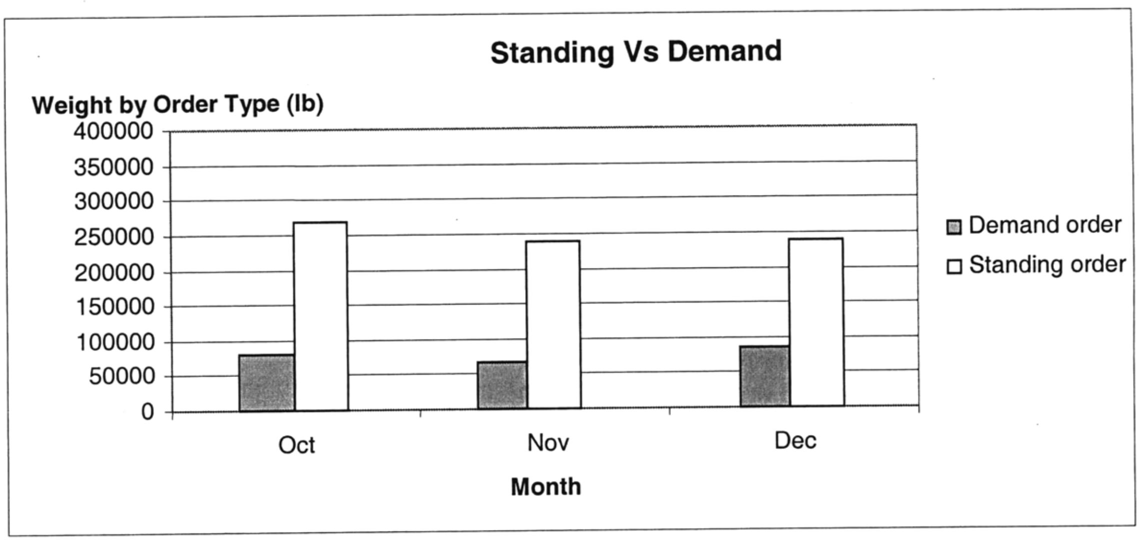
2.2.3 Distribution

Operational rhythm of the Distribution function is closely tied to production, which is tied to the inbound raw material shipment and cyclotron operation schedules. Distribution uses a THC-developed software tool called *OASIS* that facilitates order processing, packaging, labeling, and regulatory compliance, specifically meeting the

Transportation Index (TI) requirement.[4] OASIS also assists with route and transportation mode selection.

Distribution fulfills two types of orders: standing and demand. Standing orders are based on a contractual agreement between THC and their customers, and have predetermined product name, quantity, and replenishment interval. Demand orders are placed by customers through THC's call center using the phone, fax, or electronic data interface. Figure 2.2a illustrates the breakdown between standing and demand orders.

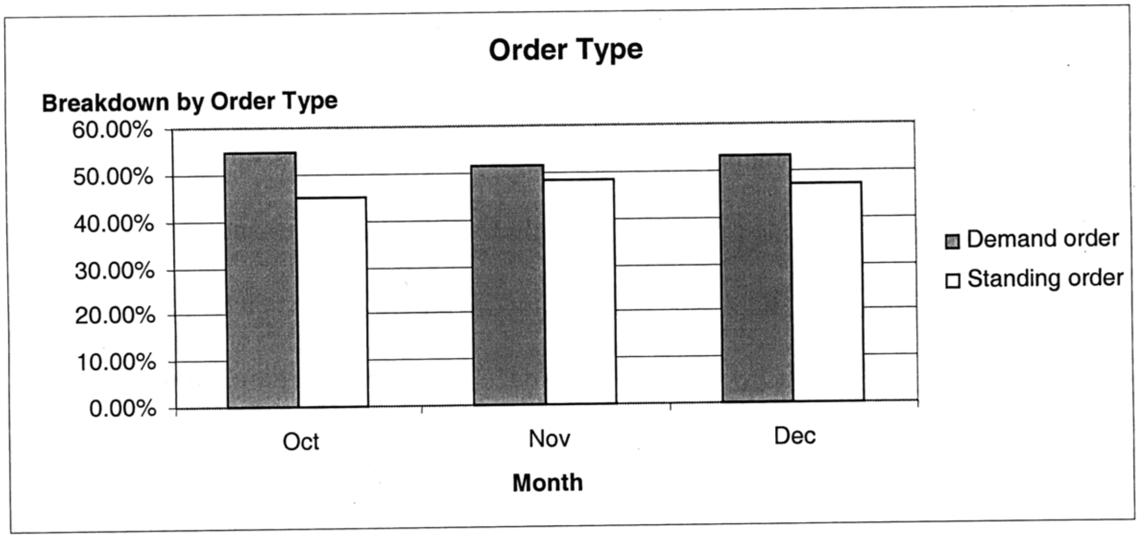
Figure 2.2a Standing Order Vs Demand Order (Weight)



As seen in Figure 2.2b, the above figure can be misleading in the sense that the actual number of demand orders only slightly exceeds that of standing orders.

[4]TI represents the maximum radiation emission at one meter from the external surfaces of a given package. Regulations mandate the measures be taken on each face of the package and be annotated on the shipping label. The TI limit is waived for linehaul, chartered air, and FedEx.

Figure 2.2b Standing Order Vs Demand Order (Number of Orders)



Demand orders cover unexpected surges in demand at the radiopharmacy level, and their volume as measured by the weight of the medicine ordered is a fraction of that of the standing orders; however, demand orders tend to be predictable over the long run (Tyco 2007). Such an observation begs the question of whether something can be done to minimize the impact of demand orders on THC's operations. Similarly, standing orders present their own complications. Because standing orders can be changed any time[5], the order classification between standing and demand is not so clear. However, standing orders and demand orders are predictable in the long run, and influence raw material purchasing decisions, production volume and scheduling, and transportation scheduling.

Once daily orders are filled, they are shipped by one of the four transportation modes: linehaul ground carrier, FedEx, commercial air carriers, and chartered airplanes. THC pays for the transportation expenses for most of the orders, while some customers share the cost with THC. First, the linehaul ground carrier typically serves

[5]Order deadlines ensure same-day delivery by allowing enough time for packaging and delivery to the gateway terminal or scheduled pickup time as specified in transportation contracts.

radiopharmacies within the 500-mile radius of the MH plant. Second, FedEx picks up orders from the MH plant at 6:00 PM and delivers to customer pharmacies by the promised time of 10:30 AM on the following day. As discussed earlier in 2.1, most pharmacies prefer the early morning (around 2 AM) arrival; therefore, FedEx is the chosen alternative for those pharmacies in remote locations or for products whose half-lives are relatively long. Third, commercial flights out of St. Louis Lambert International Airport serve many of the pharmacies located west of Missouri. Because of the regulation that limits TI to 3 or 5 per load and the limited number of eastbound flights from St Louis Lambert International, the use of this particular transportation alternative has been declining. In addition, the 2001 American and TWA merger has resulted in a drastic reduction of wide-body airplanes (THC 2007). This has forced THC to use the other transportation modes to serve the pharmacies previously served by commercial air. The final transportation mode is chartered air out of St Louis Downtown-Parks Airport. This mode is the most expensive and the most popular alternative. THC has 12 chartered flight routes serving nine gateway cities. While ground carrier and FedEx provide door-to-door service, commercial and chartered flights require local transportation from the MH plant to the two St. Louis area airports and from destination airports to radiopharmacies. Local transportation comprises a significant portion of the transportation costs between the MH plant and radiopharmacies. Table 2.2 lists THC's transportation spending during the last quarter of 2006. Linehaul and local ground transportation costs are combined. All figures are disguised due to their sensitive nature.

Table 2.2 Transportation Spending in the Last Quarter of 2006 (Disguised)

Mode	2006-10	2006-11	2006-12	Qtr 1 Sub Total
GROUND COURIER	$ 600,663	$ 575,087	$ 696,885	$ 1,872,636 (49%)
CHARTER	$ 571,950	$ 644,652	$ 232,606	$ 1,449,208 (38%)
COMMERCIAL AIR	$ 121,228	$ 76,995	$ 121,280	$ 319,502 (8%)
FEDEX	$ 54,015	$ 50,918	$ 50,829	$ 155,762 (4%)
ALL OTHER	$ 5,665	$ 3,591	$ 9,614	$ 18,870 (1%)
Grand Total	**$ 1,353,521**	**$ 1,351,243**	**$ 1,111,214**	**$ 3,815,977**

2.2.4 Marketing and Sales

THC engages in long-term contractual relationships with its customers. Recently, the increasing influence of Group Purchasing Organizations (GPO) has put pressure on price although the expectation of exceptional service level has not changed. Consequently, the marketing and sales department plays a significant role in THC's replenishment decision. In case of short supply, the marketing and sales department determines which customer receives shipment. There is no written replenishment priority policy to support the decision-making process; therefore, experience and knowledge of the personnel in these departments are the main drivers of this decision-making process.

2.2.5 Customer Service

One way to secure customer loyalty is to maintain a high level of service. As explained before, THC receives demand orders and standing order modifications until the day before shipment. There are various order and shipment cut-off times which accommodate some late afternoon orders. THC's on-time delivery rate of 98 percent has also contributed to its loyal customer base (THC 2007). In addition, each contract has specific terms that may incur further costs. For example, Cardinal Healthcare has long held a contract that entitles it to a 20 percent discount if THC does not deliver within two hours of the radiopharmacy's opening time. At the pharmacy level, the Mallinckrodt radiopharmacies have a staff pharmacist on call at any given time to meet unexpected nuclear medicine dispensing requests. The availability of fresh pharmaceuticals and high level of customer service have helped THC to remain competitive despite pricing pressure. Finally, THC does not pass on transportation costs to its customers except when required by contract.

3 Data Analysis

In this section, two comparative analyses of customer demand patterns are conducted. The first analysis compares the ordering behaviors of THC and non-THC radiopharmacies, and the second analysis compares the demand patterns of Tc-99 generators and non-generator products. The analyses are conducted by applying four evaluative criteria—order type, ordering pattern by days of the week, order volume, and geographical demand distribution. The results of the analyses form the basis for answering the research question in this study and suggest an area of the supply chain appropriate for modeling.

3.1 Hypothesis Testing and Criteria

The objective of this data analysis is to determine whether the order patterns of THC and non-THC pharmacies are significantly different from each other. If they are not significantly different from each other, the hypothesis that customer segmentation to differentiate service is viable is rejected. Then, an alternative hypothesis, the feasibility of product segmentation, is evaluated.

As mentioned in Section 2, THC considers high customer service level, defined by a 98 percent on-time delivery rate, and availability of fresh pharmaceuticals as its competitive advantage. Any service differentiation proposal should, therefore, be substantiated by significant difference in demand patterns and ordering behaviors between the two networks of radiopharmacies. To enable this examination, four evaluation criteria are applied to determine whether the difference is significant. The criteria are as follows: order type, ordering pattern by days of the week, order volume, and geographical distribution of demand. The criteria are treated in 3.3.1 through 3.3.4.

