A DECISION MODEL FOR NURSE-TO-PATIENT ASSIGNMENT

by

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ABSTRACT

A critical consequence of the current nurse shortage in the US may be an increase in the workloads on hospital nurses. Heavy workloads have been identified as a major cause of job dissatisfaction among hospital nurses and may ultimately lead to a reduction in the quality of patient care. A focus on the balancing of the workload among scheduled nurses through patient assignments can help to alleviate the chance of assigning excessive workloads to one or more nurses during a shift. Nurse-to-patient assignment, the final stage of the nurse planning was the main intention of this study. It is reasonable to assume that this stage has a direct connection to the workload on a nurse during the shift. However, in addition to balancing direct patient care needs among the nursing staff, total workload balance must also consider indirect patient care and unit-related activities that are required of nurses and which are often affected by the layout of the hospital unit. Therefore, enhanced and supplementary workload measures were considered in this study in an effort to improve upon previous nurse-to-patient assignment methodologies.

Measures of “good” and “balanced” assignments were developed through consultation with the charge nurses working on this unit and through the use of the Analytical Hierarchical Process (AHP). A new patient acuity scoring system was developed specifically for use by nurses in making nurse-to-patient assignments. A distance scoring system was also developed to indicate the total relative distance a nurse would traverse during her shift based on her assignments. The resulting nurse-to-patient assignments were found to be as good, or better, than the assignments produced manually by the unit charge nurses. Results also indicated that the variability of the nurse-to-patient assignments were greatly reduced in terms of total nurse workload, total patient workload, and total distance traveled during the shift.

This work is the first to explicitly consider incorporating travel distances into the construction of a nurse’s patient assignment and to use AHP to define the importance of each workload measure in making the nurse-to-patient assignments. Additional key findings, future work and possible research directions are discussed.

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Ilgin Poyraz Acar

TABLE OF CONTENTS

Table of Contents-Continued

CHAPTER

Table of Contents-Continued

LIST OF TABLES

List of Tables- Continued

List of Tables- Continued

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Current problems in US hospitals include the shortage and high turnover of nurses. Although the nursing shortage began with the baby boomer generation, only in the last few years has the shortage begun to have a significant effect on the healthcare system. There are changes in indicators related to the nursing shortage that are becoming increasingly alarming such as: the relative size of the population of nurses, age of nurses, enrollment in schools of nursing, and job satisfaction (USDHHS, 2008).

Size of Nurse Population

While the demand for nurses is growing, the level of patient care may ultimately decrease due to heavier patient workloads required by hospital nurses. The total Registered Nurse (RN) population increased from 2,696,540 in 2000 to 2,909,357 in 2004, but this increase (7.9%) was comparatively low considering growth between earlier report intervals (14.2% between 1992 and 1996) (USDHHS, 2008). The American Association of Colleges of Nursing (AACN) has expressed this concern in recent reports. Baby boomers and an increasing elderly population, who require a substantial amount of health care, are the main reasons for the rapid growing demand of nurses (AACN, 2008). Similarly, The National Center for Health Workforce Analysis (NCHWA) at the Health Resources and Service Administration (HRSA) has projected a growing shortage of RNs over the next 15 years, with a 12% shortage by 2010 and a 20% shortage by 2015 (Figure 1. USDHHS, 2008). NCHWA attributes the projected shortage to the expected increase in demand, coupled with a relatively stable supply of RNs (USDHHS, 2008). Thus, it appears that the demand for nurses in the health care industry will continue to be larger than the supply of nurses over the next several years.

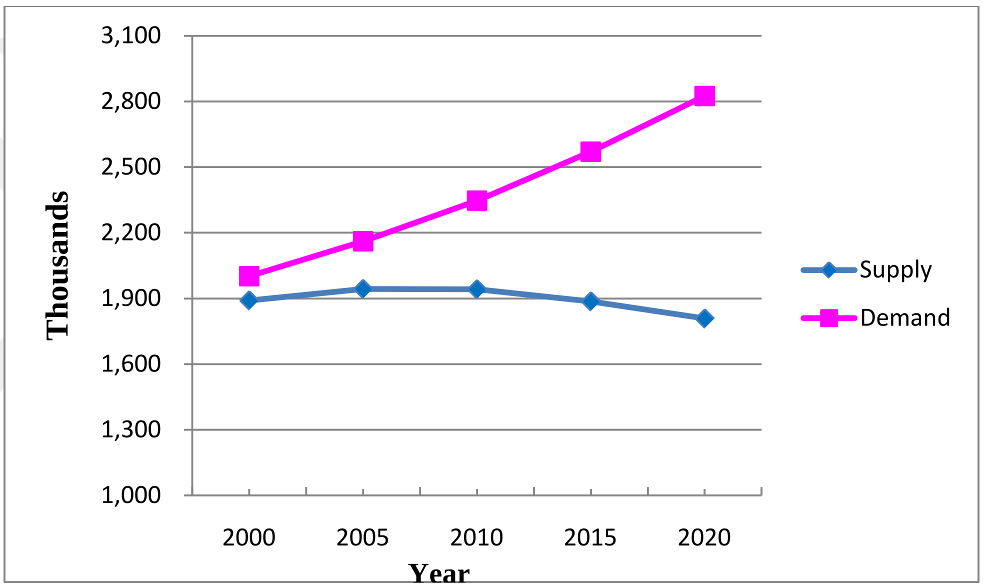

Figure 1. Demand vs Supply for Nurses (2000-2020)
(Adapted from USDHHS, 2008)

Age of Nurse Population

As of 2004, the average age of the total RN population (including those who are retired and not employed in nursing) was estimated to be 46.8 years. This is the highest average age since the inception of the survey -- more than 1 year older than the average age estimated in 2000 (45.2 years) and more than 2 years older than the average age estimate in 1996 (44.3 years). In 2004, only 8.0% of the RN population was under the age of 30, a decrease from 9.1% in 2000 and 9.0% in 1996. At the same time, in 2004, 41.1% of RNs were 50 years of age or older, which is a dramatic increase from 33.0% in 2000 and 29.7% in 1996 (Figure 2; USDHHS, 2008).

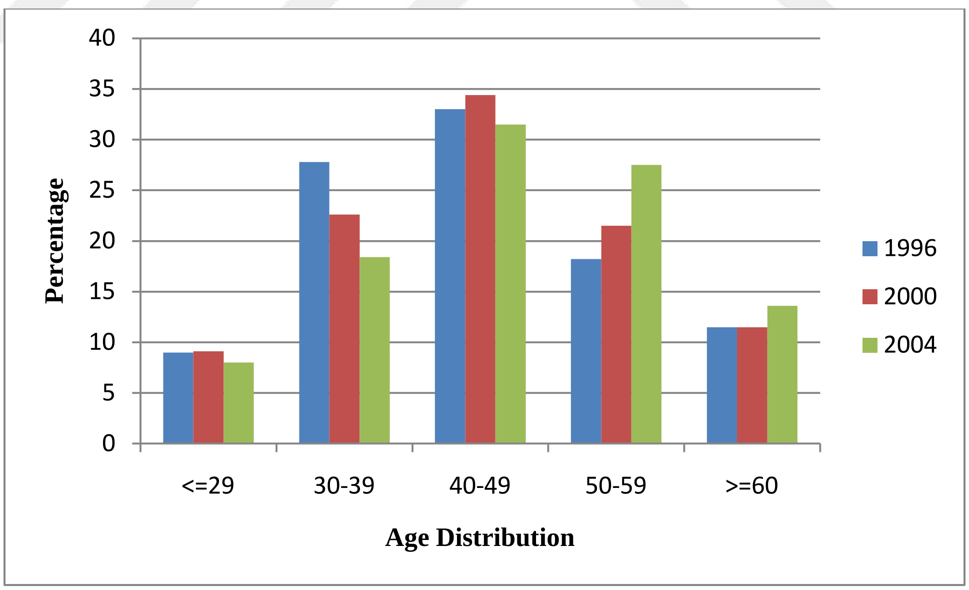

Figure 2. Age Distribution of the Registered Nurses Population, 1996-2004
(Adapted from USDHHS, 2008)

Nursing Enrollments

Enrollment in schools of nursing is not currently growing fast enough to meet the projected demand for nurses. Though AACN reported a 5.4% enrollment increase in entry-level baccalaureate programs in nursing in 2007, this increase is not sufficient to meet the projected demand for nurses (AACN, 2008). According to AACN's report on 2007-2008 Enrollment and Graduations in Baccalaureate and Graduate Programs in Nursing, in the U.S. more than 30,000 qualified applicants were turned away from baccalaureate nursing programs in 2007 due to shortage of nurse faculty, clinical sites, classroom space, clinical preceptors, and budget constraints (AACN, 2008).

Job Satisfaction

The level of job satisfaction indicates the general attitude of RNs toward their work. Job satisfaction factors, especially related to the work environment of RNs, include: management style, the impact of environmental turbulence, job strain, staff turnover, and the effects of working in magnet hospitals (Fletcher, 2001). Low turnover, high quality patient care, and fewer physical and mental injuries of health care staff may arise by improved job satisfaction. More than 75% of RNs believe that the nursing shortage presents a major problem for the quality of their work life, the quality of patient care and the amount of time nurses can spend with patients (Buerhaus et al., 2005). Greater job dissatisfaction and higher emotional exhaustion, which is strongly and significantly associated with patient-to-nurse ratios, were reported when nurses were responsible for more patients than they could safely take care of during a shift (Aiken et al., 2002). Additionally, high levels of job dissatisfaction related to scheduling, unrealistic workloads, mandatory overtime, and hospital administrators' lack of responsiveness to nurses' concerns have resulted in high turnover and early retirement among RNs (KFF, 2008).

Effects of Nursing Shortage

Projections suggest that nursing shortages will have a direct effect on patient care. The National Survey on Consumers' Experiences with Patient Safety and Quality Information showed that the most important factors related to medical errors are workload, stress, and fatigue of health professionals (74%); insufficient time spent with patients (70%); and insufficient amount of nurses in the health care system (69%) (KFF, 2004). The nature of the stress ranges from increased working hours to decreased numbers of nurses working on hospital floors, intensive care units, and clinics.

Nursing shortages also lead to insufficient nursing staff within hospitals. This may cause nurses to be overworked and emotionally stressed and may contribute to fatigue, decreased patient care, and negative patient outcomes, such as infections and deaths (KFF, 2004). In these cases, it has been noted that nurses are constantly struggling emotionally with the ethical issue of giving quality care in a limited amount of time (KFF, 2004). Nurses may be affected when they know that if they do not cover that extra shift, then their patients will not receive the care that they need and deserve.

Nurses may be expected to work double shifts, extra weekends and holidays to cover shortages. Overtime mandated by the hospital often results in high levels of fatigue and an increased number of errors (Huston, 2006). In addition, nurses routinely report working for more than twelve hours when overtime is involved, and report working erratic schedules that result in disrupted sleep patterns and fatigue (Huston, 2006). Nurses working on specialized units such as surgery, dialysis, and intensive care are often required to be available to work extra hours (on call), in addition to working their regularly scheduled shifts (Rogers et al., 2004).

With fewer nurses, patients may not be receiving the proper care that they deserve. According to a 2002 report by the Joint Commission on Accreditation of Healthcare Organizations, inadequate nurse staffing has been a factor in 24% of the 1,609 cases involving patient death, injury or permanent loss of function reported since 1997 (Joint Commission, 2002).

Typical solutions to address past nursing shortages have included wage increases and recruiting nurses from other countries, such as Canada, English-speaking Caribbean and African countries, Great Britain, India and the Philippines (KFF, 2008). Addressing the current shortage requires efforts aimed both at recruitment and retention of nurses. Recruitment refers to the need for continuously attracting new entrants into the nursing profession (KFF, 2008). Retention strategies focus on both retaining current nurses and encouraging those who have left nursing careers to re-enter the workforce (KFF, 2008).

The recruitment and retention of highly qualified nurses present ongoing challenges to nursing service administrators throughout the world. Retention of nurses has been closely linked both to job satisfaction and selected demographic factors (Ajamieh et.al., 1996).

Nursing Workload Measurement Systems

Hospitals need to overcome the effects of the nursing shortage by reviewing their workload measurement systems. Many workload measurement systems have been developed to meet patient care needs in specific areas (Siew and Ghani, 2006). Tarnow-Mordi et al. (2000) measured intensive care unit (ICU) workload per shift during each patient's stay for all admissions between 1992 and 1995 to see if hospital mortality is independently related to nursing requirements and other measures of workload. They concluded that hospital mortality might partly be explained by excess ICU workload such as inadequate numbers of nursing or medical staff, training, or supervision. Additionally, Cohen et al. (2004) studied the measurement of staff workload in Intensive Care and concluded that increasing staffing levels in facilities with high injury rates and low staffing ratios can actually decrease injuries and time-loss injuries rates.

The objective of a workload measurement system, as stated by the Nursing Professional Advisory Working Group of the Joint Policy and Planning Committee (JPPC, 1996), is to provide the basis for expressing the volume of patient care activity of a service, in terms of a standardized unit of activity or productive personnel time. Siew and Ghani (2006) stated that the workload measurement system could be categorized into two types: activity and dependency-based. The activity-based measure characterizes nursing care activities and assigns a time value for each. The strength of activity-based systems lies in their ability to measure the tasks that nurses actually do in the course of their work. The major limitation of activity-based systems is that they focus on care given and ignore the unmet needs of the patient. Dependency-based systems on the other hand, assign consumers to groups based on “critical indicators”. These indicators are on a scale of one to four or five where each increasing level denotes an increasing demand on nursing care time over a 24-hour period.