3.2 Explanation of Data Used in the Analysis

Data extraction from Oasis covering the period from October 1st to December 31st, 2006 is used in this data analysis. Orders are placed by 37 THC radiopharmacies and 690 non-THC radiopharmacies. Table 3.1 summarizes data categories used in the analysis of demand and order behavior.

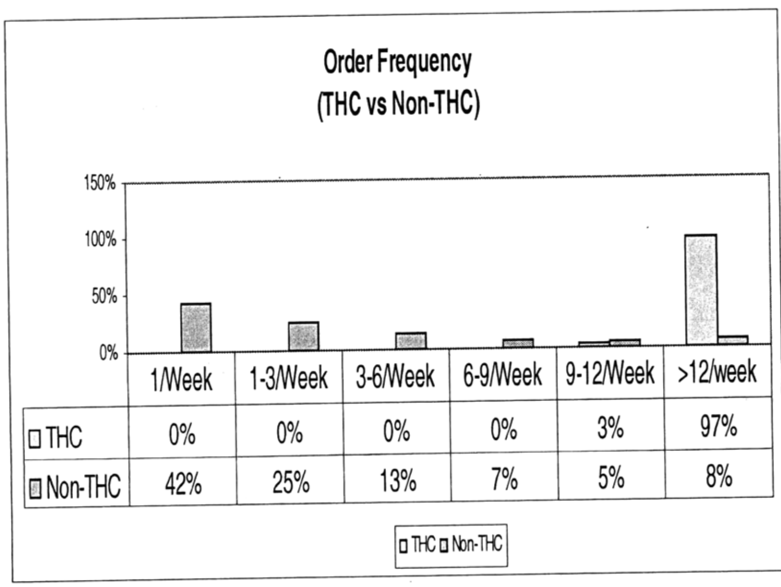
Table 3.1 Data Categories Used in the Analysis

Name	Description
Order Number	Unique identifier generated by OASIS for each order line
Order Type	Standing or Demand
Weight	Gross weight of the product with the assigned Order Number
Shipment Date & Time	Required, not actual, release time of the order
Mode	Transportation mode (chartered air, commercial air, FedEx, or ground courier)
Carrier	Service provider that transports the shipment
Customer Name	THC Mallinckrodt radio-pharmacies and non-THC independent radio-pharmacies
Customer City and State	The two fields that identifies individual pharmacies since Customer Name is not unique

3.3 Comparing THC and Non-THC Pharmacies' Order Behaviors

The order frequency analysis (Figure 3.1) shows a significant divergence between THC and non-THC radiopharmacies. While 97 percent of the THC pharmacies place their orders, on average, greater than 12 times per week, only 8 percent of the non-THC pharmacies order in a similar manner. However, 291 non-THC radiopharmacies, representing 42 percent of this network, place orders once per week or less often. Hence, it is too early to conclude that the order behavior of the THC radiopharmacies is significantly different from that of the non-THC radiopharmacies. To further investigate this criterion, the comparison focuses on the pharmacies of comparable size.

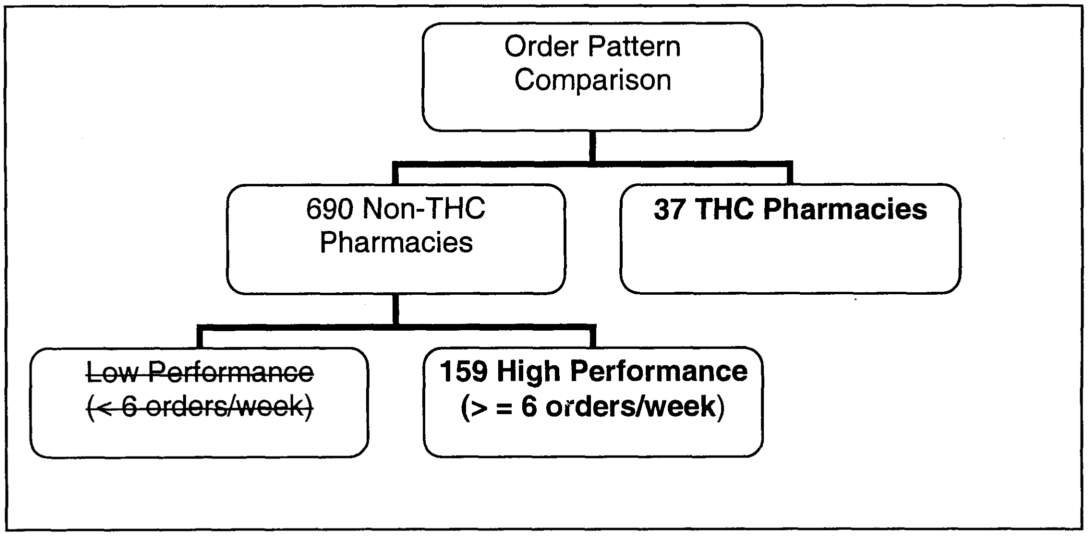
Figure 3.1: Order Frequency THC versus Non-THC



Number of Orders	Non-THC	THC
<6	534	1
6-12	106	1
>12	53	35

Figure 3.2 depicts all 37 THC radiopharmacies and the 159 high performance non-THC radiopharmacies, which order at least six times per week used in this comparative analysis.

Figure 3.2: Comparison Groups

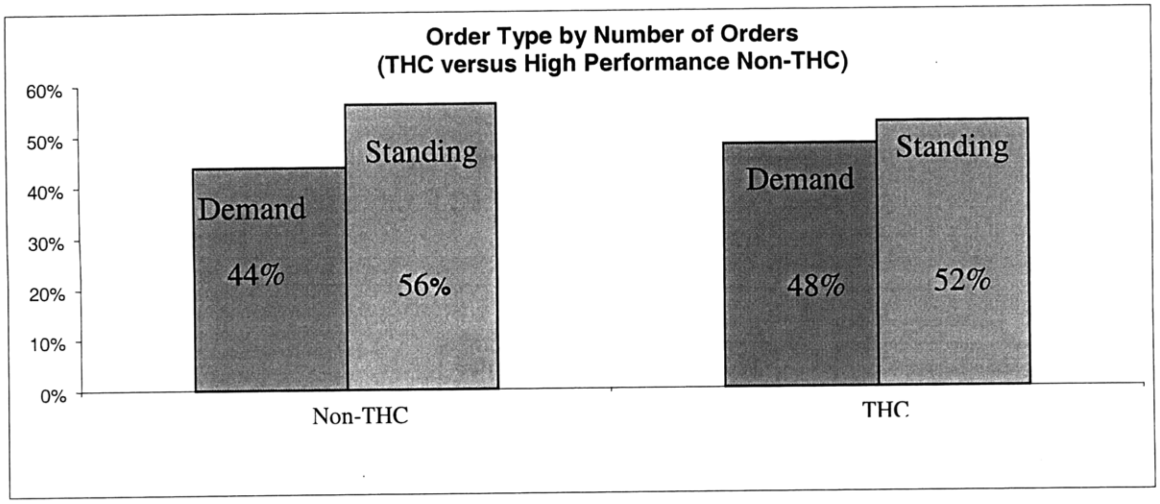


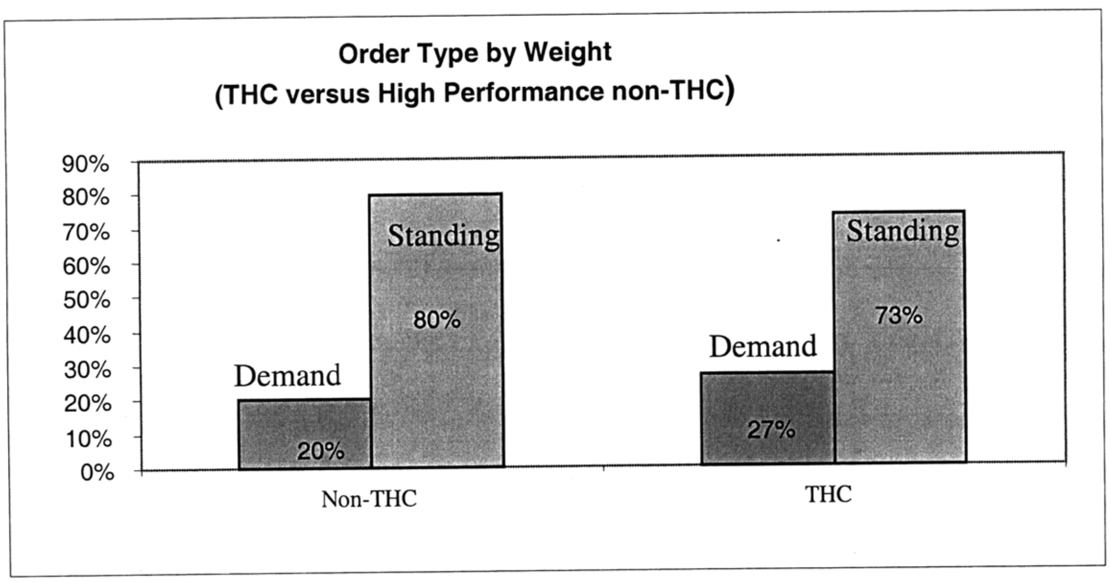
3.3.1 Order Type

As explained in Section 2, there are two types of order, standing and demanding. Demand orders are placed and fulfilled within 24 hours. Because of this short planning and execution window, THC prefers a standing order to a demand order. Second, transportation costs of fulfilling demand orders are relatively higher than that of fulfilling standing orders. Fore example, 44 percent of the demand orders are fulfilled by chartered air, the most expensive transportation mode, whereas 38 percent of the standing orders are fulfilled by the same transportation mode.

Figure 3.3 illustrates the comparison of order types between the THC and non-THC pharmacies; the order type distribution between demand and standing are similar for both THC and non-THC pharmacies.

Figure 3.3 Order Type Comparisons (THC versus High Performance Non-THC)





3.3.2 Ordering Pattern by Days of the Week

This analysis examines whether the THC and non-THC pharmacies exhibit similar temporal ordering patterns. The orders are separated by days of the week to facilitate this comparison.

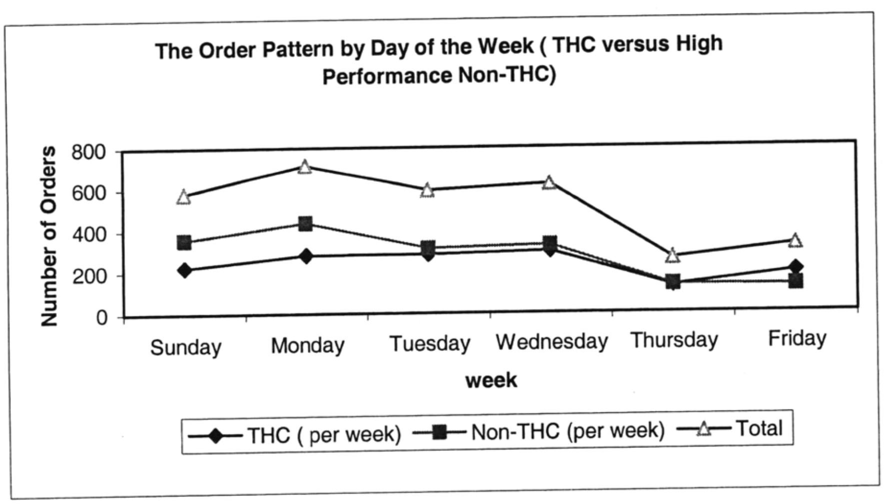
Similar to the order type analysis, this analysis is conducted between the 37 THC radiopharmacies and 159 non-THC radiopharmacies. The orders are placed over 79 working days in the fourth quarter of 2006, which includes 14 Sundays and 65 weekdays. Table 3.2 and Figure 3.4 show that THC and non-THC pharmacies exhibit similar ordering behaviors; they both order the most on Mondays and Wednesdays and the least on Thursdays.

Table 3.2 Ordering Pattern by Days of the Week Comparisons (THC versus High Performance Non-THC)

The Order Pattern by Day of the Week (THC versus High Performance Non-THC)

Number of Order	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
THC(per quarter)	3105	3648	3664	3847	1660	2537
Non-THC (per quarter)	4976	5674	4036	4219	1711	1657
Total	*8081*	*9322*	*7700*	*8066*	*3371*	*4194*
THC (per week)	222	281	282	296	128	195
Non-THC (per week)	355	436	310	325	132	127
Total	*577*	*717*	*592*	*620*	*259*	*323*

Figure 3.4 Ordering Pattern by Day of the Week (THC versus High Performance Non-THC)



One could argue that the similar ordering patterns are strongly correlated to the radiopharmaceuticals' production schedules. However, the fact that scheduled and that nuclear medicine appointments are scheduled on Fridays undermines the strength of this counter argument.

3.3.3 Order Volume

The order volume analysis compares of the order volumes (in lb and number of orders) between the THC and 159 non-THC radiopharmacies. The data obtained from the OASIS system—covering the period from October 1st to December 31st, 2006—contains 51,947 orders. This includes 49,787 orders within the US and 2,160 orders without. This study only examines the US orders.

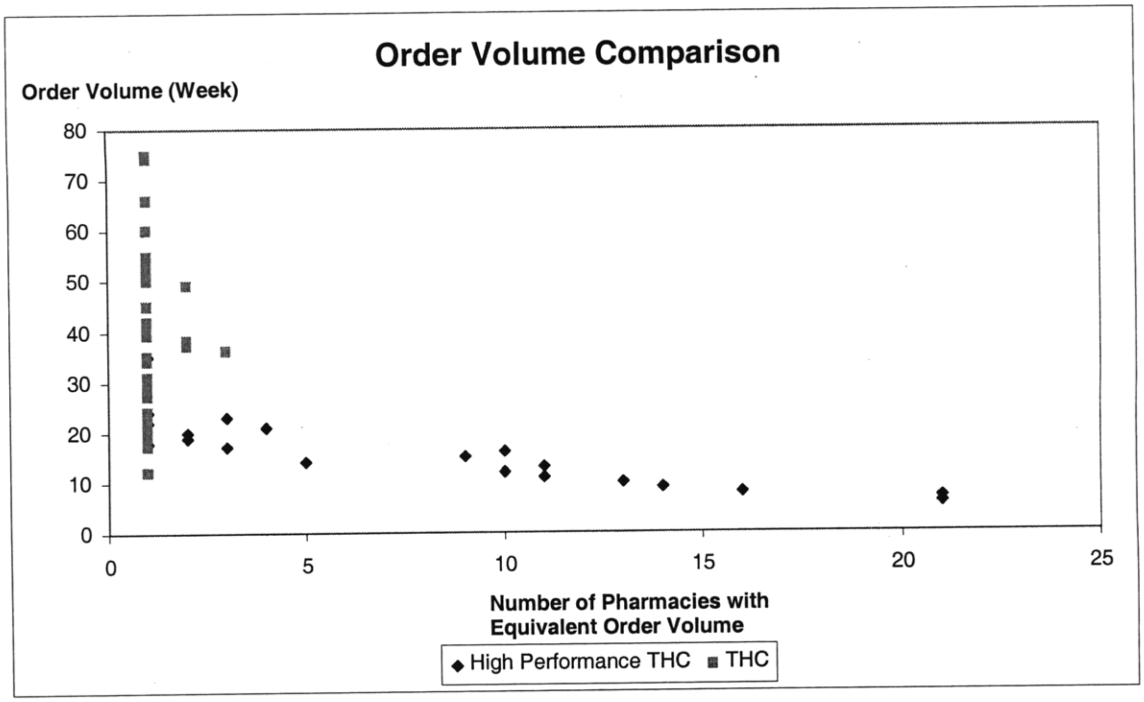
The order volume comparison by the number of orders and weight is provided in Table 3.3.

Table 3.3 Order Volume Comparison (THC versus Comparable Non-THC)

	THC	High Performance Non-THC	Low Performance Non-THC
Total Number of Orders	18,461	22,272	12,865
Average Number of Order Per Pharmacy	499	140	24
Average Number of Order Per Pharmacy Per Day	6	2	0.3
Total Order Weight (lb)	286,480	156,639	481,070
Average Order Weight Per Pharmacy (lb)	7,743	985	906
Average Order Weight Per Pharmacy Per Day (lb)	98.1	12.47	11.47

The results show a difference between THC and non-THC pharmacies. Furthermore, the difference in order volume is also pronounced between high performance and low performance non-THC pharmacies. Figure 3.5 shows that the difference in order volume exists even among the THC pharmacies. The vertical axis represents the average order volume per week. The horizontal axis represents the number of pharmacies whose average order volumes are equivalent.

Figure 3.5 Order Volume (Number of Orders) Comparison (THC versus High Performance non-THC)

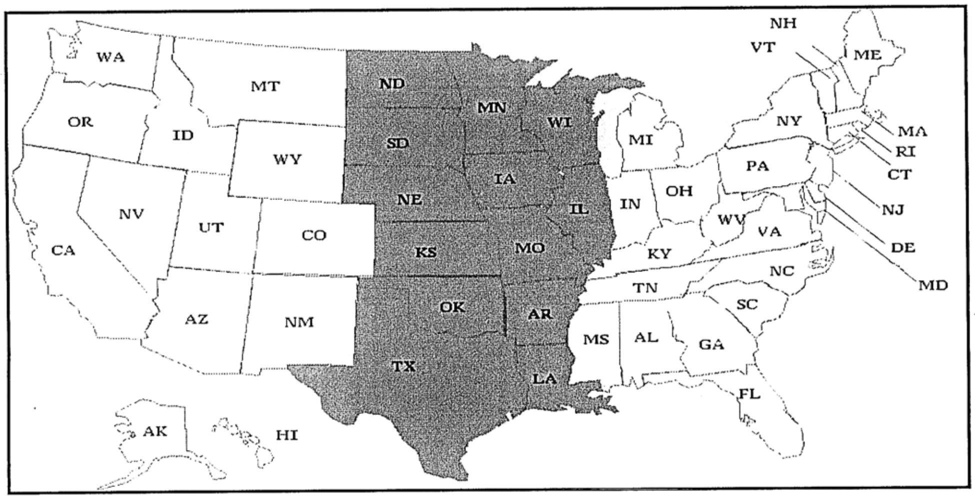


The results lead one to believe that pharmacy size, in terms of order volume, and not pharmacy affiliation, may have a greater effect on order volume.

3.3.4 Geographical Demand Distribution

According to THC's geographical grouping, the contiguous states are divided into three regions as shown in Figure 3.6.

Figure 3.6 Geographic Regions



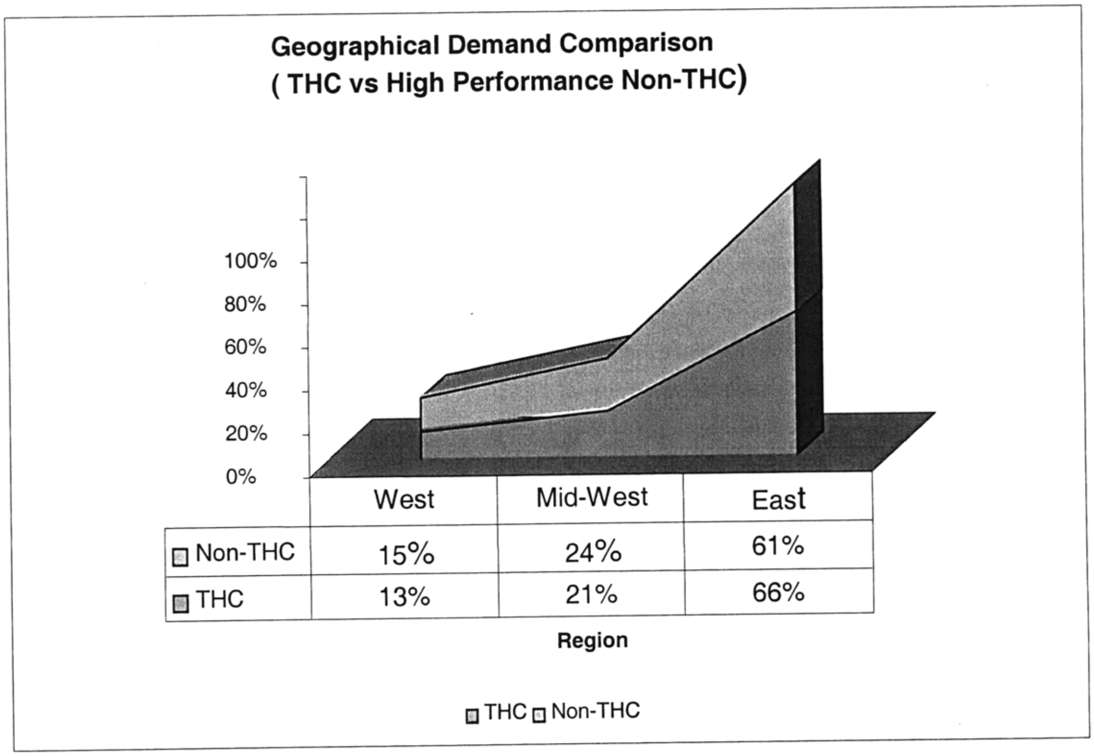
Once again the same groups of pharmacies are subject to this analysis. Table 3.4 and Figure 3.7 show geographical demand distributions by pharmacy affiliation. Order volumes are high in the east and low in the west for both THC and non-THC pharmacies.

Table 3.4: Geographical Demand Distribution

Geographical Demand Distribution

# of Order	**West**	**Mid-West**	**East**
THC	2353	3897	12211
Non-THC	3394	5387	13492

Figure 3.7: Geographical Demand Comparison (THC versus Non-THC)



3.3.5 Summary and Findings

By analyzing order type, ordering pattern by day of the week, order volume, and geographical distribution of demand (Table 3.5), one can observe that the order patterns between the THC radiopharmacies and the non-THC radiopharmacies of comparable size are not significantly different. There is a difference between the order volumes of the THC and non-THC pharmacies; the typical THC pharmacies order more product lines per order placement than do the typical non-THC pharmacies. This difference is due to the difference in pharmacy size, irrespective of pharmacy affiliation. As demonstrated in 3.3.3, order volumes are significantly different among the THC pharmacies. Lastly, three out of the four criteria reject the assertion that the order patterns between the two pharmacy networks are significantly different. Therefore, the hypothesis that service differentiation by pharmacy affiliation is viable is rejected.