Dependency is often referred to as “classification”, thus a Patient Classification System (PCS) is an example of a dependency system (Begley et al., 2004). Modern classifications systems are ideally made up of two parts: an acuity tool and a nurse-staffing tool (Walts and Kapadia, 1996). The acuity tool measures the illness of the patient or demand for nursing services, as an indication of workload. “Severity of illness”, “Acute disease classification,” and “Diagnosis related groups” are synonyms for the patient acuity. The nurse-staffing tool allocates staff to maximize the utilization of resources while best meeting the workload needs. As a result, PCS is a method for establishing nursing personnel requirements by unit, based on a patient’s acuity.

Unfortunately, assigning nurse workload based on patient acuity alone often fails to take into account other factors that may lead to inadequate staffing. Figure 3 below illustrates the relationship between inadequate staffing, and patient, nurse and financial outcomes (Unruh, 2008). As Figure 3 shows, patient acuity is only one part of a complex matrix of factors that contribute to hospital outcomes.

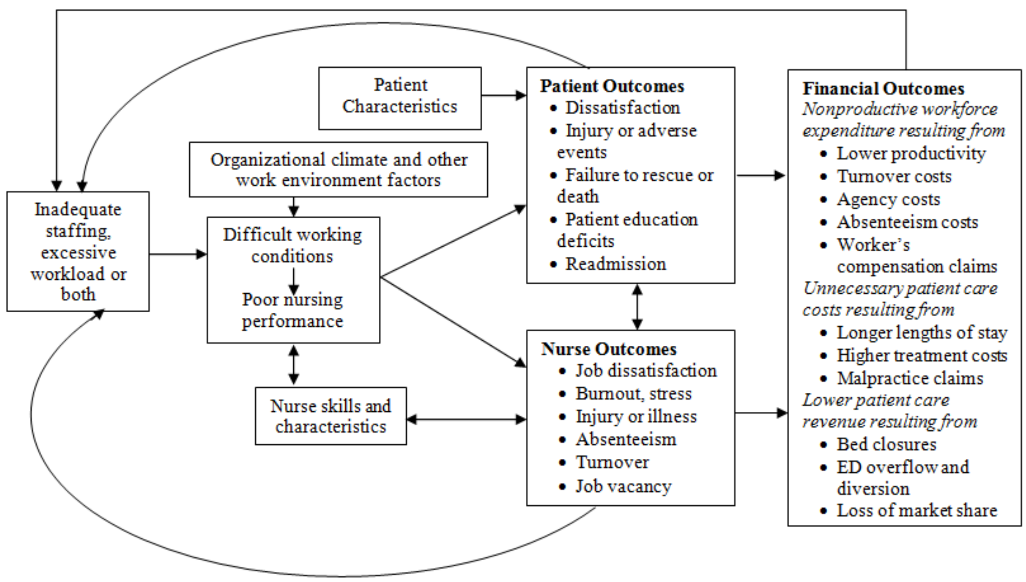

Figure 3. Conceptual Model of Patient, Nurse and Financial Outcomes Associated with Inadequate Nurse Staffing
(Adapted from Unruh, L.,2008)

Heavy workloads, stress, and fatigue are again some of the major issues that have been identified to cause job dissatisfaction for nurses and higher nurse turnover in hospitals. One possible way to ease the burden of the nursing shortage and to improve the quality of nursing work is to balance the workload of nurses or reduce excessive workload on nurses (Punnakitikashem, 2007). Therefore, matching schedules to appropriate staff and balancing workloads are extremely important for nurse-job satisfaction and potentially for the quality of patient care. As a result, nurse planning has become an important and urgent area of research.

Nurse Planning

Nurse planning in the hospital environment typically has four stages: nurse budgeting, nurse scheduling, nurse staffing and nurse assignment (nurse-to-patient assignment) (Punnakitikashem, 2007). The four stages of nurse planning are described in each of the next four sections.

Nurse Budgeting

The budgeting of nursing care is just one of the responsibilities of hospital administrators. Nurse budgeting is a plan for the allocation of nursing resources based on the needs of patient care during a financial year. Nursing accounts for the largest portion of a hospital's budgets, over 50% as a whole (G. Kazahaya, 2005). Therefore, nurse budgeting becomes an important issue for all healthcare providers. Financial planners in hospitals create an annual budget and determine the number of required full-time and part-time nurses needed for the planning horizon. (The U.S.'s healthcare bill rose to nearly $2 trillion in 2004 (Alonso-Zaldivar, 2006) and it is expected to reach $4 trillion by 2015 (Alonso-Zaldivar and Girion, 2006).)

There is very little quantitative work described in the Industrial Engineering (IE), Operations Research (OR) and nursing literature regarding the optimal budgeting for nursing resources. Two studies that specifically discuss this task are the following.

1. Kao and Queyranne (1985) implemented a stochastic programming approach to optimize the nurse budget.

2. Triverdi (1981) developed a mixed integer goal-programming model for expense budgeting in a hospital nursing department. Their model incorporated several different objectives based on cost containment and providing appropriate nursing hours for delivering quality nursing care.

Nurse Scheduling

The second stage of nurse planning is nurse scheduling. Every nurse in the hospital must be assigned a suitable set of shifts for the given planning period. Nurse scheduling (or rostering) is the midterm (several weeks) allocation of nurses to a working time period (Punnakitikashem, 2007).

In this stage, a nurse manager typically forecasts the number of patients that will enter a hospital unit during the given planning period (2 to 4 weeks) to determine the number of nurses of each skill type needed. A schedule is then created which splits a day into shifts, typically of 8 or 12-hour duration.

Nurse scheduling was a very popular academic exercise in the 1970s and early 1980s. For over 30 years, literature has addressed nurse scheduling specifically. Cheang et al. (2003), Burke et al. (2004) and Hung (1995) summarized the literature for various nurse scheduling (rostering) problems. Solution approaches for the nurse scheduling problem include linear and integer programming (Jaumard et al., 1998, Miller et al., 1976, Warner, 1990), multi-objective approaches (Arthur and Ravindran, 1981; Berrada et al., 1996; Jaszkiewicz, 1997), and goal programming (Azaiez and Sharif, 2005; Musa and Saxena, 1984; Ozkarahan and Bailey, 1988). Meta-heuristics, such as: neighborhood search (Bellanti vd, 2004; Burke et al., 2002), tabu search (Dowsland and Thompson, 2000, Dowsland, 1998) and genetic algorithms (Aickein and Downsland, 2000; Aickein and Downsland, 2003, Burke et al., 2001) have also been proposed. Other related studies include Aickelin and White (2004); Bard and Purnamo (2005); Chiaramonte and Chiaramonte (2008) and Chuang et al. (2007).

Nurse Staffing

The third stage of nurse planning is nurse staffing, also referred to as nurse rescheduling. In this stage, the set of nurse assignments scheduled for a shift are revised, if needed, 90 minutes before each shift (Punnakitikashem, 2007).) A nurse supervisor reviews the scheduled nurses based upon the activities of the previous shift, activities of other units, the patients in the emergency room, and either a census matrix or a patient classification system (Punnakitikashem, 2007). More details about the nurse staffing process can be found in Punnakitikashem (2007).

Studies have shown that the nurse staffing stage has a direct impact on nurse workload and quality of care for patients. Related papers on nurse staffing and patient outcomes can be found in Aiken et al. (2002), Lankshear et al. (2005), and Curtin (2003). Siferd and Benton (1992) have reviewed some of the issues in health care influencing the hospital nurse staffing. Studies include a stochastic model that was developed to determine the number of nurses needed for a shift based on patient load (Siferd and Benton, 1994). Strickland and Neely (1991) established a method using a standard staffing index to allocate nursing staff. In addition, Belegen et al. (1998) described the impact of nurse staffing based on the relationship between nurse staffing levels and patient outcomes.

Nurse Assignment

Nurse assignment is the final stage of nurse planning, during which each patient is assigned to a nurse at the beginning of the shift. Initial assignments often determine the amount of workload that each nurse will experience during a shift.

Two studies (Spence et al., 2006 and Yamase, 2003) showed that it is not sufficient to use patient acuity alone to estimate workload. Spence et al. (2006) concluded that the nurse's assessment of the intensity of care required, as well as organizational factors, is the important component needed for workload estimates. Similarly, Yamase (2003) indicated that the five other aspects of nurse workload are the number of nurses required, job intensity, muscular exertion, mental stress, and special skills.

Work balance is the most important consideration in nurse assignment. Workload balance during a shift is primarily the responsibility of a charge nurse, since the charge nurse assigns patient responsibilities to the allotted nursing staff on a unit during the shift. Since the patients' conditions vary over time, to develop balanced workloads for nurses becomes difficult (Mullinax and Lawley, 2002). Bostrom and Suter (1992) studied the decision making surrounding patient assignment while Shaha and Bush (1996) examined an assignment where each nurse was assigned the same number of patients on a unit.

There are a few studies, which have investigated the optimization of nurse assignment. Punnakitikashem et al. (2008) developed a stochastic integer-programming model to assign nurses to the patients by balancing workload of nurses. Rosenberger et al. (2004) developed an integer program whose objective function was to minimize excess workload on nurses where excess workload was defined as total patient workload assigned to a nurse in excess of the length of time from a time epoch until the next time epoch. Mullinax and Lawley (2002) developed a mathematical programming approach for achieving better workload balance based on acuity in a neonatal intensive care unit. They explained that a nursery can include either one large room or multiple rooms, which they referred to as zones, separated by aisles, walls, or floors. The objective function in their proposed model minimized the sum of the range of acuities over all zones. In addition, Walts and Kapadia (1996) suggested an optimization approach for the patient classification system, which is one of the measures for workload. These studies are examined in detail in the following literature review chapter.

Studies (Hendrich et al., 2008 and Butt et al., 2004) have shown that there is an influence of the unit's architectural layout on nurses' use of time and distance traveled. Butt et al. (2004) concluded that an RN's workload and shift travel distance was a function of patient acuity, room assignment, and facility design. One of the objectives in the study of Hendrich et al. (2008) was to describe the variation in distance traveled, time spent by category, and workload between units based on different physical layouts. They concluded that there was more variation in miles traveled and patient care time between nurses on the same unit than between units. The findings in their study illustrate the complex and demanding hospital work environment and suggest opportunities to improve the efficiency of nursing work. In addition, the process and policy, as well as relatively minor physical changes within a unit (such as distribution points of supplies or medications), can have a major impact on nurse workload (Hendrich et al., 2008). It was stated that changes to the process and technology of documentation, communication, and medication handling, as well as the physical design of units, could benefit nursing efficiency and the safe delivery of care.

Nurse assignment has a direct connection to important factors related to medical errors. These medical errors are cited in one of the Kaiser Family Foundation (KFF) reports (KFF, 2004). Nurses are more likely to cite workload as a cause; with nearly three out of every four nurses (74%), saying workload, stress, or fatigue of health professionals is a very important cause of medical errors. Nearly as many say that, there is insufficient time spent with patients (70%), and there is an insufficient amount of nurses in the health care system (69%). (KFF, 2004).

There are many measures available to help guide the construction of good nurse-to-patient assignments, such as patient acuity, total shift distance traveled, and nurse preferences; however many of these measures diametrically oppose one another. To date, acuity has been the focus of balancing workload in nurse-to-patient assignments. Yet, little of the published work has been successfully implemented in the hospital environment. The exclusive use of acuity primarily concentrates the balance of the workload on patient care activities and does not necessarily take into account other aspects of a nurse's work, such as physical exertion. For example, nurses with geographically contiguous patient room assignments may travel far less over a shift than nurses with assignments based solely on acuity since the associated patient rooms may not be in close proximity of one another, and in some cases may be located on different floors. Butt et al. (2004) indicated that nurses working on the same unit were traveling between 3 to 10.5 miles per 12-hour shift on General Medical Unit (GMU) based on their assignments. Therefore, while most research concerning nurse to patient assignment has focused on balancing workloads in terms of patient care activities alone, it seems reasonable that a nurse's assignment should also take in consideration the relative distances of the nurse's patient rooms to one another and to other frequently utilized locations, such as medication storage, supply rooms, and nurse stations. In fact, Butt et al. (2004) showed that key distances, which were highly correlated to the total distance traveled by nurses during their shifts, were the distances from a nurse's patient room to the nursing station, to the supply room and to other assigned patient rooms. This suggests that the nurses' assigned patient room locations have a direct effect on the nurses' physical efforts required during a shift

The focus of this dissertation is on this final important stage of nurse planning. As stated earlier, nurse-to-patient assignments have received very little attention in the literature even though they have the most direct connection to a nurses' activities on a given shift.

Furthermore, the assignments are traditionally made based solely on direct patient care requirements with no consideration of other activities that must be performed by a nurse. Therefore, additional measures and constraints were considered in this study in an effort to improve upon previous assignment methodologies and to further reduce demands placed on nurses during their shifts through improving nurse-to-patient assignments. The intended future result of this work is to foster a better work environment that will attract and retain nurses through a rewarding and satisfying career in patient care.

CHAPTER II

LITERATURE REVIEW

This literature review is focused on Nurse Assignment (nurse-to-patient assignment) in a hospital unit. Important studies that were introduced in the first chapter are more fully discussed here.

Recall that nurse-to-patient assignment, the final stage of nurse planning, is important because initial shift assignments can greatly affect the workload of each nurse during their shift. It was also noted that nurses are experiencing heavier workloads than have ever been experienced in the past. Carayon and Gurses (2008) attributed the heavier workloads to four main reasons.

(1) *Increased demand for nurses.* In the introduction, it was stated that the demand for nurses is increasing because of the increasing size of the aging population.

(2) *Inadequate supply of nurses.* Due to the higher demand, the supply of nurses is not sufficient to meet the demand. In fact, there is an increasing gap between the nursing demand and supply.