Table 3.5 Summary of Results (THC and Non-THC pharmacies)

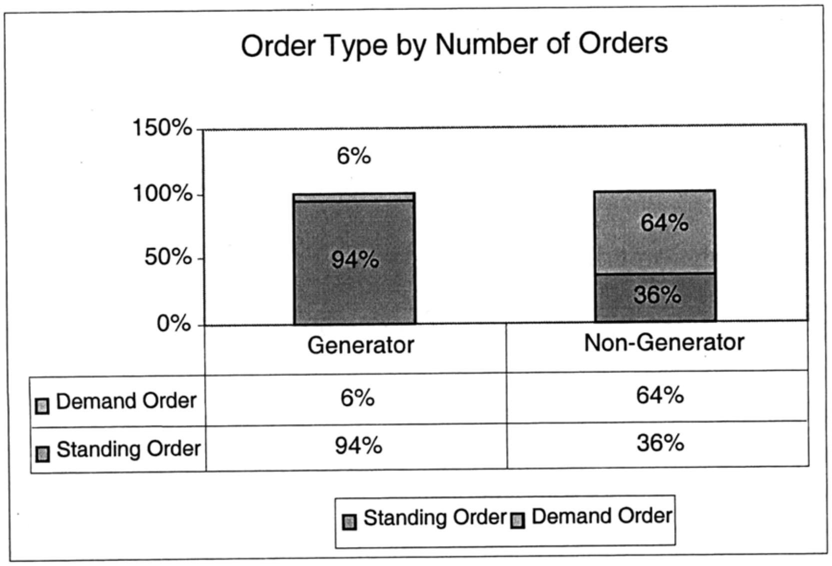
	Order Type Standing Vs Demand	Ordering Pattern by Days of the Week # of order	Order Volume # of order per pharmacy per day	Geographical Demand # of order
THC	48%: 52%	High: Monday and Wednesday Low: Thursday	6	High: East Low: West
Non-THC High Performance	44% : 56%	High: Monday and Wednesday Low: Thursday	2	High: East Low: West

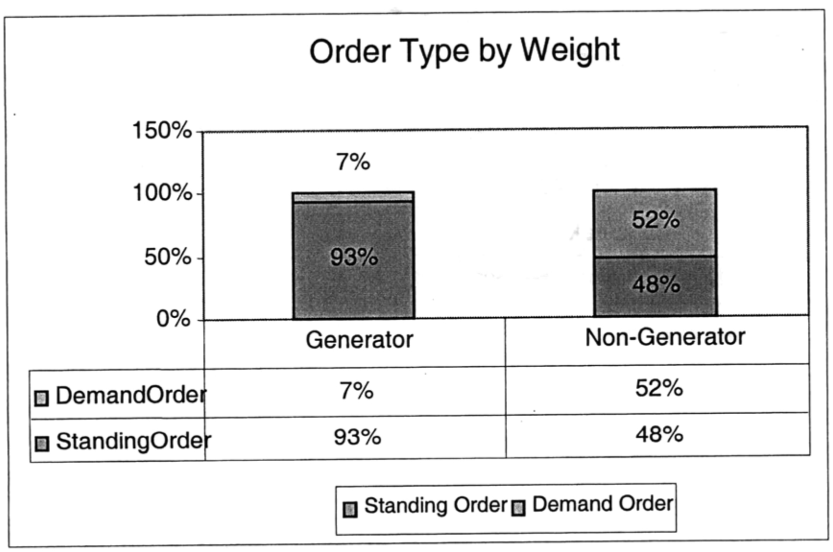
As addressed in the beginning of this section, an alternative hypothesis is explored from this point forward. Since the ratio between standing orders and demand orders vary greatly depending on the measurement used and the unit weight of generators is much greater than those of the rest of THC's products, product segmentation between generators and non-generator products is considered.

3.4 Comparing Generator and Non-Generator Products

As introduced in the previous section, the alternative hypothesis that product segmentation is a viable option is tested by comparing the demand characteristics of THC's nine products. Specifically, the demand patterns of the Tc-99 generator and non-generator products are compared using the same four criteria first introduced in 3.1. The reasons for differentiating the Tc-99 generator and non-generator products are as follows: first, the Tc-99 generator has the highest sales volume by weight; second, the generator is

Figure 3.8 Order Type Analysis (Tc-99 Generator versus Non-Generator Products)



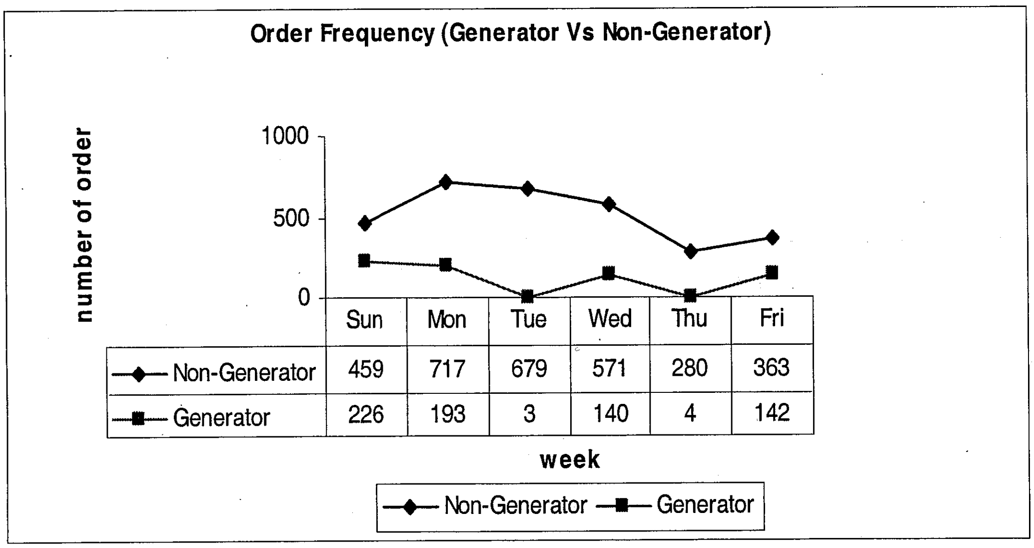


The significant difference in order type distributions between Tc-99 generator and non-generator product support is present.

3.4.2 Ordering Pattern by Days of the Week

The ordering patterns of the Tc-99 generators and non-generator products are examined in this section. Figure 3.9 illustrates that the demand for Tc-99 generator is relatively high on Monday and zero on Tuesday and Thursday. On the other hand, the non-generator products show a different ordering pattern.

Figure 3.9 Ordering Pattern by Days of the Week Comparison (Tc-99 Generator versus Non-Generator)



	Sun	Mon	Tue	Wed	Thu	Fri
Non-Generator	459	717	679	571	280	363
Generator	226	193	3	140	4	142

3.4.3 Order Volume

In this section, 9,430 Tc-99 generator orders and 40,350 non-generator orders placed by 727 pharmacies from October 1 to December 31, 2006 are examined. Once again, the generator and non-generator order volumes are compared by number of orders and by weight. Figure 3.10 shows that the Tc-99 generators represent 19 percent of total number of orders. However, the generators comprise a much greater portion of order

Figure 3.9 Ordering Pattern by Days of the Week Comparison (Tc-99 Generator versus Non-Generator)

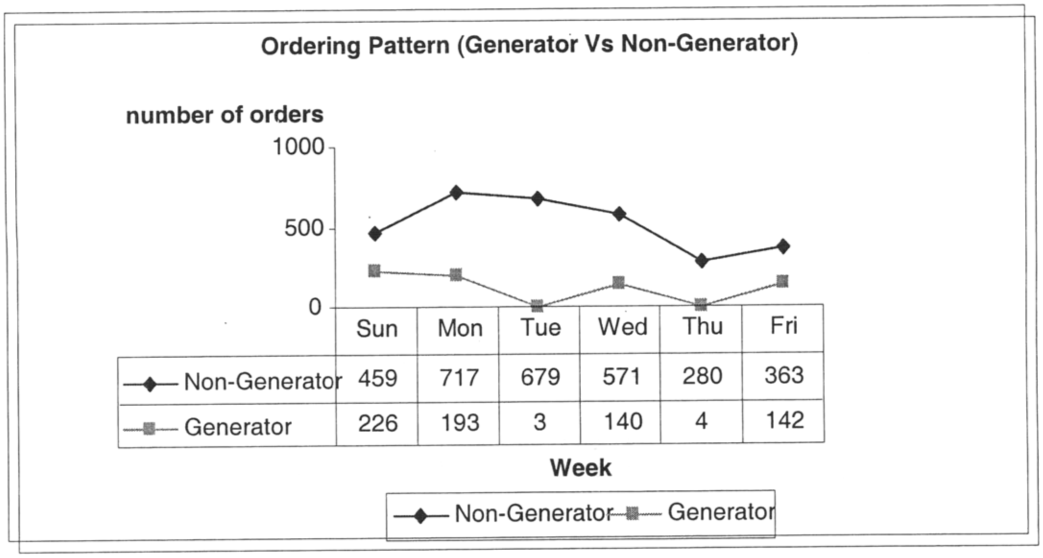


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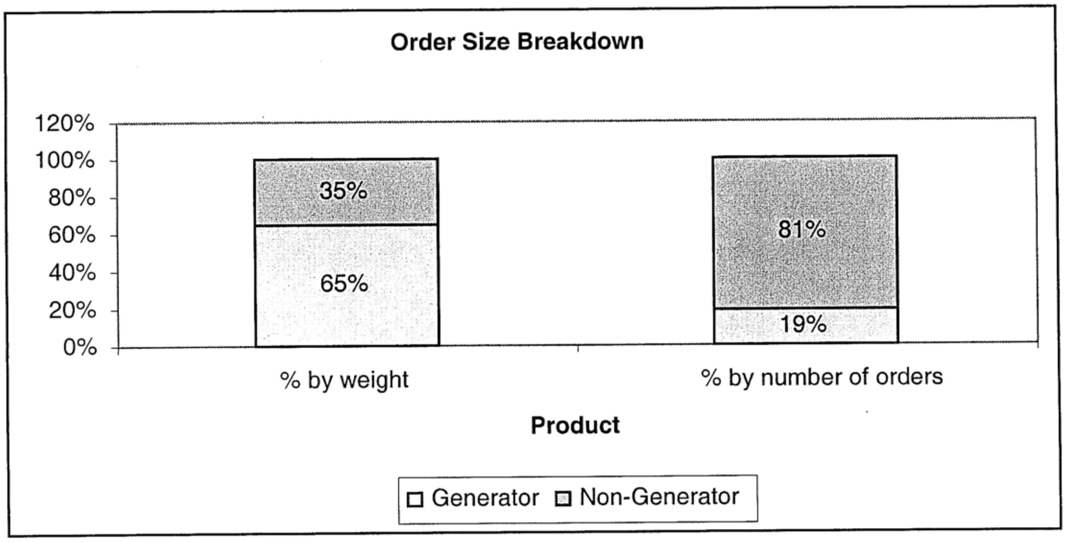
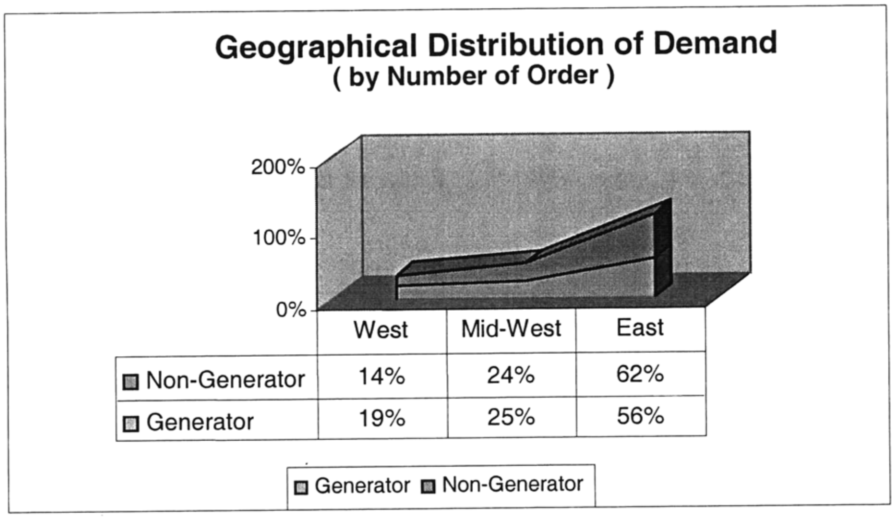
Figure 3.10: Order Size Breakdown (Tc-99 Generator versus Non-Generator)

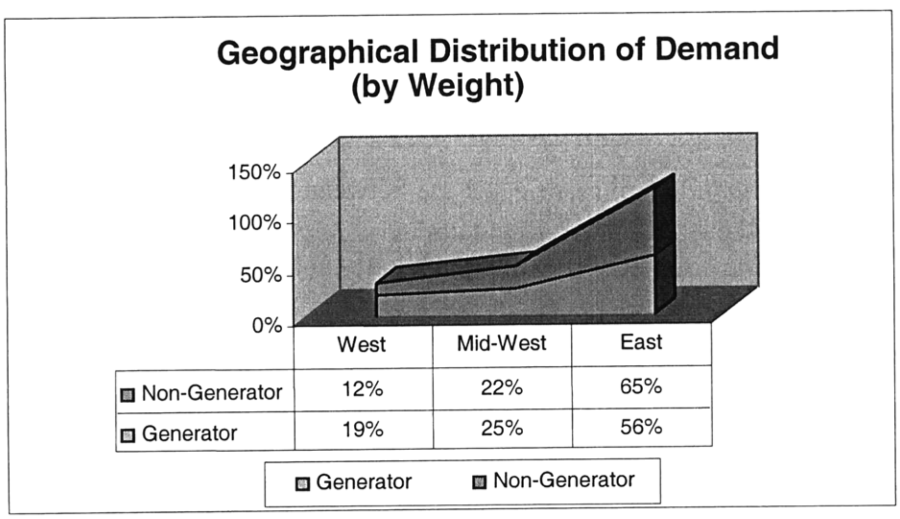


3.4.4 Geographical Demand Distribution

This section compares the geographical distributions of demand for generator and non-generator products. Figure 3.11 illustrates that the geographical distributions of demand for generator and non-generator products are not significantly different from each other.

Figure 3.11 Geographical Demand Comparisons (Tc-99 Generator versus Non-Generator)





3.4.5 Summary and Finding

The results of the comparative analysis of demand for the generator and non-generator products (Table 3.6) support the assertion that their order patterns are significantly different. With the exception of geographical distribution of demand, all of the criteria point to a sufficient degree of difference between the ordering patterns of generators and non-generator products.

Table 3.6 Summary of Results (Generator and Non-Generators)

Comparison Summary (Generator vs Non-Generator)

	Order Type Standing vs Demand	Order Frequency Number of Order -- Order Size	Order Volume Number of Order -- Order Size	Geographical Demand
Generator	93 vs 7	High: Sunday Low: Tuesday and Thursday	19% --- 65%	High: East Low: West
Non-Generator	36 vs 64	Highe:Monday Low:Thursday	81% --- 35%	High: East Low: West

3.5 Conclusion and Recommendation

The results of comparing the demand patterns of THC and non-THC radio-pharmacies reject the hypothesis that differentiating service between them is a viable option. Although the order volume comparison exhibits a significant difference, such a difference can be attributed to pharmacy size rather than pharmacy affiliation.

On the other hand, based on the results of comparing the demand patterns of the Tc-99 generator and non-generator products, one cannot reject the alternative hypothesis that product segmentation is a viable alternative. Moreover, the demand characteristics of Tc-99 generator are predictable and present a case for coordinating replenishment planning and operations.

The next section proposes a coordinated replenishment policy to take advantage of the Tc-99 generator's inherent attributes and deterministic demand pattern.

4 Proposed Policy for Coordinated Replenishment

The Mallinckrodt pharmacies are responsible for 18.4 percent of generator demand even though they comprise only 5 percent of the THC's pharmacy network. As discussed in Section 1, the integrated information systems and shared processes make coordination of replenishment activities between THC and its pharmacies possible without any significant investments. Therefore, a better coordination of generator replenishment can be a high impact proposition with minimum task management requirements.

This section discusses the feasibility of implementing a coordinated replenishment policy (CRP) in the network of THC pharmacies. The first part discusses how Equation 1.1, the variation of the EOQ introduced in Section 1, can be applied to the Tc-99 replenishment. This discussion includes whether Tc-99 and its demand pattern meet the assumptions of the classic economic order quantity (EOQ) model. This is followed by application of the EOQ model to a representative Mallinckrodt radiopharmacy. Transportation costs incident to applying the EOQ are compared to those of the pharmacy's current policy to quantify the economic benefit. Finally, capabilities and limitations of the EOQ-based CRP are discussed. The second part of the discussion extends implementation of the EOQ-based CRP to the rest of the Mallinckrodt radiopharmacies. This part evaluates the feasibility of implementing the CRP on a larger scale and the CRP's capabilities and limitations at the pharmacy network level. Lastly, an economic analysis on implementing the CRP is conducted to quantify the results.

4.1 Applying the EOQ to Tc-99 Generator Replenishment Planning

Before determining whether it is possible to apply the EOQ in the nuclear medicine supply chain, it is important to first review its assumptions. In no particular order, the assumptions of the EOQ are listed below:

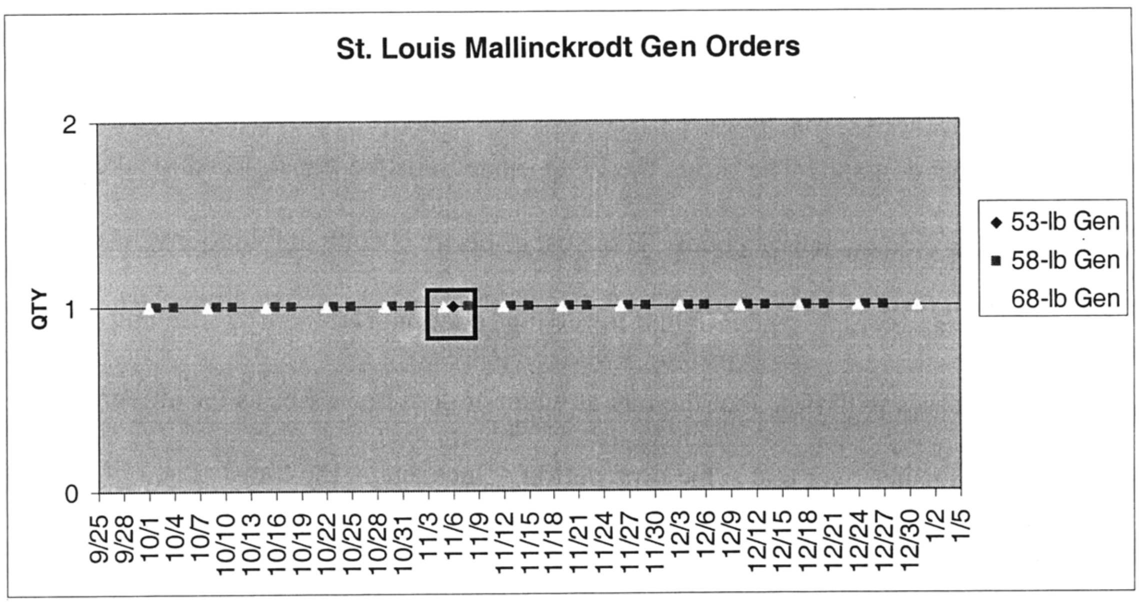
- The demand rate is constant and deterministic.
- The order quantity need not be an integral number of units.
- The unit variable cost does not depend on the replenishment quantity. In particular, there are no discounts in either the unit purchase cost or the unit transportation cost.
- The cost factors do not change appreciably with time.
- The replenishment lead time is either zero or deterministic.
- The planning horizon is very long.
- The entire order quantity is delivered at the same time.

The Tc-99 generator has product and replenishment characteristics that are appropriate for applying the EOQ. Tc-99 is one of few products of which radiopharmacies maintain inventory because of its two-week shelf life and end-user demand. Second, most of the radiopharmacies, especially high-volume ones, purchase generators using the standing order arrangement, and therefore have a near-deterministic demand rate and longer planning horizon. Third, THC neither offers discounts to its customers nor receives transportation discounts from its carriers. Finally, THC's 24-hour lead time is as close to the zero lead time as possible in the nuclear medicine market.

4.1.1 St. Louis Mallinckrodt Radiopharmacy

To verify the assertion that TC-99 meets the criteria and that the EOQ is appropriate for coordinating its replenishment, the St. Louis Mallinckrodt radiopharmacy's Tc-99 demand is examined. Figure 4.1 depicts the radiopharmacy's Tc-99 orders from October to December 2006. Each point represents a specific generator type ordered on that day. This radiopharmacy has a standing order of one 68-lb generator that arrives on Sunday and one 58-lb generator that arrives on Monday and Wednesday.

Figure 4.1 TC-99 Generator (Gen) Demand at St. Louis Mallinckrodt Pharmacy



As conjectured in the previous paragraph, this radiopharmacy's generator orders follow a predetermined order schedule. Only on one occasion, identified by the square in Figure 4.1, has the periodic order quantity been changed. In addition, the radiopharmacy is within ground transportation distance from the MH plant and has historically maintained a 93 percent dispensing rate.[6] As this pharmacy has already demonstrated high performance and service level, any significant improvement as a result of applying the EOQ in this pharmacy's policy can serve as the benchmark for the rest of the radiopharmacies served by THC. If this pharmacy can reap significant gains in cost savings as a result of implementing the EOQ, the potential benefit of wider implementation makes a strong case for a system-wide replenishment policy.