(3) *Reduced staffing and increased overtime.* Hospitals cannot acquire sufficient nursing staff and have implemented mandatory overtime policies to meet unexpected high demands.

(4) *Reduction in patient length of stay.* Hospitals often want to reduce patients' stays to increase revenues. However, hospital nurses today take care of patients who are

more ill (older) than in the past; therefore, their work is often more intensive (Aiken et al, 1996).

Nursing workload can be defined as the amount and intensity (in terms of the effort required) of work a nurse performs within a given period (Unruh, 2008). Because so many variables can affect workload, including number and acuity of patients, unit design, available resources, and skill mix (O'Brien-Pallas et al., 1997), developing a reliable assessment method has proven difficult.

Figure 4 outlines the major components that Morris, et al. (2006) found influence the level of work a nurse must complete. This figure illustrates that nursing workload is comprised of (Morris, et al.2006):

a) Direct care-related nursing activities or the work-related activities that the nurse performs in the presence of and on behalf of the patient -- these activities might include the administration of medication or assessment of blood pressure.

b) Indirect care-related nursing activities or the work-related activities that the nurse performs away from but on the behalf of the patient -- making a phone call on behalf of patient and organizing a referral or ordering a medication are examples.

c) Non-patient care-related nursing activities such as: nursing student education, attending staff meetings and supporting unit/ward management.

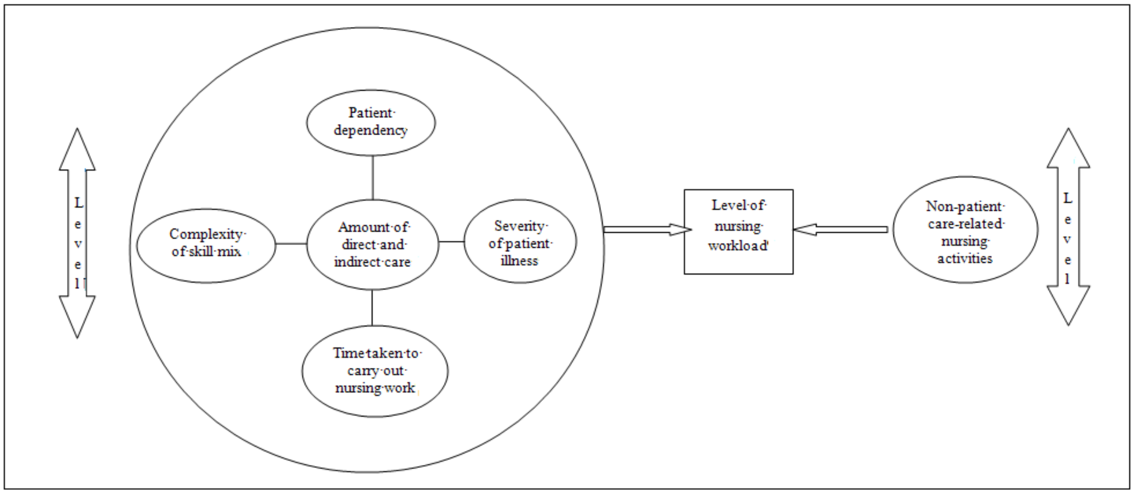

Figure 4. A Model of Nursing Workload
(Adapted from, Morris, et al.2006).

The level of direct/indirect patient-related nursing work activities can be evaluated by nursing intensity. Moore and Hastings (2006) stated in their study that nursing intensity measurement was the process of sorting and grouping patients for the purpose of predicting the demand for nursing care time in a given healthcare setting. They noted that the level of nursing intensity has a direct impact on the level of nursing workload and is influenced by the dependency of the patient, the severity of the patient's illness, the time taken to administer patient care and the complexity of care required in order to care appropriately for the patient. Moore and Hastings (2006) also stated that the level of the nurse's workload is also directly influenced by the non-patient care-related nursing activities that they must carry out over any given nursing shift.

The TNA Staffing Committee (2008) suggested that a number of critical factors (from patient characteristics to nurse characteristics) affect the ability of a nurse to carry out a patient assignment effectively. Factors affecting the nurse-to-patient assignment are found in Figure 5 (TNA Staffing Committee, 2008).

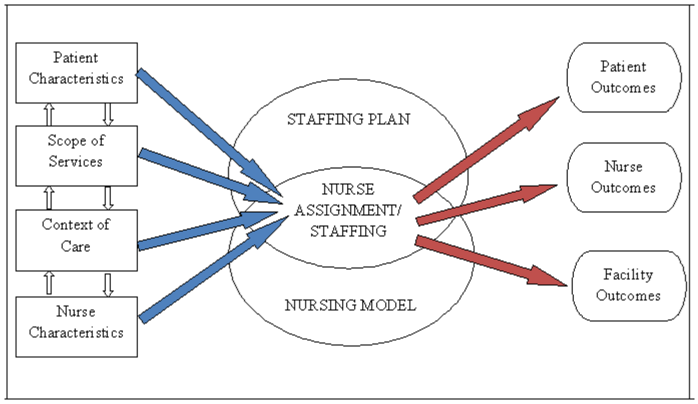

Figure 5. Individualized Patient Staffing Model
(Adapted from TNA, 2008)

In the Figure 5, patient characteristics, scope of services, context of care and nurse characteristics are seen to interact with each other to contribute to the staffing plan and nursing model. The interface of the staffing plan, nursing model, and nurse assignment then contributes to the three proposed outcomes in terms of patient, nurse and facility. With respect to outcomes, dissatisfaction, injury or adverse event, failure to rescue or death and readmission are possible negative patient outcomes. Job dissatisfaction, burnout, stress, injury or illness, and absenteeism are possible negative nurse outcomes. And negative facility outcomes include increased costs, high turnover and longer lengths of stay (Joseph, 2007).

Mullinax and Lawley (2002) developed a mathematical programming approach to achieve better workload balance of nurses on a neonatal intensive care unit. They first developed a detailed neonatal acuity system to compute the nursing workload associated with each patient. They then developed an integer program to assign patients to nurses by minimizing the difference between the maximum and minimum sum of acuities for assigned patients. The objective of the assignments in their study was to minimize the range of group acuities assigned to the nurses. Since it was difficult to achieve the optimum solution computationally, they used a zone-based heuristic in which the unit was divided into a number of physical zones. They concluded that this zone-based heuristic provides good improvements in workload balance with relatively little computational effort. Their assignment problem is formulated as follows (Formulation 1).

Formulation 1 (Mullinax and Lawley, 2002):

$$\text{Minimize} \sum_{k=1}^{p}\left(Y_{k,max}-Y_{k,min}\right) \tag{1}$$

Subject to

$$\sum_{j=1}^{m} X_{ij}=1 \qquad j=1,\ldots,n \tag{2}$$

$$\sum_{k=1}^{p} Z_{jk}=1 \qquad j=1,\ldots,m \tag{3}$$

$$\left\{\sum_{i=1}^{n} S_{ik}C_iX_{ij}\leq Y_{k,max}\right\}\left(1-U_j\right) \qquad j=1,\ldots,m;\ k=1,\ldots,p \tag{4}$$

$$\left\{\sum_{i=1}^{n} S_{ik}C_iX_{ij}\geq Y_{k,min}\right\}\left(1-U_j\right) \qquad j=1,\ldots,m;\ k=1,\ldots,p \tag{5}$$

$$\left\{\sum_{i=1}^{n} S_{ik}X_{ij}\leq B_kZ_{jk}\right\}\left(1-U_j\right) \qquad j=1,\ldots,m;\ k=1,\ldots,p \tag{6}$$

$$\left\{1\leq\sum_{i=1}^{n} S_{ik}X_{ij}\leq b_kZ_{jk}\right\}\left(U_j\right) \qquad j=1,\ldots,m;\ k=1,\ldots,p \tag{7}$$

$$\left\{\sum_{i=1}^{n} S_{ik}C_iX_{ij}\leq a_k\right\}\left(U_j\right) \qquad j=1,\ldots,m;\ k=1,\ldots,p \tag{8}$$

$Y_{k,max} \leq A_k$ $\quad\quad k=1,\ldots,p$ $\quad\quad$ (9)

Variables

$X_{ij} = \begin{cases} 1 & \text{if patient i assigned to nurse j} \\ 0 & \text{otherwise} \end{cases}$

$Z_{jk} = \begin{cases} 1 & \text{if nurse j assigned to zone k} \\ 0 & \text{otherwise} \end{cases}$

$Y_{k,max}$= maximum assigned acuity of zone k

$Y_{k,min}$= minimum assigned acuity of zone k

Parameters

$S_{ik} = \begin{cases} 1 & \text{if patient i is in zone k} \\ 0 & \text{otherwise} \end{cases}$

$U_{j} = \begin{cases} 1 & \text{if nurse j is an admit nurse} \\ 0 & \text{otherwise} \end{cases}$

A_k = specified upper bound on the total non-admit acuity of zone k

a_k = specified upper bound on the total admit acuity of zone k

B_k = specified upper bound on the number of patients for non-admit nurses in zone k

b_k = specified upper bound on the number of patients for admit nurses in zone k

C_i = acuity of patient i

The objective function (1) in the Mullinax and Lawley (2002) model minimizes the sum of acuity ranges over all zones, thus balancing nurse workload. Constraint (2) assures that each patient is assigned to exactly one nurse, while (3) assures that each nurse is assigned to exactly one zone. Constraint (4) establishes $Y_{k,max}$ as the maximum assigned acuity among non-admit nurses in zone k, while (5) establishes $Y_{k,min}$ as the minimum. These two constraints interact with the objective function to minimize the range in zone k. Constraint (6) assures that a non-admit nurse is assigned to no more than a specified number of patients, while (7) assures the same for admit nurses. Constraint (7) also guarantees that each admit nurse will be assigned at least one patient. This is necessary since admit nurse acuity is not included in the objective function, and thus it is possible that an admit nurse would not receive an assignment. Constraint (8) assures that the total amount of acuity assigned to an admit nurse does not exceed a specified threshold, while (9) does the same for non-admit nurses. This model distributes the nurses among zones so that the optimal assignment of patients to nurses is found.

In another study on nurse assignment, Punnakitikashem et al (2008) presented a brief overview of the four stages of nurse planning. They also developed a two-stage stochastic programming model for patient assignment in order to minimize excess workload, defined as the difference between the required workload and the time available for care. Their model addressed several important issues, such as patient uncertainty, fluctuations in patient care and differences in nurses, which were often ignored in other academic studies and patient classification systems. They assumed that a Charge Nurse (CN) determined which nurses could be assigned to which patients before optimizing nurse assignment. When there were new admissions, nurse assignments were not changed. In one of their assumptions, direct care needs must be performed within a given time period, while indirect care could be performed in any time period prior to the end of the shift. In addition to this assumption, they assumed that nurses optimally allocated their indirect care to minimize excess workload. The last assumption that they made was that the set of patients to be assigned included potential unanticipated patients, so that the number of patients assigned could be considered fixed.

In the Punnakitikashem et al (2008) study, patient-to-nurse ratio constraints are introduced to balance the workload of nurses as well as improve the overall performance of the algorithm. In their model, P and N were the sets of patients and nurses for a shift, respectively. For each patient $p \in P$, N(p) was the set of nurses which could be assigned to patient p. For each nurse $n \in N$, P(n) was the set of patients that could be assigned to nurse n, that is, $P(n) = \{p \in P | n \in N(p)\}$. For each patient $p \in P$, and nurse $n \in N$, the *assignment variables* were

$$X_{pn} = \begin{cases} 1 & \text{if patient } p \in P \text{ is assigned to nurse } n \in N(p) \\ 0 & \text{otherwise} \end{cases}$$

In their model, Ξ was a set of random scenarios, and for each $\xi \in \Xi$, Φ^{ξ} was the probability that scenario ξ occurs. A shift was divided into a set of time periods T. They modeled the penalty for assigning workload to nurses as a monotonically nondecreasing piecewise linear function with k pieces. For each time period $\tau \in T$ and each nurse $n \in N$, $A^{\xi}_{\tau ni}$ was the amount of workload assigned to nurse n between $m_{\tau ni}$ and $m_{\tau n(i+1)}$ in scenario $\xi \in \Xi$. Other notation and variables can be found in their paper. The stochastic programming model in their study was formulated as follows (Formulation 2):

Formulation 2 Punnakitikashem et al (2008)*:*

$$\min \sum_{\xi \in \Xi} \sum_{n \in N} \sum_{\tau \in T} \sum_{i=1}^{k} \Phi^{\xi} \alpha_{\tau ni} A^{\xi}_{\tau ni} \tag{10}$$

$$\sum_{n \in N(p)} X_{pn} = 1 \qquad \forall p \in P, \tag{11}$$

$$\sum_{p \in P(n)} e^{\xi}_{tpn} X_{pn} = \sum_{\tau = t}^{|T|} E^{\xi}_{t\tau n} \qquad \forall t \in T, n \in N, \xi \in \Xi, \tag{12}$$

$$\sum_{p \in P} d^{\xi}_{\tau pn} X_{pn} + \sum_{t=1}^{\tau} E^{\xi}_{t\tau n} = \sum_{i=1}^{k} A^{\xi}_{\tau ni} \qquad \forall \tau \in T, n \in N, \xi \in \Xi, \tag{13}$$

$$X_{pn} \in \{0,1\} \qquad \forall p \in P, n \in N(p), \qquad (14)$$

$$E^{\xi}_{t\tau n} \geq 0 \qquad \forall t, \tau \in T, t \leq \tau, n \in N, \xi \in \Xi, \qquad (15)$$

$$m_{\tau n(i+1)} - m_{\tau ni} \geq \mathrm{A}^{\xi}_{\tau \mathrm{ni}} \geq 0 \qquad \forall t, \tau \in T, 1 \leq i \leq k, n \in N, \in \Xi, \qquad (16)$$

In the above model, the objective function (10) minimizes the workload penalty on nurses. The nurse assignment constraint (11) ensures that every patient is assigned to a nurse. The indirect care constraint in (12) determines the total indirect care performed by nurse n from the beginning of time period t until the end of the shift. For each time period $\tau \in T$, the workload of nurse $n \in N$ consisting of direct care and indirect care is defined by workload constraint (13). Constraint (14) requires that the assignment variables be binary and constraint (15) ensures that the indirect care variables are non-negative. Constraint (16) gives the upper and lower bounds on the marginal workload variables. The authors stated that given an assignment $\bar{X}$, the constraints (12), (12), (15) and (16) can be decomposed by nurse and scenario resulting in $|N| \times |\Xi|$ recourse subproblems. Hence, they proposed a Bender's decomposition approach to solve this problem. Moreover, they developed an optimal greedy algorithm for solving the recourse sub-problems, and then they discussed patient-to-nurse ratio constraints to improve computational efficiency of their procedure. They concluded that decisions made in earlier stages of nurse planning can have a dramatic effect on possible nurse assignments.