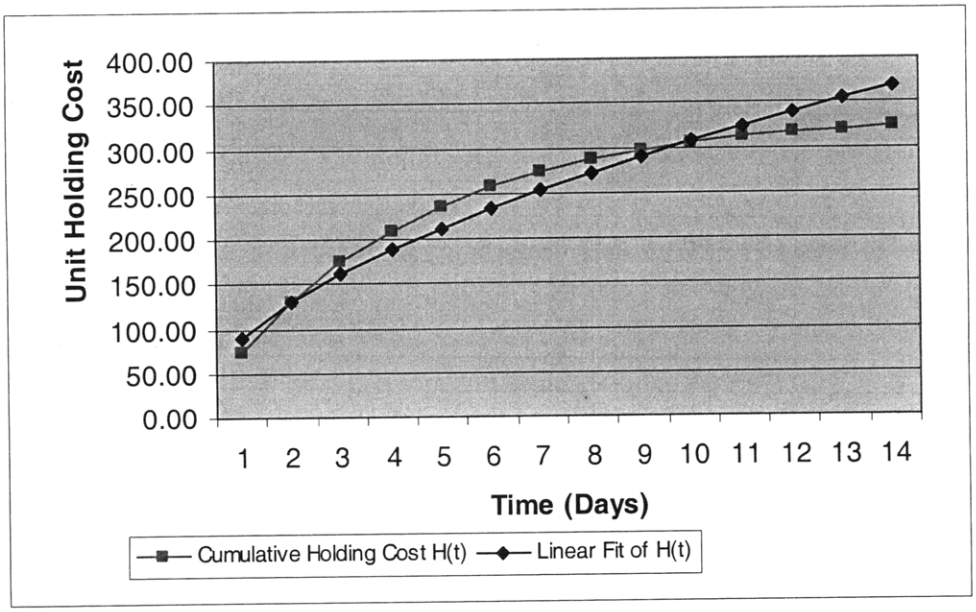
How would the St Louis radiopharmacy's order pattern be affected after applying the EOQ? To carry this discussion forward, it is pertinent to discuss the variation of the EOQ model first introduced in Section 1. Because of the costliness of radioactive decay, most radiopharmacies prefer to reduce the amount of unused radioactivity by ordering just enough to meet demand. Therefore, the EOQ model must be transformed to take the effect of radioactive decay into account. This cost of decay is comparable to inventory holding cost and can be represented by the following function: $H(t) = ht^{\gamma}$. The unit holding cost increases with time, but the rate at which it does decreases as the amount of radioactivity diminishes over that same time period. Once again, the transformed EOQ is illustrated as follows:

$$EOQ = \left(\frac{1}{h} \left(1 + \frac{1}{\gamma} \right) AD^{\gamma} \right)^{\left(\frac{1}{1+\gamma} \right)} \qquad \text{Equation 1.1}$$

When cumulative holding cost, or cost of radioactive decay, is plotted, the graph is consistent with that of the function $H(t) = ht^{\gamma}$ in Figure 4.2.

[6] Dispensing rate is defined as the ratio between the amount of radiopharmaceuticals it purchases and the amount it dispenses to the client hospitals and clinics. This is an important performance metric for THC pharmacies as is for independent pharmacies.

Figure 4.2 Cumulative Holding Cost (per curie) of TC-99 Generator



One can immediately recognize that the marginal holding cost diminishes over time; this makes sense because the holding cost is more elastic with respect to time when the amount of residual radioactivity is high, the period immediately following calibration. To estimate the parameters γ and h, one can take a natural logarithm of the $H(t)$ function, which will result in $LN\,H(t) = LNh + \gamma LNt$. By applying a linear regression to this logarithmic function, it is possible to obtain the estimates of γ (the slope of the regression) and h (obtained by applying *EXP* to the y-intercept). With the estimates obtained, it is now possible to find the EOQ for this radiopharmacy. Table 4.1 summarizes the input values of the EOQ model. Some of the values are disguised.

Table 4.1 Input Values to EOQ (Disguised)[7]

	St Louis Mallinckrodt (10/01/06-12/31/06 Data)
EOQ	**27.00**
Decay Rate	0.22
D: Demand	1382
A: Admin Costs	75.00
Fixed Trans Cost	26.85
h(=vr) estimate	89.48
Gamma	0.54
V	333.00
Variable Trans Cost	0.77
D/Q	51.48
Order Interval	**7.09**

For the St. Louis radiopharmacy, the economic order quantity is 27 curies replenished every seven days.

4.1.2 Estimated Cost Savings from Applying the CRP

Before comparing the EOQ and the radiopharmacy's current order policy, it is important to address the transportation constraint that requires the relaxation of one of the assumptions of the EOQ. Because no single transportation platform can carry more than 20 curies at a time, it is infeasible to replenish the entire quantity in one trip. Since transportation resources are limited, it is not possible to make multiple trips in a short period of time. Therefore, the EOQ of 27 curies cannot be applied without dividing the order quantity into allowable sizes.

The Mallinckrodt pharmacies already have an in-house software tool that assists the pharmacist with selecting the optimal generator models. With the CRP, the pharmacist has the reference parameters that can assist him with choosing the optimal

[7] See Appendix II for a detailed explanation and applied assumptions.

replenishment policy, not only for his pharmacy but also for the network. This subject is treated in more detail in 4.2.2.

In terms of cost savings, the St Louis radiopharmacy can realize a 25 percent reduction by decreasing the number of replenishments from 40 to 31 over three months[8]. Since this pharmacy is served strictly by ground transportation, or linehaul, the actual value of savings is considered to have only a low impact. However, linehaul is the least costly of the four transportation modes; therefore, THC can realize significant savings in those pharmacies that require replenishment by more expensive transportation modes like chartered air and commercial air. A more exhaustive economic analysis is presented in 4.2.4.

4.1.3 Capabilities and Limitations of the CRP

The coordinated replenishment policy's (CRP's) most important capability is minimization of channel costs. Presently, most radiopharmacies are not charged freight and fixed order costs; therefore, they have a tendency to over-consume these limited resources. This local maximization of profits results in a behavior distortion costly to THC; the radiopharmacies order frequently in small quantities to minimize radioactive decay costs at THC's expense. Furthermore, this behavior distortion is most likely being observed among smaller pharmacies as observed in the order volume analysis in Section 3. The CRP addresses this shortcoming by determining the order quantity that minimizes THC's fixed costs and as well as radioactive decay costs. In addition, the CRP enables the manager to identify those pharmacies that exhibit inefficient order behaviors. The

[8] This percentage is calculated using the actual input values.

manager can create incentives for inefficient pharmacies to change their behaviors or, in case of the THC pharmacies, enforce the CRP. Finally, the CRP is robust enough to be used with other products. Tl-201 is a popular product and many pharmacies keep stock. By changing input parameters, THC can use the CRP with this and other appropriate products.

In addition to the relaxation of one of the assumptions, the CRP is subject to other limitations. First, an element of arbitrariness is present. Allocating transportation costs and dividing the economic order quantity require that the decision maker use his discretion when selecting feasible values. Furthermore, Tc-99 and other radiopharmaceuticals are subject to radioactive decay; holding costs, the denominator of Eq. 1.1, is a proxy for the perishable nature of a radiopharmaceutical. The more of the product becomes useless the longer it sits on the shelf.

Despite these limitations, the CRP's strategic importance and potential for significant cost savings make it worthwhile to consider its implementation. Furthermore, its ancillary benefits are no less significant; the CRP provides the manager with an additional decision and control tool.

4.2 Implementing the Coordinated Replenishment Policy

In the previous section, the economic benefit of implementing an EOQ-based replenishment policy is shown to be substantial. This section examines the feasibility of implementing the CRP on a greater scale. This wider implementation is critical, because not all costs are avoidable. THC has procured transportation services that are lumpy; cost savings realized by its implementation will not be significant unless the CRP influences significant product volume. Once again, the Tc-99 generator's product and demand characteristics position it as the most attractive candidate for a large-scale CRP implementation. Unlike the other products, the generators are packaged and handled separately due to the weight of the exterior casing and high concentration of radioactive material. Therefore, implementing coordinated replenishment policy for this product can stand alone whereas the other products require a more integrated approach across multiple product lines. In addition, some of the fixed transportation costs can be shared among assorted shipments that include generators since other orders are often bundled with them. Hence, implementing the CRP with regard to generator replenishment can serve as a precursor to implementing similar policy for other products.

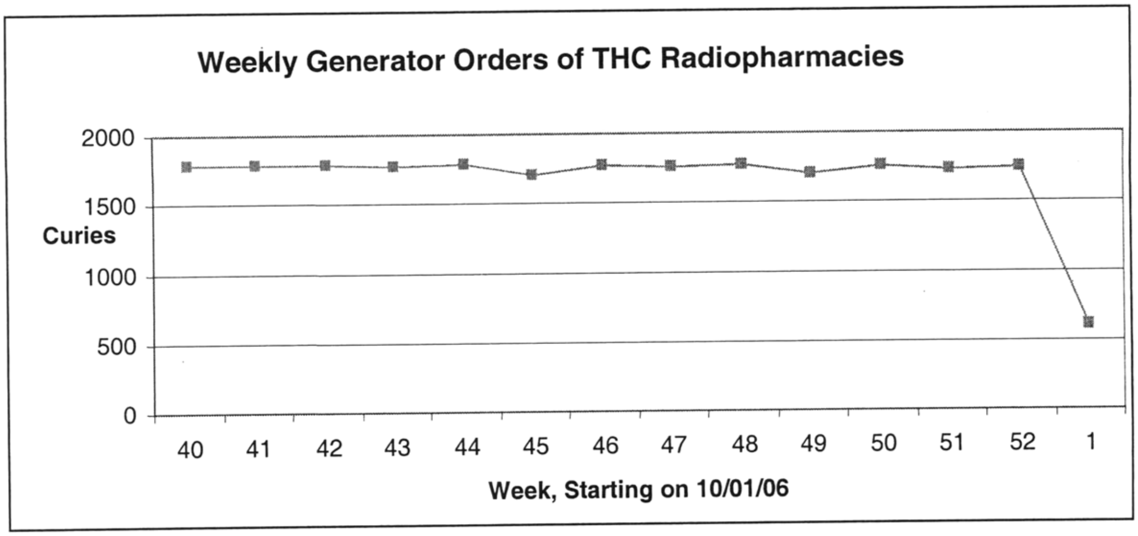
In this section of the study, the EOQ-based CRP is applied to all of the THC radiopharmacies. The 37 Mallinckrodt pharmacies share similar processes to include information management, order-to-cash processing[9], and performance metrics; therefore, such an implementation alternative is more attractive and less disruptive than the alternative dealing with the non-THC pharmacies or the entire network. Similar to the evaluative process used in 4.1, this section first evaluates whether the assumptions of the EOQ are violated at the pharmacy network level. Then, the economic order quantity and order interval are determined for each Mallinckrodt radiopharmacy. Furthermore, a discussion on benefits and costs of implementing the CRP ensues. Finally, the last section discusses different replenishment scenarios and their economic impact.

[9]With the Mallinckrodt radiopharmacies, THC realizes revenues only when hospitals and clinics make payments. On the other hand, THC bills and receives payments directly from the independent radiopharmacies.