Similarly, Rosenberger et al (2004) used an integer program to assign nurses to patients in several scenarios while the objective function was to minimize excess workload on nurses. They defined excess workload as total patient workload assigned to a nurse in excess of the length of time from a time epoch until the next time epoch. They presented a stochastic model to generate patient scenarios while they presented an integer program for the initial assignment of nurses to patients for a nursing shift in a hospital unit. They assumed that the charge nurse knows the number of patients entering and leaving the unit and the required workloads of each patient. For each patient $p \in P$ and each time epoch $t \in T$, the workload a_{tp} is a known realization of the random variable $\tilde{a}_{tp}$. Let N be the set of nurses in the shift. The authors assumed that a charge nurse determines which nurses can be assigned to which patients before optimizing patient assignment. For each patient $p \in P$, let N(p) be the set of nurses which can be assigned to patient p. For each nurse $n \in N$, let P(n) be the set of patients that can be assigned to nurse n, that is, S(n) $=\{p \in P | n \in N(p)\}$. For each patient $p \in P$, and nurse $n \in N$, the *assignment variables* were then defined as:

$$X_{pn} = \begin{cases} 1 & if\ patient\ p \in P\ is\ assigned\ to\ nurse\ n \in N(p) \\ 0 & otherwise \end{cases}$$

For each time epoch $t \in T$ and each nurse $n \in N$, the *excess workload variable*, O_{tn}, was the total patient workload in excess of d_t assigned to nurse *n* at time *t*. Their patient assignment model is given in Formulation 3 below:

Formulation 3 Rosenberger et al (2004)*:*

$$min \sum_{t \in T} \sum_{n \in N} O_{tn} \tag{17}$$

$$\sum_{n \in N(p)} X_{pn} = 1 \qquad \forall p \in P \tag{18}$$

$$\sum_{p \in P(n)} a_{tp} X_{pn} \leq d_t + O_{tn} \quad \forall t \in T, n \in N \tag{19}$$

$$X_{pn} \in \{0,1\} \qquad \forall p \in P, n \in N(p) \tag{20}$$

$$0 \leq O_{tn} \qquad \forall t \in T, n \in N \tag{21}$$

Objective (17) minimizes excess workload. The first constraint, *patient assignment constraint* (18), ensures that every patient is assigned to a nurse. For each time epoch $t \in T$, a *workload constraint* in (19) limits the workload of nurse $n \in N$ to the duration of the epoch plus the excess workload. Constraint (20) requires that the assignment variables are binary, and constraint (21) ensures that the excess workload variables are nonnegative.

In one of the earliest studies to determine a patient classification system, Walts and Kapadia (1996) developed a patient classification system integrating a patient acuity system based on an optimization algorithm. The problem in their study was identified at the Herman Hospital in Houston, Texas. The nursing administration at the hospital decided to abandon the commercial patient classification system in use because of a lack of validity in measuring patient acuity and the inability of the system to allocate staff on a prospective basis. They implemented a manual system, which integrated the classification of patients, distributed the nursing staff on a real-time basis, and projected fiscal requirements for budget in a simple format based on the actual practice of the specific hospital. They proposed a computer optimization algorithm and trend analysis. The model they proposed in their study is given below in Formulation 4. In this model, the objective was to minimize the total number of nursing staff needed to meet the acuity needs of several clinical units in the hospital.

Formulation 4 (Walts and Kapadia, 1996):

$$\min \sum_{i=1}^{u} \sum_{j=1}^{3} \sum_{k=1}^{u+1} p_{ijk}\ x_{ijk} \tag{22}$$

s.t

$$a_i \le 8 \sum_{k=1}^{u+1} x_{i1k} + 6 \sum_{k=1}^{u+1} x_{i2k} + 4 \sum_{k=1}^{u+1} x_{i3k} \le b_i \quad i = 1, \dots \dots, u \tag{23}$$

$$x_{ijk} \ge c_i \qquad i = 1, \dots \dots, u \tag{24}$$

$$\sum_{i=1}^{u} x_{ijk} \le s_{jk} \qquad j = 1,2,3 \ \ and\ k = 1, \dots \dots, u \tag{25}$$

$$\sum_{i=1}^{u} x_{iju+1} \le f_j \qquad j = 1,2,3 \tag{26}$$

$$x_{ijk} \ge 0 \tag{27}$$

Where:

x_{ijk} = *number of nursing personnel in unit i of type j from unit k (note that nurses belonging to the float pool are defined as belonging to unit u+1,where u is the number of units).*

p_{ijk} = *penalty associated with assigning nursing staff from unit k to unit i of type j.*

p_{iji} = *1 (since the penalty associated with assigning personnel to their home units is assumed minimal).*

a_i, b_i = *the lower and upper limits of personnel demand in the i^{th} nursing units, respectively.*

c_i = *minimum number of RNs required to staff the i^{th} nursing unit.*

s_{jk} = number of personnel of type j in nursing unit k available for allocation to other nursing units.

f_j = number of personnel of type j from unit u+1 that could be floated out to other units.

In the above formulation, the objective function (22) minimizes the sum of the total penalty points involved in the allocation of nursing personnel to the various nursing units. These penalties include:

1. A large penalty for hospital staff pulled from their home unit to another unit.
2. A small penalty for use of float pool staff.
3. A minimal penalty for use of staff within their home unit.

Constraint (23) ensures the total number of nursing care points available to the unit that must be between the upper and lower limits of required acuity for the unit. Constraint (24) ensures the minimum number of RNs required to staff each unit on a given shift. The supply constraint (25) represents the total number of nursing personnel of type j from nursing unit k that is allocated to all the nursing units and may not exceed the total number of type j personnel available in unit k. The constraint (26) ensures the upper limit to the number of float nurses from outside the system who may be used in any shift. Walts and Kapadia (1996) also performed sensitivity analysis with respect to this model by changing different parameters of the problem and determining the effect on the optimal solution. They specifically considered the following changes:

- changes in the values of the penalty coefficients in the objective function,

- changes in the tightness of the demand constraints (23),
- changes in the staff values of the demand constraints (24)

The first group of changes showed that the new model could maintain a prioritizing order that was consistent with hospital policy. Thus, the preference for allocation of unit personnel or float pool could be changed by changing their weights in smaller increments, while the penalties for using between-unit floats would need a significant change before the current optimal solution would be affected.

The second set of changes was performed by changing the upper and lower bounds of total acuity. It was observed that the model responded to these changes by cancelling, adding or trading the personnel among the units to approximate the desired total acuity.

The last set of changes was implemented by changing the staff weights by expert nurses. Although most of the staffing patterns on the unit remained the same, available total nursing staff affected the assignment of float staff to two of the staffing units considered in the model.

Another early study investigated the decision-making process for nurse-patient assignment (Bostrom and Suter, 1992). The aims of this study were to determine the factors that nurses consider in making patient assignments, to assess the relative importance of these factors in the decision making process, and finally to test Benner's (1984) concepts of novice and expert in the context of the patient assignment decision process.

Bostrom and Suter (1992) conducted their study at a 600 bed tertiary care medical center and a 300 bed community hospital. Three types of unit, medical, surgical and critical care, were included in the study. They interviewed and asked six nurses, two nurses from each of their areas whom the assistant directors of nursing felt were most knowledgeable, to identify decision-making factors regarding patient assignment. Data from the interviews and criteria for assignments obtained from textbooks were used to construct a questionnaire. After minor modifications were made, there were 19 decision making factors listed on the final questionnaire. In addition, there were two specific items included to compare the use of hospital guidelines versus clinical judgment in the assignment process. Nurses were asked to use a Likert scale that ranged from 1 (most important) to 5 (not important at all) and they were asked to write additional factors that were not included on the list. Item mean scores and standard deviations are given in their study in detail. Besides the defined 19 factors, respondents wrote in 45 additional factors. The most commonly added factors were nurse-patient match (47 respondents), anticipated admissions and discharges (18 respondents), and insufficient staffing (14 respondents). Consequently, over 48 different items were included in the list of the top five most important factors. The authors concluded that patient acuity information was the most often listed (146 times) and cited most important factor. The authors then took each of the nurses' top 5 most important factors and assigned a score of 5 to the most important factor, 4 to the second most important and so on to determine the priority among the entire sample. The resulting sum of scores for each factor among all nurses ranged from 1 to 770. Results of the 15 top scoring items and their associated mean Likert scores and standard deviations are shown in Table 1.

The authors concluded that there was considerable diversity in the ways in which charge nurses assign patients to nurses. It was also indicated that although patient acuity systems are often used to determine how many nurses are needed to staff a unit, assigning these nurses to specific patients is generally a unit-based decision.

Table 1

Priority Scores of Top 15 Decision Making Factors

Item	**Total Priority Score**	**Likert Score**	
		Mean	**SD**
Patient acuity information from previous shift	770	1.63	1.04
Nurse experience / expertise with this type of patient	636	1.79	0.84
Clinical judgment of patient nursing needs	397	1.75	0.69
Nurse experience with this patient	395	1.80	0.74
Nurse preference	307	2.14	0.76
Orientation needs of new nurses	153	2.01	0.70
Primary care patient assignments	86	3.84	1.03
Patient (or family) preference	82	2.84	0.96
Patient / nurse language match	81	2.66	1.06
Location of patient on the unit	74	3.14	1.17
Other duties of nurses (administrative, orientation)	69	2.41	0.88
Nurse licensure (RN, LVN, etc.)	63	2.75	1.25
Nurse Level (SNI, etc.)	61	3.19	1.26
Years of nursing experience	57	2.81	1.11
Amount of time that patient will be away from the unit	47	2.59	0.96

Gaps in the Literature

Even though other measures are identified in the literature, to date all nurse-to-patient assignment models have focused their objective functions only direct (and sometimes in-direct) on balancing patient care activities in one form or another. However, nurse-to-patient assignments determine not only patient care workload for a nurse during a shift, but they also define assigned patient room location in relation to the position of frequently utilized locations, such as the nurse station, medical cart, and supply room. Thus, while most research concerning nurse to patient assignment has focused on balancing workloads, it does not account for the required physical movements performed by the nurse on the unit. Thus, total travel distance, or total travel time, is one aspect of a nurse's activities that may affect the performance of a nurse's duties over a shift.

Hendrich (2008) assessed distance traveled in a study performed in 36 hospital units. In their study, the drivers of inefficiency in nursing work processes and nursing work design were identified. Nurses from 36 medical-surgical units were invited to assess how nurses spend their time, nurse locations and movements, and nurse physiologic responses. Distance traveled was evaluated across types of unit design. They also conducted time and motion studies in the 36 hospital medical-surgical units. They concluded that the three main targets for improving the efficiency of nursing care were the following:

1. documentation,
2. medication,
3. administration and coordination.

In addition, the minimization of the distance between frequently visited locations was investigated. They concluded that frequently traveled paths may affect the physical demands placed on the nurse by increasing the time to travel between two locations (in-transit time) during the nurse’s shift. Hendrich (2008) found that reducing in-transit times, and hence distance traveled, may help to minimize the physical demands placed on nurses and reduce risks of negative outcomes associated with fatigue and physical stress. Currently there are no published studies regarding nurse-to-patient assignment models which include balancing workload relative to distance traveled by nurses during a shift. To further illustrate the impact of assigned patient room locations on the total distance traveled by a nurse during a shift, in the following chapter a simulation model was developed based on data collected from a neonatal unit of a southwest Michigan hospital.

CHAPTER III

IMPACT OF NURSE ASSIGNMENTS ON DISTANCE TRAVELED

In this chapter, a simulation model was developed to study nurse activities and travel paths within a hospital unit based on data collected through direct continuous observation over a three year period (Fredericks et al., 2008). This simulation model was used to aid in evaluating nurse-to-patient assignments, not only based on the relative locations of the assigned patient rooms to one another, but also to other important facilities on the unit.

Due to the complexity and the structure of health care systems, simulation has become a popular and effective tool to determine the appropriate allocation of health care resources. Additionally, a simulation model can be used to more easily represent changes in nurse-to-patient assignments and process the effects of these changes empirically. There have been several healthcare studies conducted using simulation. Draeger (1992) used an emergency department simulation model to evaluate alternative nurse staffing and patient population scenarios. Trilling et al. (2006) implemented a hybrid approach combining integer linear programming and a simulation model for efficient shift design. Finally a data–integrated nurse activity simulation model was developed by Sundaramoorthi et.al (2008).

This chapter describes a study conducted to investigate the effect of a nurse's patient room assignment on total in-transit time. In-transit time was defined as the time during the shift in which the nurse was moving between locations, and thus is highly correlated to the distance between the same locations. The simulation model considered both the nurse activities and the travel paths completed by a nurse within the hospital unit. The unit studied was a neonatal unit in a southwest Michigan hospital where each patient was assigned to a single patient room.