4.2.1 Applying the CRP to the Network of THC Pharmacies

Do the assumptions of the EOQ hold true for the network of Mallinckrodt radiopharmacies? The near-deterministic demand pattern observed in the St. Louis pharmacy is also observed in the network of THC pharmacies. Figure 4.3 illustrates the Mallinckrodt radiopharmacies' near-deterministic demand for the Tc-99 generator.

Figure 4.3 Mallinckrodt Weekly Tc-99 Demand



Except the week of Christmas and New Year's Days, the weekly aggregate demand pattern shows little deviation. Furthermore, each Mallinckrodt radiopharmacy behaves like the St. Louis pharmacy. The Mallinckrodt radiopharmacies use standing orders to receive generator replenishments. To summarize, all of the factors that support the use of the EOQ-based CRP at the St. Louis radiopharmacy are also present in the network.

4.2.2 Results of Applying the CRP

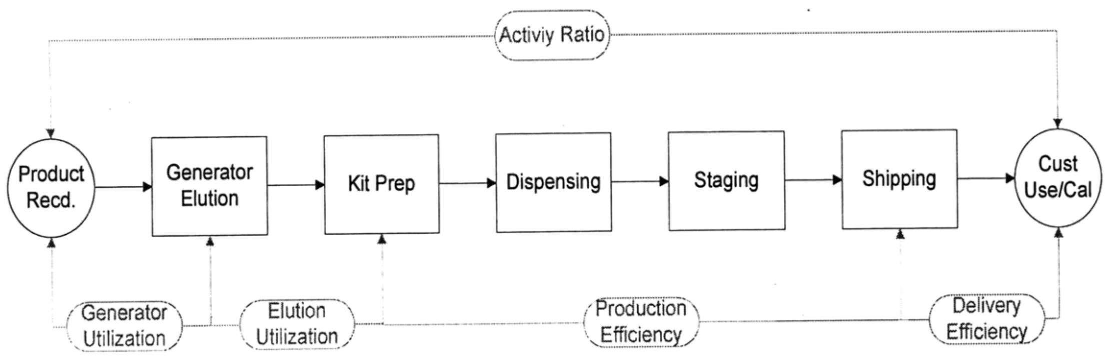
The economic order quantities vary significantly among the Mallinckrodt pharmacies.[10] The variance in demand is one explanation, but the variance in fixed transportation costs is also telling. In some instances, current order frequency and order quantity values of several pharmacies—for example Saginaw, Valley View, and St. Paul—are closer to the values generated by the CRP than those of other THC pharmacies. These pharmacies share two characteristics; their demand for the generators is relatively high, and they are served by linehaul. With low-volume pharmacies like the Hazelwood pharmacy, the findings are not so definitive; the CRP proposes almost 30 days between replenishments. This is not an acceptable value for a product whose life span is around 14 days. The relaxation of the assumption that the entire economic order quantity be delivered all at once is more challenging at the pharmacy network level. Overcoming this challenge requires either complex calculation to which there may not be a solution or a degree of arbitrariness that exceeds the manager's comfort level. For this reason, it is difficult to estimate cost savings realized from implementing the CRP. For the CRP to become operationally feasible, the aforementioned challenge requires a conceptually sound and empirically defensible solution.

To reduce the amount of arbitrariness in selecting practical replenishment quantity, it is important to describe the management tool mentioned earlier in the section. Mentioned several times in this thesis is a THC-developed tool, *Technetium Utilization Tools: User Instructions* (TUT). This suite of software tools assists the pharmacist to monitor and improve his processes and to facilitate business change. Figure 4.4 depicts

[10] Refer to Appendix III for summary data.

the core processes of a typical radiopharmacy. In oval are the five performance metrics that the TUT is designed to monitor and support.

Figure 4.4 Key Metrics of the Technetium Utilization Tools[11]



Source: Murphy, 2006

The TUT has been in use among the Mallinckrodt radiopharmacies since early 2006. This ubiquitous, voluntary use presents a strong case for the presence of synergy between the TUT and CRP.

One of the tools at disposal is the *Generator Modeling Tool*. Using this tool, the pharmacist can simulate Tc-99 usage for a period up to four weeks. The model can simulate standing order replenishments that occur every week or every other week. The pharmacist inputs generator bundles and monitors performance metrics to select the most effective bundle. This modeling tool can also interface with other tools like *TRON*, which assists with day-to-day operations and short-term planning, to support decision making. The use of the EOQ and replenishment frequency can support the model bundle selection. Furthermore, the TUT can validate the CRP and facilitate acceptance at the pharmacy level.

[11] Refer to Appendix IV for the description of each metric.

4.2.3 Benefits and Costs of Implementing the CRP

In addition to the benefits stated in 4.1.3, implementation on a larger scale can result in additional benefits. The CRP can facilitate the long-term raw material procurement planning, transportation planning, and improved productivity. It can also assist THC with closer integration of information systems and proper cost allocation at the individual order level. Finally, the CRP enables the manager to quickly identify customers who exhibit inefficient ordering behaviors.

Costs are also significant. The CRP reduces the number of replenishments and increases the quantity of replenishment. Such a change may strain production capacity and negatively impact customer service. Furthermore, the arbitrariness with regard to cost allocation and inability to trace all costs are not completely eliminated. The difficulty of capturing unavoidable costs weakens the argument for implementing the CRP. Finally, raw material purchase can be adversely affected by implementing the CRP which proposes general increase in order quantity. Since generator raw material suppliers are few, any change in procurement policy requires cooperation from them. In conclusion, careful deliberation in all phases of CRP implementation is essential to its success.

4.2.4 Economic Analysis of Implementing the CRP

To address the shortcomings discussed in 4.2.3, considered in this section are five scenarios in which the number of replenishments per pharmacy is reduced by one per month up to five. As a comparison, the theoretical optimum, which is rounded to the nearest multiple of four, is added as the sixth scenario.[12] Total relevant costs are calculated for each of the scenarios to quantify the economic benefit of implementing the CRP. As discussed in 4.2.3, the analysis is not practical unless one considers additional decay due to the increased length of interval as well as additional transportation capacity due to the increase in replenishment quantity. Hence, such considerations are included in this economic analysis.

There are three intermediate steps to calculating the total relevant costs of the six scenarios. In the first step, fixed ordering costs for each scenario are determined by adding all relevant fixed costs as defined in Table 4.1. Table 4.2 shows fixed cost savings achieved by each scenario; the comparison base is the actual fixed ordering costs.

Table 4.2 Cost Savings Achieved by Reducing the Number of Replenishment

by -- 1 /month	2/month	3/month	4/month	5/month	Adjusted # of Replenishments
6.5%	13.1%	19.6%	26.2%	32.7%	69.4%

Second, the total cost of replenishment via chartered air is added to the value from step one. It is important to note that increasing quantity does not necessarily translate to carrying more generators per replenishment. Since the chartered air carrier charges a fixed fee per trip, THC can reduce per unit costs by consolidating shipments by using the heavier shielding cases that can pack more activity. However, there is a limit to consolidating shipments and reducing the number of chartered trips. This threshold is estimated by calculating additional activity required in each scenario. The additional activity is then subtracted from the current load capacity (masked) inferred from average activity carried per replenishment. When this value becomes negative, additional trips

[12]Adjusted Number of Replenishment: the generators are manufactured four days of the week on Saturday, Sunday, Tuesday, and Thursday, and most deliveries take place by the following morning.

become necessary. Table 4.3 is the summary data for estimating additional chartered flight costs.

Table 4.3 Cost of Adding Charted Air Capacity

	Number of Replenishments (QTR) Reduced by:					
	1/month	2/month	3/month	4/month	5/month	Adj. # of Replenishments
Add. Activity per Rep. (CI) via Chartered	23	50	82	124	187	690
Additional Chartered Trips	0	0	0	1	1	2
Additional A/C Costs (Qtr)				$286,432	$286,432	$572,865

Finally, the cost of decay due to the increase in the length of replenishment interval is estimated. This is accomplished by first calculating the difference in service intervals of the base case and each scenario. This value is multiplied by holding costs, *h*, and number of replenishment during the quarter. Total relevant costs are the sum of the values obtained from the three intermediate steps. Table 4.4 summarizes the result of the above process.

Table 4.4 Total Relevant Costs of Six Replenishment Scenarios ($ thousand)

Cost Category	As-Is	Reducing 1/month	Reducing 2/month	Reducing 3/month	Reducing 4/month	Reducing 5/month	Adj. Number of Replen.
Fixed Costs	173	162	151	139	128	117	53
Chartered Air	285	266	246	225	490	464	661
Add. Decay Costs	NA	14	28	43	57	71	134
Total Relevant Costs	459	442	425	407	674	651	848
Savings (QTR)	NA	3.55%	7.32%	**11.24%**	-47.05%	-42.03%	-84.86%

While economies of scale due to consolidation can be observed, adding more chartered air capacity becomes cost prohibitive. The above results indicate that reducing, on average, three replenishments per month per pharmacy is the most cost efficient scenario.

As the analysis is performed at the pharmacy network level, it presents the manager with baseline data that can guide his or her long-term resource planning. While the element of arbitrariness still remains, the recognition and treatment of the constraints specified in 4.1 and 4.2 bring the CRP a step closer to actual implementation.

5 Conclusions

The objective of this study is to answer the following research question: should THC differentiate its service between the Mallinckrodt radiopharmacies and the independent, non-affiliated radiopharmacies? The analytical approach consisted of applying a set of evaluative criteria to determine whether there is a significant difference in demand characteristics between the two pharmacy networks. This study concludes that the difference is not significant enough to merit service differentiation. Besides answering the research question, this study addresses a fundamental and strategic issue. THC's core capability is providing a high and consistent level of customer service, prompted by special characteristics inherent in radiopharmaceuticals and the competitive environment. Therefore, THC's strategy is to minimize costs while providing the highest service level possible. We believe that service differentiation by pharmacy affiliation can adversely affect member pharmacies' ability to provide the expected level of service.

The study alternatively proposes product segmentation, although its aim is not to facilitate service differentiation. Instead, product segmentation leads to a policy which reduces customers' inefficient ordering behavior and minimizes channel costs. THC's most popular line of products, Tc-99, has characteristics conducive to a system level coordination of replenishment activities. The Coordinated Replenishment Policy (CRP) provides an economically attractive option as well as ancillary benefits. The objective of the CRP is to improve the efficiency of the supply chain by minimizing fixed costs incident to each transaction and inventory holding costs related to the diminishing potency of radiopharmaceuticals. To that end, THC can achieve at least an 11 percent reduction in costs by implementing the CRP in the network of THC pharmacies. It is believed that THC can achieve greater savings as its pharmacies refine their operations. In conclusion, coordinating the replenishment of radiopharmaceuticals illustrates a shifting of the push-pull boundary from the central manufacturing and distribution facility to the pharmacies to improve the overall efficiency of the supply chain.

5.1 Significant Findings

First, the portion of replenishment costs that is considered fixed is between 45 and 60 percent of total transportation costs. In addition, fixed costs incurred by activities related to order receipt, invoicing, and processing are as significant as fixed transportation costs. Therefore, these two categories of costs which have minimally influenced THC's replenishment decisions are fully captured in and applied to the CRP.