An intensive care unit, or ICU, is a specialized section of a hospital that provides comprehensive and continuous care for persons who are critically ill and who can benefit from treatment. Many hospitals also have designated intensive care areas for certain specialties of medicine. Some of these are the Coronary Care Unit (CCU), Medical Intensive Care Unit (MICU), Surgical Intensive Care Unit (SICU), Pediatric Intensive Care Unit (PICU), Neuroscience Critical Care Unit (NCCU), Overnight Intensive Recovery (OIR), Shock/Trauma Intensive Care Unit (STICU), Neonatal Intensive Care Unit (NICU), and other units as dictated by the needs and available resources of each hospital.

NICU generally provides health care to critically ill infants with needs ranging from intermittent care to continuous monitoring. NICU is the extreme case among the other intensive care units since the nurse must not only care for the infants' illness but also for all of the infants' other needs. This makes the measurement of nursing workload and the development of indicators of nursing intensity in a NICU, very difficult. Nursing workload is one of the most important determinants of patient safety and quality of care in NICU (Carayon and Gurses, 2005). Yet there are few tools for measuring neonatal nursing workload available in the literature. Much of the available literature outside of NICU describes methods of determining appropriate staffing levels; however, most of this is not applicable to neonates.

The unit studied is divided into a critical care area for infants in poor health and a step-down area for infants who have stabilized and where families can learn specialized care before the infant is discharged.

For any given shift, there are multiple core (anchor) nurses in each area assigned to at least two to three patients in one of the three designated hallways in the critical care area. The step-down area also has a set of core nurses, but since continuous monitoring is not typically necessary, nurses in the step-down area have larger assignments of three to four patients. The remaining patients are assigned to float nurses, who are familiar with all three hallways and the step-down area. A float nurse was described as a nurse who is available for any assignment temporarily. They are typically used when there are unusually heavy workloads on the unit or there is a decrease in the normally available nursing personnel. The charge nurse is primarily responsible for determining how many float nurses are needed in each area and assigning available nurses to the critical care hallways and the step-down area. Float nurses are given similar patient loads to the core nurses in their assigned area.

There is a patient acuity system in the hospital which projects the level of nursing care needed for each patient. Although this system is available to assist the charge nurse in deciding patient assignments, typically all of the infants in this unit have the same assigned acuity level and as such, the current acuity level is not very useful for discriminating between patients or making nurse-to-patient assignments. The simulation model was used to study the effect of a nurse’s assignment on the total in-transit time during a shift, under the assumption that a nurse’s behavior will not change with respect to activities and travel patterns with a change in their patient assignment.

Facility Layout

The facility layout was a critical element in determining how a change in a nurse's assignment alters the in-transit time of the nurse during their shift. The NICU consists of 45 single patient rooms, which allows the family to have more privacy, but also increases the relative distances between locations within the unit. The critical care area and step-down area of the unit are located on separate floors connected by a staff staircase and a public elevator. Figure 6 illustrates a depiction of the critical care area and staff only wing located on the fourth floor. The critical care area is divided into three hallways, two longer halls (hallways 1 and 3) with 12 patient rooms each, and one shorter hall (hallway 2) with 8 patient rooms. A nurse station, medical cart and milk/formula refrigerator are located on one end of each hallway. The step-down area on the 3rd floor consists of an additional 13 patient rooms and has a centralized nurse station with nearby medical cart and milk/formula refrigerator. The staff only wing includes equipment and cleaning rooms, staff lounge, staff bathroom, and the unit administration offices. Most of the equipment and supplies are located in the main equipment room in this wing. There are also smaller supply rooms located at the back of the main critical care patient area and in the front of the step-down area. In order to counteract the extra distance between the single patient rooms and the supply rooms, each patient has a care cart stocked with the basic supplies needed for the infant's scheduled care time. These carts are generally stocked for the nurses by ancillary nursing staff, which reduces the need for a nurse to go to the supply and equipment rooms during their shift.

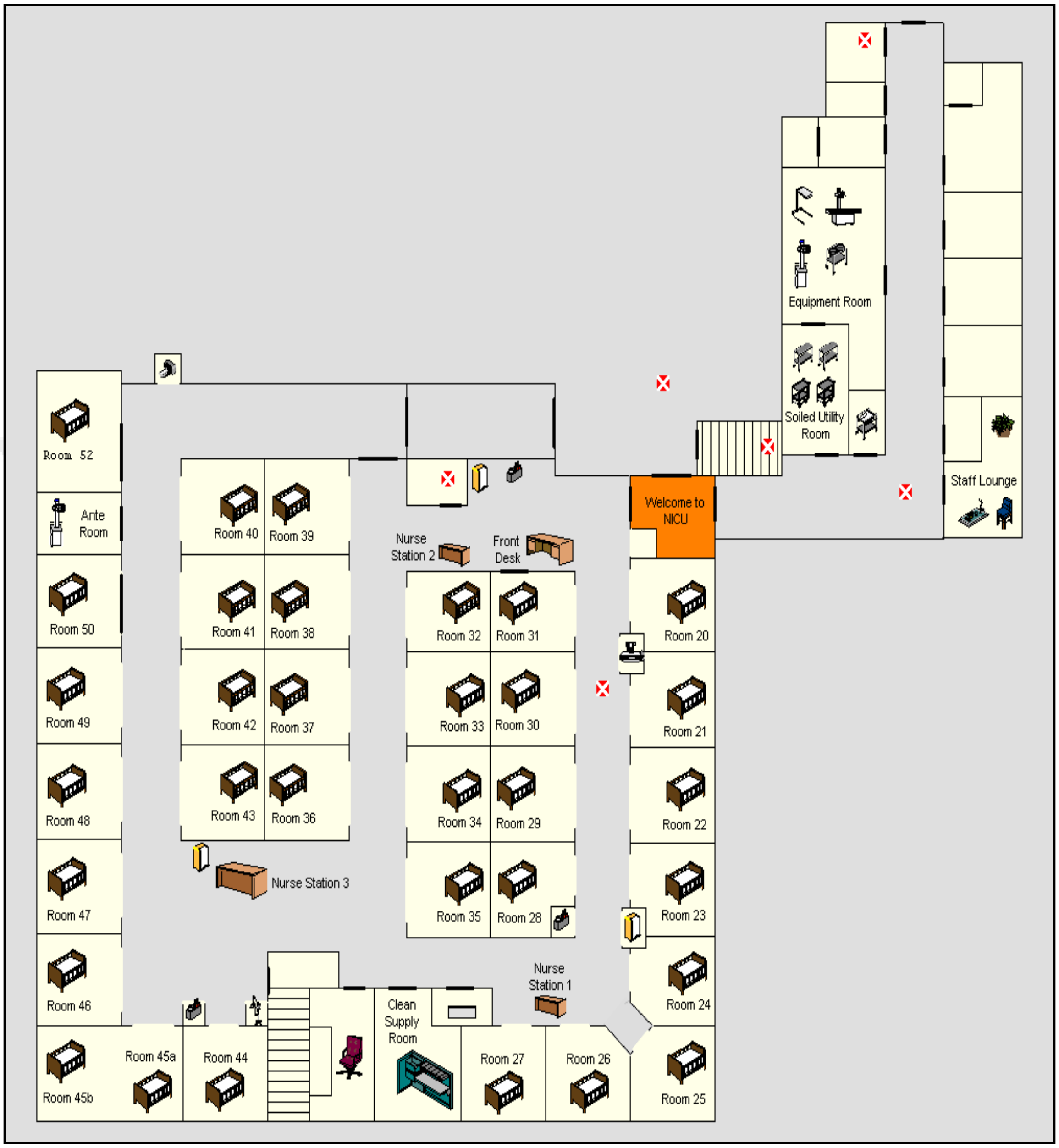

Figure 6: Facility Layout of NICU at Southwestern Michigan Hospital

Data Collection

This unpublished university study was completed over three summer periods from 2006 to 2008 (Fredericks et al., 2008). The team which collected the data at the hospital consisted of trained graduate and undergraduate students from Western Michigan University. The management team which oversaw the data collection process included university faculty members from the Industrial & Manufacturing Engineering Department at Western Michigan University and hospital administrators from the hospital in which the data collection took place. Prior to data collection, the study was explained to the nurse manager, unit coordinator, and nurse scheduler on the NICU. Data collection commenced following approval of the study by the university and hospital institutional review boards. Approximately 40 registered nurses agreed to participate in the direct observation study. The data collection was conducted at the hospital during the two regular 12-hour nursing shift periods (7:00 am - 7:00 pm and 7:00 pm - 7:00 am). Personal digital assistants (PDAs) were used to collect continuous time study data by an observer throughout the entire shift. Nurses were also asked to wear pedometers and heart rate monitors to measure the distance traveled and to approximate nurses' metabolic rates during the shift. Collection took place over two summer periods, totaling 4 months of data collection. The collection resulted in data from almost 100 complete 12-hour shifts, with approximately 20 of these in the step-down area. Nursing behaviors and times were divided into 12 primary categories such as direct care, indirect care, and in-transit times. These categories were then further divided into specific actions resulting in 86 unique activities. The 12 primary categories of activities are given in Table 2 including the percentage of a Registered Nurse's (RN's) times spent completing activities in each category and the percentage of the total activities performed by an RN, which fall in each category. Over 138,500 activities were observed throughout the data collection periods. On average, 1,296 observations were recorded per shift per nurse.

Table 2

Percent of RN Total Time and Percent of RN Total Activities Spent Completing Specific Types of Categorized Activities

Category	**Percent of RN time**	**Percent of RN activities**
Indirect Care	35.8	20.8
Direct Care	23.0	22.9
Personal Time	23.2	12.9
In-transit	5.3	14.4
Unit-related	6.9	10.4
Fetching	2.3	16.7
No observation	0.8	0.1
Off unit	0.6	0.1
Idle Time	0.9	0.5
Searching	0.3	0.7
Waiting	0.3	0.3
Other	0.6	0.2

Stochastic Modeling

After the data were collected and extracted into a spreadsheet, transition times and movement probabilities between specific locations were analyzed. Since the step-down area is on a separate floor and the infants on step-down require different kinds of care, the locations utilized with high frequency were different from those in the critical care area.

For this study, only data from the critical care area of the unit were used for analysis, which included nearly 4,000 in-transit observations. In order to study the effect of the assignment on transitions, patient rooms were grouped into assigned rooms and unassigned rooms. Transition probabilities were developed by finding the steady state probabilities of the transition matrix constructed from the data collected. Table 3 identifies locations included in the transition matrix. The locations were divided into locations within the patient hallways, shared unit locations related to patient care, and locations designated for staff only use (not directly related to patient care).

The most frequently traveled paths were between an assigned patient room and the nurses' station (~25%), between two assigned patient rooms (~21%) and between an assigned patient room and an unassigned patient room (~9%). The most frequently visited locations within the patient hallways were the nurse's assigned patient rooms (~50%), the nurse station in the assigned hallway (~20%), and then other patient rooms in that hallway (~10%). The main duties of the nurse are related to direct care in the patient rooms such as giving medication, changing diapers, and feeding the infants, which accounted for approximately 23% of a nurse's time. Indirect care activities, such as charting, medication preparation and formula preparation, occurred either in the patient room or at the nursing stations and account for an additional 3% of a nurse's time.

Table 3

Locations Used in the Transition Matrix

Hallway Locations		Unit Locations		Staff Locations
Assigned Patient Room		Equipment Supply Room		Staff Lounge and Surrounding Area
Nurse Station		Clean Supply Room		Staff Restroom By Front Desk
Other Patient Room		Front Desk		Staff Restroom By Staff Lounge
Patient Hallway Area		Formula Preparation Room		Off Unit
Medical Cart		Soiled Utility Room		Staff Work Room
Milk/formula Refrigerator		Step-Down Unit		
		Isolette and Crib Holding Room		

Scenarios

The simulation scenarios focused on assignments in hallway 1 of the critical care area. Hallway 1 is the closest hallway to the staff wing and entrance to the unit, and is located relatively close to the critical care clean supply room and formula preparation room. The length of hallway 1, and the location of the nurse station, medical cart, and milk/formula refrigerator at one end of the hallway increased the distance walked by nurses assigned to the patient rooms at the other end. Three scenarios were developed for comparison based on the relative location of the rooms to the nursing station and to each other. In scenario 1, all assigned patient rooms were located on the nursing station end of the hall (rooms 25, 26, and 27). Scenario 2 modeled an assignment where all assigned rooms were located on the opposite end of the hallway (rooms 20, 21, and 30). The final scenario (scenario 3) represented an assignment with rooms spread throughout the hallway (rooms 20, 27, 29). These three scenarios were compared to an actual assignment observed during data collection (rooms 22, 23, and 29). The actual assignment had a similar room pattern to that of scenario 1, where all rooms were located near the nursing station. All developed scenarios and the actual assignment consisted of three patient rooms assigned to one nurse.

Study Results

The simulation model was developed within the MedModel Version 6.0 (Promodel, 2009) modeling environment. Each simulation scenario was run for 500 trials. To validate the simulation model, a comparison was made between the in-transit times collected during the continuous time studies and the simulated in-transit times for the same assignment. In both the simulated and observed cases, nurses were in-transit between 5% to 8% of the 12-hour shift. It was found that the simulated in-transit times were not statistically different from the observed in-transit times.

To determine if any statistical differences existed between the in-transit times of the three scenarios and the actual assignment, ANOVA testing with Tukey post-hoc analyses were performed. The ANOVA and the Tukey homogeneous subsets are found in Figure 7. The in-transit times for the actual assignment and scenario 1 were not statistically different (p-value = 0.769). The final two scenarios represent the other possible assignment patterns under consideration, both of which produce statistically higher (p-value = 0.000 for all pairwise comparisons) total in-transit times than the actual assignment and scenario 1. The scenario with patient rooms spread throughout the hallway, scenario 3, resulted statistically in the highest in-transit time (p-value = 0.000

for all pairwise comparisons). Table 4 summarizes the in-transit times for each of the developed scenarios and the actual assignment for 500 trials of each scenario.

c	***df***	***SS***	***MS***	***F***	***p***
Scenarios	32	36951.2	12317.1	140.72	0.000
Error	1996	174712.2	87.5		
Total	1999	211663.2			
Means: *Actual = 54.7 Scenario 1 = 54.53 Scenario 2 = 60.21 Scenario 3= 64.9*					
Tukey Homogeneous Subsets: (Actual, Scenario 1)(scenario2)(Scenario 3)					

Figure 7. ANOVA and the Tukey Homogeneous Subsets for Comparison of Scenarios Including the Actual assignment

Table 4

Statistical Summary of Simulated In-Transit Time (min) by Scenario

Scenarios	Mean	Standard deviation	Minimum	Maximum
Simulated Actual Assignment	54.7	8.9	28.8	82.0
Scenario 1: Near Nurse Station	54.5	8.9	27.2	82.7
Scenario 2: Away From Nurse Station	60.2	9.6	33.1	87.3
Scenario 3: Spread Throughout Hallway	64.9	9.9	39.1	97.6

It was found that the model results closely resembled the results found through direct continuous observation of nurses during 12-hour shifts. Results of this comparison showed that nurse-to-patient assignments do affect the in-transit time, and thus the walking distance, of a nurse during a shift (All walking speeds were kept at a constant rate in the simulations).

The original intention in this dissertation was to use simulation to contrast and validate nurse-to-patient assignments in NICU. However, it was determined that such a model in the NICU had several barriers that must be overcome.

Typically, a CN is responsible for making nurse-to-patient assignments on a unit with input from the nurses. This was not the case on NICU. On the NICU, assignments were made as follows. The CN was only responsible for assigning nursing staff to hallways. After assigning nurses to the hallways, the core nurses on a hallway collectively assigned patients to nurses through discussion and consensus. It was noted that the criteria used to make assignments could change from day to day and from hallway to hallway. Modeling such behavior with a mathematical model on a simulation model was essentially impossible since all criteria could not be captured fully and consistently. Since not all hospitals have a NICU, it was decided that this work would have more applicability by modeling another common hospital unit such as a General Medical Unit (GMU). Therefore, the focus of this study turned from NICU to a GMU on which the nurse-to-patient assignments were responsibility of the CN.

In the future, the NICU simulation model could be used to aid in determining nurse-to-patient assignments based on the relative locations of the assigned patient rooms. The model could also be adopted to include measures of patient acuities by allocating weighted transition probabilities to each of the assigned patient rooms. In general it is difficult to use simulation to “optimize” all competing objective function components, such as acuity, location and nurse preferences. Therefore, in this dissertation a Multi Criteria Decision Making (MCDM) approach was employed and is described in Chapter 4.

CHAPTER IV

OBJECTIVE, PROBLEM STATEMENT AND FORMULATIONS

Research Objectives

The main objectives of this research were to 1) investigate the process of assigning nurses to patients within a hospital unit consisting of single patient rooms and 2) develop a solution methodology that would aid in the construction of equitable nurse-to-patient assignments.

A comprehensive literature review regarding hospital nurse-to-patient assignments were presented in Chapters 1 and 2. From this review, the objective function measures and constraints that have been used to construct nurse-to-patient assignments in previous studies were identified. In Chapter 3, a simulation model of Neonatal Intensive Care nurses working on a unit was developed to highlight the large disparities of total nurse in-transit times that could occur on a shift due to difference in nurse-to-patient assignments. The results indicated that unbalanced demands with respect to non-patient care activities may be placed on nurses working on the same unit. Hence, one element of balancing workload on a unit must consider the additional demands placed on the nurses outside of patient care activities. This is particularly true in a single patient room environment where crucial unit facilities may be located further apart than in a semi-private or a ward environment. Therefore, ancillary measures and restrictions were considered in this study in an effort to improve upon previous methodologies and to balance the conflicting demands placed on nurses during their shifts.

While several potential measures were reported in the literature (O'Brien-Pallas et al., 1997, Morris et al., 2006, Moore and Hastings, 2006), in all published studies only patient acuity, and/or workload defined in terms of direct and indirect patient care needs, have been used to balance workload among the available staff. Many elements comprise the workload of a nurse during a shift and in many cases these elements are in conflict. The conflict encountered in this project was that of trying to optimally balance the distance traveled by nurses during a shift while also balancing the sum of patient acuities assigned to the nurses. Thus, to optimize the competing elements of the nurse-to-patient assignments, a multi-objective decision making (MODM) strategy was employed. Prior to this research, no authors have considered such an approach to the nurse-to-patient assignment problem. Ultimately, a decision model was constructed for a hospital unit

Hospital Setting

The hospital that participated in this study is a not for-profit hospital serving all of southwest Michigan and northern Indiana. This hospital has 380 licensed beds, each located in a private room. This hospital provides virtually every medical specialty including cardiology, orthopedics, surgery, emergency medicine, neurology, and oncology. The unit considered for the development and validation of the resulting methodologies was a 29-bed Adult Medical/Oncology Unit (GMU). The majority of the patients on this unit are admitted through the Emergency Room (ER) with a smaller amount coming as direct admits and transfers from other units in the hospital. The hospital provided information regarding its facilities and data related to nursing staff mix, shift lengths, shift times, typical nurse assignment preferences, methodology to make assignments, historical data on bed census and patient acuity, and applicable nurse-to-patient ratios. At the time of this study, GMU employed a total of 45 full-time nurses, 26 of which were chemo-certified nurses.

Nursing staff on GMU consists of a Unit Coordinator, Charge Nurses (CNs), Registered Nurses (RNs), Patient Care Assistants (PCA), and student nurses that function under the supervision of their instructor and Unit Coordinators. The care delivery method on this unit is a coordinated managed care system utilizing a team approach. The Unit Coordinator oversees the provision of patient care, manages unit variability, and serves as a clinical resource person. The CN oversees unit nursing and scheduling activities during a shift. RNs plan for the progression of care of their patients during a shift, evaluate patient progress, provide patient continuity, and make appropriate referrals. PCAs provide direct and indirect non-professional nursing care for their assigned patients during a given shift under the nursing supervision of their assigned RNs. PCA duties include such activities as taking vital signs, helping with hygiene needs, charting patient progress, getting lab specimens, ordering and receiving supplies. Patient to team (RN/PCA) ratios are based on factors as noted in the department staffing plan. Additional services provided by the RN/PCA team on this unit include: assisting with activities of daily living (ADLs) and mobility, pain control, chemotherapy administration, IV and hyper alimentation management, tube feedings, administering medications, administration of blood and blood products, specimen collection, documentation and the provision of emotional support. On this unit each patient is assigned to one RN. PCAs are not assigned directly to patients but to work with one or more RNs during their shift period. Therefore, only RN assignments to patients were considered in this work.

Facility Layout

In the previous chapter, it was concluded that facility layout was a crucial element in determining how a change in assignment would alter the in-transit time of a nurse during a shift. The GMU consists of one long hallway with 29 single patient rooms. The single patient room environment on this unit is configured so that each room has a window. The current unit layout also increases the relative distances between locations within this unit in comparison to previous semi-private units in this hospital. Figure 8 presents a graphical depiction of the unit. (The dimensions in this figure are given in feet.) In this figure, the patient rooms are the numbered rooms on the periphery of the layout (450-478).

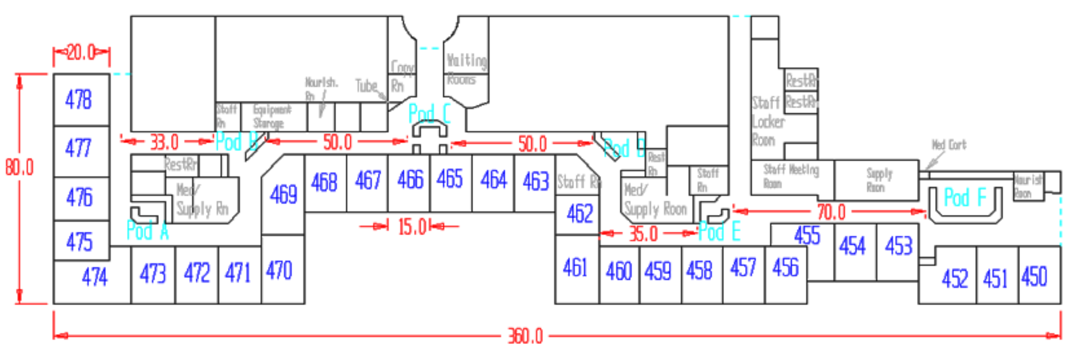

Figure 8. Facility Layout of GMU at a Southwestern Michigan Hospital

There are six nursing stations called “pods” (A, B, C, D, E, and F) and three medical/supply rooms located within this unit. Very few patients can be monitored directly from an assigned pod in GMU. Patient charts can be moved from pod to pod to accommodate a nurse’s assignment, but typically remain at one pod throughout a shift. Pod A and pod B share one medical/supply room where there is one staff room, one storage room and one nourishment room near pod B. The copy room, waiting rooms and a tube station (for transportation of documents throughout the hospital) are located near the centralized pod (pod C). Pod E has a medical/supply room, a staff room and a staff meeting room. Pod D also shares the same medical/supply room with pod E. There is another staff room near pod D. To further isolate chemo patients, the staff preferably locate chemo patients nearest to Pod F, which has a medical cart, a nourishment room, and a supply room.

Data Collection

Prior to data collection, the study was explained to the nurse manager, unit coordinator, and charge nurse (CN) on the GMU. Data collection commenced following approval of the study by the university and hospital institutional review boards. Data collection included acquiring historical data from the unit coordinators and the CNs. Responses to questions related to patient dependency and the CN’s decision making strategies relevant to making the nurse-to-patient assignments were also collected. Two week (14-day) daily rosters for both day and night shifts were obtained. These rosters included patient room assignments, charge sheet information and other patient related information. Patient acuity information sheets were also reviewed and were typically used in staffing/acuity determinations.

Although the hospital recognized six patient acuity levels, the information was not found to have value in making nurse-to-patient assignments and was not used by the CNs. Because the GMU did not use the existing hospital-wide acuity measures for constructing assignments, the first step in the modeling process was to develop a consistent unit-specific acuity scoring system for quantifying patient care needs. Measuring patient workload required a detailed acuity system specific to this unit. It was found that the RN who was assigned to a patient determined the acuity level of this patient through a recording of measures identified in the “Patient Chart Sheet” and “Staffing/Acuity Determination Sheet”. These sheets included the special needs or status that is often required by patients on this unit including: isolation, specialty, high-risk medication (heparin, Insulin, Morphine and Chemo), Diabetic Ketoacidosis (DKA) Patients, lab trending, and step down patients. Examples of these sheets are given in Figures 9 and Figure 10, respectively. From these sheets, the CNs and unit coordinators helped to compile the list of these important care measures needed to make nurse-to-patient assignments. Prior to this study, each CN used her own personal judgment in the determination of the required patient workload from these reported measures.

Room Number	Name	Age	Admission Date	Code	Physician	Isol	Spec	CL	Diagnosis	High Risk Meds	DC Plan/ DC Date	Lab Trending	CHF/RF/V accines	Notes
450														
451														
452														
453														
454														
455														
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Figure 9. Patient Chart Sheet

Staffing / Acuity Determination

Date & Time ________ Census 0400 ____ 1600_____

Charge Nurse

Charge nurse to fill in your shift information

# of Admissions __________ Discharges ______________

High Acuity Patients

DKA pts – 1 less pt assigned

Room #s _______

____

____

Drips- Insulin, Heparin, Morphin, = 4 pts per nurse with 1 drip,

Room #s ______

______

______

______

______

Chemo

Rm #s ________

____

____

____

Step down pts = 3 pts per nurse

Rm #s _________

____

____

Rapid Response calls (code whites)____

Other special Needs

____

Nurses just off orientation - 4 pts per nurse ____________________

Actual staffing; RNs________ PCAs_______ Census_______

Did charge have pts? _______ Room #s______ ______ ________

What additional staffing did you need and why-

____

____

Recommendations

____

____

Place form under manager's door at the end of shift

Figure 10. Staffing/Acuity Determination Sheet

Since the individual judgments of the CNs were used to develop the acuity measures needed to make the nurse-to-patient assignments, reconciling the opinions and the importance of each measure among the nurses in a consistent manner was necessary.

Many Multi-Criteria Decision Making (MCDM) methods require the use of weights to distinguish the importance of competing measures in the objective function. Analytic Hierarchy Process (AHP) is one of those MCDM methods and was employed in this study (Saaty, 2008). AHP is introduced in the following section.

Analytic Hierarchy Process (AHP)

AHP is a method used to solve problems with complex decisions. In AHP, the complexity is structured as a hierarchy and then ratio scales are derived through pairwise relative comparisons. The input of AHP can be obtained from actual measurements such as prices and weights, or from subjective opinion such as individual judgments and preferences. AHP is a MCDM technique that can combine qualitative and quantitative factors into the overall evaluation of alternatives. Since AHP is an effective method for determining the priority ordering of different competing criteria, AHP was used in this study to obtain relative objective function weights (Saaty, 2000) for the acuity measures and the distance measures used on GMU.

AHP uses a fundamental scale that captures individual preferences with respect to quantitative and qualitative values. (Saaty, 2008). This scale ranges from 1-9 and is shown in Table 5.