Second, cost allocation down to the individual order level offers additional insights previously unavailable. Such an endeavor is valuable in estimating the cost of serving each radiopharmacy, but is time-consuming and rigorous. However, a more sophisticated costing system helps to identify inefficient processes, lanes, and customers.

Finally, the Mallinckrodt pharmacies and comparably sized independent pharmacies exhibit similar demand patterns. However, low-volume pharmacies display a wide range of demand patterns. Over 40 percent of independent pharmacies order, on average, one product per week. These pharmacies are just as problematic to THC as those pharmacies that order small quantities frequently. Since demand orders are generally preferred by low-volume pharmacies, the transportation mode most sensitive to short-term fluctuations in demand is more frequently used than the others. This transportation mode, the local ground carrier, represents a significant amount, about 30 percent, of the department's transportation spending.

5.2 Recommendations

This thesis recommends implementation of the EOQ-based Coordinated Replenishment Policy. Before full implementation, it is recommended that THC conduct a trial run by using the existing Technetium Utilization Tools at the Mallinckrodt radiopharmacies. The EOQ and replenishment interval values should guide the selection of generator model bundles. Once the generator model bundles and replenishment intervals are chosen, THC's procurement, production, and distribution managers should analyze their overall impact on the supply chain. The economic analysis found in 4.2.4 provides a starting point for a more extensive study. Following this analysis, THC should implement the CRP first in the Mallinckrodt radiopharmacy network. Once the CRP is validated, it is important that THC commits to the CRP fully since partial implementation will most likely undermine the objective of network-wide coordination and significant cost savings. In addition, THC should explore the use of the CRP with other products like Tl-201 which possesses product and demand characteristics similar to Tc-99.

To realize the CRP's greater potential, THC must influence its customer pharmacies by adopting one or more of the following actions. First, THC can share with its inefficient customers how their ordering behavior is burdening the supply chain and putting upward pressure on price. Second, THC can charge a fixed ordering fee. THC can substitute a periodic price increase with a portion of its fixed ordering costs. By so doing, THC can influence its customers to order more efficiently without penalizing efficient customers. Third, THC can pass on a portion of cost savings resulted from implementing the CRP to encourage more efficient ordering behaviors.

As stated above, cost allocation to the individual order level has provided useful insights. It is recommended that THC refine the allocation scheme used in this study and apply it periodically. Such an endeavor is rigorous and costly, but it serves as a means to support management and control.

This study also advocates additional studies to better understand the downstream demand fulfillment activities between the pharmacies and their customers. The researchers hypothesize that the end user's demand pattern is closely correlated to, or even responsible for, the pharmacy' ordering behavior. Understanding the dynamics between the two parties can help THC to further develop its long-term capacity and demand planning.

In conclusion, coordination of planning and operations is essential to THC's maintaining its competitive advantage. The product's short half-life should not limit THC from carrying out disciplined and forward-looking business plans.

Appendix I: Derivation of the Economic Order Quantity (Weiss 1982)

Consider a product facing a constant demand rate *D*. Fixed ordering cost is *A*, replenishment lead time is constant, and holding cost per unit increases with time *t* that the product has been in stock according to $H(t) = ht^{\gamma}$, γ and h are constants and are greater than zero. The objective is to choose an order quantity that minimizes average combined ordering and holding costs over an infinite horizon. With an order quantity of *Q*, and constant demand rate *D*, the length of an order cycle is *Q/D*. Because all order cycles are equal, consider the first order cycle [0, Q/D]. First, note $ht^{\gamma} = \int_0^t \gamma h u^{\gamma-1} du$; this is the total holding cost if one unit is kept in stock during the period [0, t]. During the first cycle, the inventory level *I* varies with time *I(t)=Q-dt*. Therefore, the average holding cost during the cycle [0, Q/D] is:

$$\overline{H} = \frac{1}{Q/D} \int_0^{Q/d} I(t)\gamma h u^{\gamma-1} du$$

$$= \frac{1}{Q/D} \int_0^{Q/d} (Q - du)\gamma h u^{\gamma-1} du = \frac{hQ^{\gamma}}{(\gamma+1)D^{\gamma-1}} . (1)$$

Equation (1) is also the average holding cost in an infinite horizon. Average inventory cost is then:

$$F(Q) = \frac{hQ^{\gamma}}{(\gamma+1)D^{\gamma-1}} + \frac{D}{Q} A . (2)$$

Applying the first order condition to the average cost function (2), we obtain the EOQ as:

$$EOQ = \left(\frac{1}{h} \left(1 + \frac{1}{\gamma} \right) AD^{\gamma} \right)^{\left(\frac{1}{1+\gamma} \right)} . \quad (3)$$

Equation (3) agrees with the classic EOQ model when $\gamma = 1$.

Appendix II: Input Values of the EOQ

Transportation Spending as a Portion of Ordering Cost

The most challenging aspect of obtaining input values of the EOQ is determining the fixed portion of transportation spending that is a part of ordering cost, A. The first step in this process is extracting relevant data from disparate data sources. THC maintains separate order transaction and transportation spending data. While the former, maintained by OASIS, make data analysis at the individual order level possible, the latter reside in a number of different systems. Since the EOQ determined at the pharmacy level requires a rational allocation of transportation spending to each order line, pertinent data are extracted from a number of transportation spending reports provided by THC. For those spending categories where tracing costs down to the required level of detail is not possible, the rates used by Bourassa (2006) are applied as discussed below.

The second step involves applying a costing system to allocate the aggregate transportation spending obtained from the first step. Figure A.1 illustrates the cost pools to which THC's transportation spending from October to December, 2006 are assigned. (2), (4), (7), and (8) are those categories where charges are applied to each shipment, load, or trip regardless of the number or weight of packages. These charges are considered fixed costs. (5), (6), (9), and (11) are those categories where charges are assessed by weight, and therefore are considered variable costs. (1), (3), and (10) are the allocation bases to rationally divide charges applied to orders grouped by either Trip Number or date. Total Trans, (12), is the sum of transportation spending.

Figure A.1 Transportation Spending Categories and Allocation Bases

(1) Trip Number	(2) Origin Ground	(3) # of Stops	(4) Destination Ground	(5) FedEx	(6) Linehaul

(7) Linehaul Stop	(8) Charter	(9) Commercial	(10) # of Orders in a Load

(11) Surcharges	(12) Total Trans

(1) is obtained by assigning a unique identifier to each group of orders that are shipped on the same day and time grouped by transportation alternatives. The estimated costs of $100 per trip to St. Louis Downtown-Parks Airport and $75 per trip to St. Louis Lambert International Airport are used (Bourassa 2006). (3) represents the number of orders shipped to each pharmacy on the same date. This is the charge of $100 per pharmacy stop (Bourassa 2006); (4) is calculated by dividing the $100 charge by (3). (5) is calculated by multiplying the appropriate FedEx rate (per unit weight) and the total weight of each order. (6) is calculated by multiplying the average linehaul rate per unit weight ($0.07/lb) and the total weight of each order (Bourassa 2006). (7) is calculated by dividing the estimated rate per stop, $100, by (3). (8) is calculated by dividing the fixed fee per trip (varies from route to route) by the number of (1). The rates used in (9) are obtained from Bourassa (2006) and validated by THC. Finally, a hazardous material surcharge of $55 is allocated among orders in the same load; $55 is divided by (10). There were a total of 49,775 individual order lines in the OASIS extract covering the period between October and December, 2006, and each order line is now allocated a portion of transportation spending.

Other EOQ Input Values

D: Demand—the amount of radioactivity measured in curies (quarterly aggregate is multiplied by four to obtain annual demand)

A: Ordering Cost—the sum of historical administration costs (back office order-to-cash estimate, $70-75 for the THC Imaging Division) and fixed transportation costs (THC 2007)

h: Holding Cost—the cost of radioactive decay

As outlined in Section 3 and above, all values except ***D*** are estimates. Although the number of cost pools is eight, the total transportation spending as estimated using the costing system has an accuracy of 99 percent (the accuracy rates, at its worst, go down to 88 percent at the transportation mode level).

Appendix III: Summary Data of the 37 THC Pharmacies

*All values are disguised.

No.	City	State	EOQ (Curies)	Replenishment Interval (Days)
1	BELTSVILLE	MD	44	7
2	BETHLEHEM	PA	40	10
3	CINCINNATI	OH	40	12
4	COLUMBUS	OH	32	15
5	COMMERCE	CA	51	8
6	CRESTWOOD	IL	42	8
7	DALLAS	TX	46	13
8	DAYTON	OH	46	7
9	DENVER	CO	43	9
10	EBENSBURG	PA	43	8
11	ELK GROVE	IL	48	6
12	FOLCROFT	PA	35	12
13	FORT LAUDERDALE	FL	48	7
14	HARRISBURG	PA	43	8
15	HAZELWOOD	MO	22	29
16	HICKSVILLE	NY	46	5
17	HOUSTON	TX	42	11
18	KANSAS CITY	MO	40	10
19	LOMA LINDA	CA	45	11
20	MARIETTA	GA	38	10
21	MEMPHIS	TN	42	13
22	MIAMI	FL	34	13
23	MILFORD	CT	46	8
24	NORTH ATTLEBORO	MA	39	10
25	ORLANDO	FL	26	15
26	PINE BROOK	NJ	34	12
27	PITTSBURGH	PA	41	9
28	PORTLAND	OR	32	8
29	SAGINAW	MI	46	7
30	SAINT LOUIS	MO	27	7
31	SAINT PAUL	MN	50	7
32	SAINT PETERSBURG	FL	42	6
33	SAN FRANCISCO	CA	48	10
34	TOLEDO	OH	38	10
35	VALLEY VIEW	OH	55	5
36	WARREN	MI	17	48
37	WILKES BARRE	PA	44	8

Appendix IV: Key Metrics of Technetium Utilization Tools

Key Metrics

The Tc Utilization tools are based on the measurement system developed as part of the Tc Utilization projects. The project team identified five key metrics that can be used to monitor performance of the Tc production process. The figure below illustrates the portion of the process measured by each metric.

- **Activty (Tc/Mo) Ratio –** The activity of Tc-99m doses at the customer's calibration time divided by the activity of Mo-99 (generators) received. This metric will alert users to a mismatch between customer demand and generator purchases.
- **Generator Utilization –** The activity of generator elutions divided by the theoretical activity of the generators. (The theoretical activities of generators are calculated using a model based on an aggressive but reasonable elution pattern.) This metric will alert users to inefficient use of generators.
- **Elution Utilization –** The activity of kits prepared divided by the activity of generator elutions. This metric will alert users to excessive residual waste and decay of elutions or overfill of kits (overfill that is not reported in TRON).
- **Production Efficiency –** The activity of Tc doses at the time their shipment is confirmed divided by the activity of kits prepared. This metric will alert users to residual waste and decay of kits or overfill of doses.
- **Delivery Efficiency –** The activity of Tc doses at the customer's calibration time divided by the activity of Tc doses at the time their shipment is confirmed. This metric will alert users to decay that occurs between the time doses leave the pharmacy and the time they are used.

Source: Murphy, 2006

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