Table 5

Fundamental Scale of Absolute Numbers (Adopted from Saaty, 2008)

Intensity of Importance	**Definition**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or Slight	
3	Moderate Importance	Experience and judgment slightly favor one activity over another
4	Moderate Plus	
5	Strong Importance	Experience and judgment strongly favor one activity over another
6	Strong Plus	
7	Very Strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, Very Strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

A basic assumption of AHP is that if alternative A is absolutely more important than alternative B and the comparison is scored a 9, then B must be absolutely less important than A and the comparison in this order is assigned 1/9. After constructing a hierarchical structure for an AHP problem, the first activity in the process is to carry out pairwise comparisons of all factors that will be considered in the problem. A decision matrix is then built from the scale values resulting from these comparisons. From the decision matrix, the eigenvector is determined by deriving a list of the relative weights, importance, or values, of the factors. The last stage of the process is to calculate a Consistency Ratio (CR) to measure how consistent the relative judgments are to one another. CR must be between 0 and 0.10 for the judgments to be considered consistent. A decision matrix A, is said to be consistent if $a_{ij} * a_{jk} = a_{ik}$ for all i, j and k. If CR is at a value of 0.1 or smaller, then inconsistency is assumed to be at an acceptable level. If the CR is greater than 0.1, then judgments need to be revisited and revised. These steps of AHP are illustrated with the following example.

Let us assume that we wish to choose a new office in a new building with four alternatives X, Y, Z and W (for instance, north wing, south wing, east wing and center of the hallway, respectively). Consider four criteria, A, B, C and D (for example, size, access to the supply room, visibility and shape, respectively), from which to base the choice for the new office. The hierarchical structure for this example is given in Figure 11. In this Figure, level 0 is the goal of the problem, level 1 is the criteria level, and level 2 is the alternative level of the problem.

The first step in AHP is to ignore the alternatives and determine the relative importance of the criteria. Pairwise comparisons of the criteria are performed using the fundamental scale. When comparing criteria i and criteria j, if a_{ij} is the element value of the i^th^ row and j^th^ column of the decision matrix, then $a_{ii} = 1$, and $a_{ji} = 1/a_{ij}$ where all the elements in the matrix are positive.

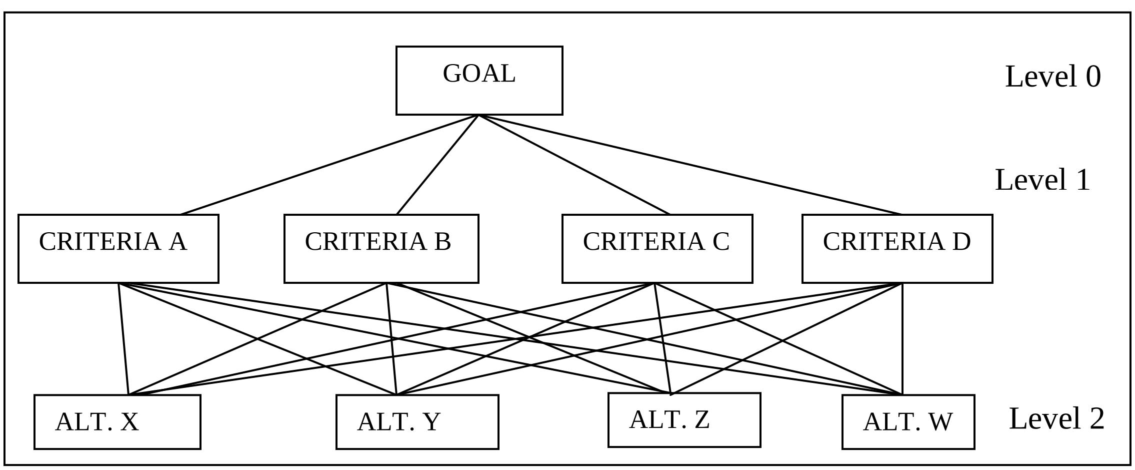

Figure 11. Hierarchical Structure of AHP

In the matrix given in Table 6, A = size, B = access to supply room, C = visibility, and D = shape. According to the decision maker (DM), access to the supply room is judged to have stronger importance than size, while visibility has moderate importance in comparison to size. In this problem it could not be determined whether size has equal importance or moderate importance over shape, thus it was rated as weak or of slight importance.

Table 6

Preferences on Criteria

	A	B	C	D
A	1	1/5	1/3	1/2
B	5	1	2	4
C	3	1/2	1	3
D	2	1/4	1/3	1

From Table 6 each matrix element is normalized by the sum of elements in the corresponding column and then the sum of each row of normalized values is normalized to calculate the priorities (Eigenvalue). For example, for the a_{11} entry in Table 7 the resulting value is calculated from the first column in Table 6 as follows:

$$\frac{1}{1+5+3+2} = 0.091$$

The results of similar calculations for all table elements are given in Table 7. Since the row sums are normalized, the sum of all elements in the priorities column is 1. The priorities (Eigenvalues) column gives the relative weights (importance) given to each criteria for the decision making process.

Table 7

Weights on Criteria and Eigenvalue

	A	B	C	D	Priorities (Eigenvalue)
A	0.091	0.102	0.091	0.059	0.086
B	0.455	0.513	0.545	0.471	0.496
C	0.273	0.256	0.273	0.353	0.289
D	0.182	0.128	0.091	0.118	0.130

The next step is to evaluate all alternatives on each criterion. For example, let us begin with criterion A (size). If the DM prefers a large office, then the pairwise room comparisons may be as listed in Table 8 based on the four room alternatives, and again using the fundamental scale.

Table 8

Preferences on Criterion A

	X	Y	Z	W
X	1	1/2	1/3	5
Y	2	1	1/2	7
Z	3	2	1	9
W	1/5	1/7	1/9	1

Similar steps are then used to transform Table 8 into Table 9 as were used to go from Table 6 to Table 7. The relative weights for each alternative and priorities are given in Table 9 for criterion A (size).

Table 9

Weights on Alternatives for Criterion A

	X	Y	Z	W	Priorities (Eigenvalues)
X	0.161	0.137	0.171	0.227	0.174
Y	0.322	0.275	0.257	0.312	0.293
Z	0.484	0.549	0.514	0.409	0.489
W	0.032	0.040	0.057	0.045	0.044

This resulting matrix indicates that the office located on the east wing (Z) has the highest priority with respect to criterion A (size). The same process is then completed for the other three criteria. Table 10 shows all priorities (Eigenvalues) for each alternative with respect to each criterion.

Table 10

Eigenvalues of Alternatives with Respect to the Four Criteria

	X	Y	Z	W
A	0.174	0.293	0.489	0.044
B	0.050	0.444	0.312	0.194
C	0.210	0.038	0.354	0.398
D	0.510	0.012	0.290	0.188

The overall score for the office alternative on the north wing (X) is calculated as follows using Tables 7 and 10.

$$(0.174)(0.086) + (0.050)(0.496) + (0.210)(0.289) + (0.510)(0.130) = 0.164$$

Values for the other alternatives are 0.256 for Y, 0.335 for Z and 0.238 for W. Thus, the preferred office is the one located on the east wing of the hallway with value 0.335 (the highest score among the alternatives). Although the preferred choice is obtained by these calculations, the consistency ratio of the comparisons must still be calculated. First, the Principal Eigenvalue can be calculated from the product of the preference matrix (Table 6) and its associated priorities (Table 7). The resulting vector is then divided by the Eigenvalue in Table 7 to get the final set of Eigenvalues. The highest Eigenvalue is the Principal Eigenvalue ($\lambda_{\max}$).

$$\begin{bmatrix} 1 & 1/5 & 1/3 & 1/2 \\ 5 & 1 & 2 & 4 \\ 3 & 1/2 & 1 & 3 \\ 2 & 1/4 & 1/3 & 1 \end{bmatrix} * \begin{bmatrix} 0.086 \\ 0.496 \\ 0.289 \\ 0.130 \end{bmatrix} = \begin{bmatrix} 0.347 \\ 2.024 \\ 1.185 \\ 0.522 \end{bmatrix}$$

$$\begin{bmatrix} 0.347 /0.086 \\ 2.024 /0.496 \\ 1.185 /0.289 \\ 0.522 /0.130 \end{bmatrix} = \begin{bmatrix} 4.029 \\ 4.081 \\ 4.100 \\ 4.018 \end{bmatrix}$$

Thus, the value 4.100 is the Principal Eigenvalue. Saaty (2000) proved that for a consistent reciprocal matrix, the largest Eigenvalue must be equal to the size of comparison matrix. A measure of consistency, called the Consistency Index (CI) is defined as the deviation or degree of consistency using the following formula (where n is the column dimension of the matrix).

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

In our example, $\lambda_{\max} = 0.033$. The next question is how to use this index. Saaty (2000) proposed an appropriate consistency index called the Random Consistency Index (RI) to be compared with CI. This index is given in Table 11 for various values of n.

Table 11

Random Consistency Index (RI)
(Adapted from Saaty, 2000)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Finally, Saaty (2000) determined a ratio, called the Consistency Ratio (CR). CR is the result of the division of CI by the RI, or simply:

$$CR = \frac{CI}{RI}$$

In our example

$$CR = \frac{0.033}{0.9} = 0.037 \cong 0.04.$$

This value is less than 0.1, thus our individual judgments about office selection are consistent. When dealing with a small example, all calculations can be easily done manually. However, as the problem size gets much larger in the number of criteria, alternatives or sub criteria, the problem becomes more difficult to manage the pairwise comparisons and matrix commutations by hand. Hence, AHP analyses in this study were completed using a software called Expert Choice 11.5 (2008) developed by Expert Choice, Inc.

AHP and GMU

Measures of “good” and “balanced” nurse-to-patient assignments on GMU were developed through consultation with the CNs on this unit and through the use of AHP. Based on the interviews with the CNs, there was not a detailed acuity scoring system on this unit and acuity was measured based on the CN’s and RN’s judgments through the information in the two sheets given in Figures 9 a and b. In addition to acuity, the CNs considered distance traveled when balancing the workload among nurses.

To develop an acuity system for this study, key attributes in the “Patient Chart Sheet” (Figure 9) and “Staffing/ Acuity Determination Sheet” (Figure 10) were identified by CNs as the important workload measures. The CNs were then asked to rank the attributes through pairwise comparisons in AHP. Expert Choice 11.5 (2008) was used to obtain the weights of the attributes for ranking. The attributes and their resulting normalized weights are given in Table 12.

Table 12

Weights of Attributes

Acuity Attributes	CN 1	CN 2	CN 3	CN 4 (Unit Coordinator)
DKA patient	0.447	0.371	0.421	0.391
Step-down patient	0.335	0.219	0.353	0.351
High Risk Medication	0.106	0.082	0.096	0.129
Lab Trending	0.063	0.194	0.067	0.060
Isolation	0.024	0.060	0.038	0.037
Specialty	0.024	0.074	0.026	0.031

It can be seen that the designations of DKA patient and Step-down patient were highly important attributes relative to the other attributes for all CNs and the unit coordinator. The weighting of the other attributes where relatively consistent with some difference seen in the lower weighted attributes. The unit coordinator weightings (CN4) in Table 12 were compiled during a second session with AHP to reconcile difference between the four CNs.

As stated earlier, total workload balance must also consider indirect patient care and unit-related activities, which are affected by the layout of the hospital unit. Thus, distance traveled by nurses between a patient room and the pod, a patient room and the supply room and a patient room to another patient room were considered in an effort to develop better nurse-to-patient assignments. These distances were chosen for consideration based on interviews and the papers written by Butt et al. (2004) and Hendrich (2008). After finishing with acuity measures alone, the unit coordinator, who was also a CN, was asked to compare and score four-patient room assignments with respect to two main criteria, acuity and distance. Attributes of the acuity system were considered as sub criteria in the AHP structure. The distance traveled measure had three sub criteria to be considered:

- Distance between two patient rooms,
- Distance between a patient room and the nearest supply room,
- Distance between a patient room and the nearest pod

Expert Choice 11.5 (2008) was used to obtain the weights for these measures following the comparison of the patient rooms. The relative weights of the comparisons with respect to the acuity system were given in Table 12. Overall weights of acuity and distance, including the sub-criteria weights, are given in Table 13.

Table 13

Overall Weights of Measures

Acuity	0.833	
	DKA	0.391
	Step-down	0.351
	High Risk Medication	0.129
	Lab Trending	0.060
	Isolation	0.037
	Specialty	0.031
Distance	0.167	
	patient room -patient room	0.637
	patient room -supply room	0.258
	patient room- pod	0.105

Acuity was rated approximately five times more important (0.833 / 0.167 = 4.988) than the distance measure in constructing nurse-to-patient assignments. This is consistent with the literature in this area. CNs, for the most part, take acuity into consideration when assigning patients. Ignoring the acuity, room assignments in which rooms are adjacent to one another, are highly preferred. While the distance traveled was a function of the maximum distance between assigned patient room and the nearest supply and the maximum distance between assigned patient room and pod (Butt et al.,2004), according to the nurses, the distance between patient room and supply was twice as important as the distance between the patient room and the pod. The use of these weights is described in the following sections.

Problem Statement

Nurses typically work three 12-hour shifts per week on this unit. There are seven RNs, one CN and one shift coordinator working on the day shift and 6 RNs and 1 CN working on the night shift. Nurses can work two consecutive days; however, they cannot work two consecutive shifts. If there is a lack of required nurses available, float nurses can be assigned on the unit with the same patient loads as the GMU RNs. Since there is a great deal of variation in patient conditions on the unit, the assignment process can become very complex. Thus, the manual development of balanced nurse-to-patient assignments for a shift is very difficult.

Nurses on GMU are assigned 3 to 5 single patient rooms (typically 4 rooms on the day shift, 5 rooms on the night shift) during a shift. However there are often high acuity patients on this unit that effect nurse assignments. The possible attributes of these high acuity patients are as follows.

1. Diabetic Ketoacidosis (DKA) Patients: DKA is a state of inadequate insulin levels resulting in high blood sugar and the accumulation of organic acids and ketones in the blood. If a nurse has one DKA patient in her assignment, her patient ratio of DKA to non-DKA patients is 1:3 and her maximum patient load is set to one less patient.
2. Chemo Patient: Chemotherapy is the treatment of disease by chemicals especially for killing microorganisms or cancerous cells.
3. Drip Patients: Patients who are taking high intravenous dose medicines such as: Insulin, Heparin, and Morphin.
4. Step-Down Patients: Contrary to NICU, Step-Down patients on this unit require more nursing than normal GMU patients and have high acuity.

5. Isolation Patients: A patient has to be isolated when he/she has a communicable disease to prevent the spread of the disease. There are three types of isolation on this unit.
    a. *Contact precautions* that require the nurse to wear a gown and gloves when entering the room for any reason. This is for organisms that are spread only by contact (shown with C on the chart sheet).
    b. *Droplet isolation* requires nurse to wear a gown, gloves, goggles and a mask. This is for organisms that can be spread through body fluids, or when the patient coughs (shown with D on the chart sheet).
    c. *Airborne precaution* is when the patient has a disease that can become airborne such as Tuberculosis (TB). This requires a nurse to wear a gown, gloves, goggles and a respirator mask (shown with A on the chart sheet).
6. Specialty Patient: This is used for many things including fall precautions, skin precautions, and remote telemetry.
    a. *Fall precautions* is for a person who has a high risk of falling. This person is on a bed alarm that alerts when the patient gets up without assistance. This person requires more frequent checks.
    b. A person on *skin precautions* is someone who has fragile or already broken down skin. This person is turned every 2 hours to

prevent sores forming on pressure points. This person may also require some type of wound care.

c. When a patient is on *remote telemetry*, they are hooked up to a heart monitor that is watched on the cardiology unit. This means that they have some cardiac issue that is being watched. It requires monitoring of telemetry strips and also upkeep of the telemetry boxes.

7. Lab trending: This category can be used for several attributes.

    a. *Low red blood cell counts and platelets*, which would require a patient to receive blood products and must be watched by the RN.

    b. *Patients with electrolyte imbalances*. These patients sometimes receive electrolyte replacement.

    c. *Monitoring bleeding times* to determine if the patient is likely to bleed during a procedure.

    d. Specific conditions such as *renal failure*, *dialysis* and others.

At the beginning of each shift the CN assigns a set of patients to each RN working on that shift. Since the CN generates a new assignment at the beginning of every shift, she has approximately 30 minutes to perform this assignment task. Some patients require more care than others, so tending to the needs of a few patients may consume most of a nurse's shift time, while other patients may require only minimal care. It is essential that a nurse remain in close physical proximity to his/her assigned patients, and thus, nurses should not be assigned patients in distant locations. Due to the number of patients and the number of nurses on this unit, if a nurse has five patients on her assignment, the CN nurse will typically take one of her patients. Additionally, if there is a new patient admitted to this unit through a shift, the nurse whose patient was discharged during the shift is assigned the new patient. This unit runs at patient census capacity, and rarely has an empty bed.

Model Assumptions

There were several assumptions considered in the development of the mathematical model for the nurse-to-patient assignment problem on GMU. These assumptions were as follows:

- *Assumption 1:* A CN determines which nurse is assigned to each patient on the unit at the beginning of the shift.
- *Assumption 2:* Since a new admit patient is assigned to the room from which a patient was discharged, nurse room assignments are not changed during a shift.
- *Assumption 3:* Pod C is located at the entrance of GMU and is only used as a reception desk. It is not used by nurses to monitor rooms or to keep patient charts.
- *Assumption 4:* GMU nurses can be assigned a maximum of 5 single patient rooms.
- *Assumption 5:* Adjacent patient room assignments are considered ideal by the nursing staff.
- *Assumption 6:* An assignment of 3 high acuity patients in close proximity can be equal to 5 low acuity patients that not located in close proximity to one another.

- *Assumption 7:* The workload of a step-down patient is approximately equal to that of a DKA patient.
- *Assumption 8:* The patient care workload of a DKA patient is equivalent to caring for two non-DKA patients.
- *Assumption 9:* A nurse's maximum patient load will be reduced by one if the nurse is assigned to a DKA patient.
- *Assumption 10:* A nurse can only be assigned one DKA patient on a shift.
- *Assumption 11:* Balancing workload consists of balancing both assigned patient acuity and distance traveled during a shift.
- *Assumption 12:* There is always a sufficient number of chemo-certified nurses on a shift. Therefore, a patient assignment, which contains a chemo-certified can always assigned to a chemo-certified nurse.
- *Assumption 13:* A chemo patient and an isolated patient cannot be assigned to the same nurse.
- *Assumption 14:* A maximum of 3 step-down and DKA patients can be assigned to the same nurse.
- *Assumption 15:* In general, nurses prefer to be assigned to patients that they were assigned to one shift earlier, but such assignments are not required. Balancing workload among nurses is a higher priority.

Nurse-to-Patient Assignment Model

The CN's objective is to balance workload by distributing the total sum of acuity of the unit patients as uniformly as possible among nurses while minimizing the distance traveled by each nurse throughout the shift. To achieve this goal in the model, the objective function considered was to minimize the maximum sum of patient acuity assigned to any nurse during a shift and to minimize the maximum sum of key distances traveled by any nurse during a shift. Since the majority of the literature and the nurse coordinators and CNs on GMU concluded that acuity was the more important workload measure when assigning patients, acuity received a higher priority (weighting) in the objective function. The weighting of acuity and distance in the objective function were based on the AHP findings from GMU.

Nurse schedules are typically manually constructed and based on historical patient acuity levels in a given unit (Butt et al. 2004). The hospital where this study was conducted recognizes six hospital-wide patient acuity levels; however, the GMU unit found that the current hospital acuity system was not adequate to assign patients to nurses. Thus, a scoring system for determining the acuity level was developed with the help of the unit coordinators, CNs and RNs on this unit. As discussed in the previous section, AHP was used to determine the weights of the assignment attributes to be used in the objective function and constraints of the developed model. These weights were given in Table 14, and included both weights for acuity measures and distance measures based on GMU staff judgments.

Table 14

Weights and Additional Acuity Scores of Acuity Measure Based on AHP

Attribute	Weight	Additional Acuity Score
DKA	0.391	1
Step-down	0.351	1
High Risk Medication	0.129	0.4
Lab Trending	0.06	0.2
Isolation	0.037	0.1
Specialty	0.031	0.1

A set of acuity attribute “scores: was then developed based on the derived AHP weights and model assumptions. Since DKA patients and step-down patients are considered to require similar patient care workload requirements by nurses and since a nurse’s patient load is reduced by one patient when caring for a DKA patient, it was assumed that caring for a DKA (or step-down) patient was equivalent to caring for two non-DKA patients. Therefore, the acuity “scores” used in the objective function of the model needed to reflect such a situation. With respect to the scores used for acuity, a GMU patient that had no additional attribute given in Table 14 was assigned a base acuity score of 1 (which equates to caring for 1 “base level” GMU patient). By the discussion above, a DKA patient or a step-down patient should then have a total score of 2, which is the base score of 1 plus the additional acuity score of 1. Since the AHP weight for DKA and step-down patients were very similar, the scores for the remaining attributes were developed by dividing each of the respective weights by the smaller of the DKA and step-down AHP weights, which was 0.351. The resulting additional acuity scores are listed in Table 14. Since a patient will never be designated as both a DKA and step-down patient, the maximum acuity score that can be accumulated by a patient is 2.8. That is, if a DKA patient (or a step-down patient) has high risk medication, lab trending, isolation and specialty checks on his/her chart sheet, then the acuity score will be equal to:

$$1 + 1 + 0.4 + 0.2 + 0.1 + 0.1 = 2.8$$

An illustrative example of how the total acuity scores are assigned is given in Table 15. The resulting scores were used as a parameter input for the objective function in the model with respect to acuity.

In addition to acuity scoring, distance scores were also developed. The number of standard-width patient rooms between locations was used in place of actual distances to approximate distances on GMU. For example, going from room 450 to room 452 is 2 standard widths or a distance of 2. Butt et al.(2004) developed meaningful regression models to predict the distance traveled and the energy expenditure of a nurse over a 12-hr shift on this same GMU hospital unit in 2004. In their study, the authors reported the most frequently traveled paths traversed by RNs in a 12-hour shift. The GMU regression model reported in their study indicated that in addition to the relative location of the assigned patient rooms, two other distances were highly correlated with a nurses total travel distance over a shift. These two distances were:

1) PR-to-SR: The maximum distance between an assigned patient room and the nearest supply room.
2) PR-to-Pod: The maximum distance between an assigned patient room and the nearest pod.

Table 15

An Example of Scoring Acuity for the 29 GMU Patients

Patient Room	Base	DKA	Step-down	High risk Medication	Lab Trending	Isolation	Specialty	Acuity
450	1.0						0.1	1.1
451	1.0				0.2			1.2
452	1.0				0.2		0.1	1.3
453	1.0	1.0					0.1	2.1
454	1.0				0.2		0.1	1.3
455	1.0							1.0
456	1.0					0.1		1.1
457	1.0					0.1	0.1	1.2
458	1.0			0.4	0.2		0.1	1.7
459	1.0						0.1	1.1
460	1.0		1.0		0.2		0.1	2.3
461	1.0				0.2		0.1	1.3
462	1.0				0.2		0.1	1.3
463	1.0				0.2			1.2
464	1.0						0.1	1.1
465	1.0						0.1	1.1
466	1.0			0.4				1.4
467	1.0				0.2	0.1	0.1	1.4
468	1.0					0.1		1.1
469	1.0			0.4	0.2		0.1	1.7
470	1.0				0.2		0.1	1.3
471	1.0							1.0
472	1.0	1.0				0.1		2.1
473	1.0							1.0
474	1.0							1.0
475	1.0						0.1	1.1
476	1.0						0.1	1.1
477	1.0							1.0
478	1.0				0.2		0.1	1.3

Due to Assumption 5 above, and the previous study conducted on the same unit (Butt et al., 2004), weights for maximum distance between patient rooms and the nearest supply room and weights for maximum distance traveled between patient rooms and the assigned pod were investigated. CNs were asked to compare three distance attributes, as described earlier using AHP. The three distances and their associated AHP weights are as follows:

- Distance between assigned patient rooms (0.637),
- Distance between assigned patient room and nearest supply room (0.258),
- Distance between assigned patient room and nearest pod (0.105)

Once the workload measures for acuity and distances were quantified, a mathematical model that assigns patients to nurses was developed subject to constraints. The decision variables, parameters and formulation are given below.

<u>Notation</u>

$$P = total\ number\ of\ patients\ on\ the\ unit\ during\ shift\ (Capacity\ of\ unit\ is\ 29)$$

$$p = patient\ index, p = 1,2,3, \dots, P$$

$$p_2 = alias\ of\ patient\ index, p_2 = 1,2,3, \dots, P$$

$$N = total\ number\ of\ nurses\ working\ on\ the\ unit\ during\ the\ shift\ (N\ is\ typically\ 8\ including\ Charge\ Nurse)$$

$$n = nurse\ index, n = 1,2,3, \dots, \mathrm{N}$$

<u>Parameters</u>

$$q_1 = weight\ of\ acuity\ score\ in\ objective\ function$$

$$q_2 = weight\ of\ distance\ score\ in\ objective\ function$$

$$q_3 = small\ penalty\ for\ assigning\ more\ than\ one\ patient\ to\ the\ same\ nurse$$

$$m_1 = weight\ of\ supply\ room\ measure\ in\ distance\ score$$

$$m_2 = weight\ of\ nursing\ station\ measure\ in\ distance\ score$$

$$m_3 = weight\ of\ patient\ room\ measure\ in\ distance\ score$$

a_p = acuity score of patient p

$$C_p = \begin{cases} 1 & \text{patient } p \text{ is a chemo patient} \\ 0 & \text{otherwise} \end{cases}$$

$$I_p = \begin{cases} 1 & \text{patient } p \text{ is an isolation patient} \\ 0 & \text{otherwise} \end{cases}$$

$$K_p = \begin{cases} 1 & \text{patient } p \text{ is a DKA patient} \\ 0 & \text{otherwise} \end{cases}$$

$$ST_p = \begin{cases} 1 & \text{patient } p \text{ is a step} - \text{down patient} \\ 0 & \text{otherwise} \end{cases}$$

U_n = upper bound on the number of patients that can be assigned to nurse n

sr_p = distance from patient room p to nearest supply room

s_p = distance from patient room p to nearest nursing station (pod A, B, D, E and G)

v_{pp_2} = distance between patient rooms p and p

Formulation 5 (Model 1):

$$\text{minimize } Z = q_1 A + q_2 D + q_3 \left[\sum_{n=1}^{N} \sum_{p=1}^{P} \sum_{p_2=p+1}^{P} Y_{npp_2} \right] \tag{27}$$

Subject to

$$\sum_{n=1}^{N} X_{np} = 1 \qquad \forall p \tag{28}$$

$$\sum_{p=1}^{P} a_p X_{np} = W_n \qquad \forall n \tag{29}$$

$$W_n \leq A \qquad \forall n \tag{30}$$

$$M_n \leq D \qquad \forall n \tag{31}$$

$$\sum_{p=1}^{P} C_p X_{np} + \sum_{p=1}^{P} I_p X_{np} \leq 1 \qquad \forall n \tag{32}$$

$$\sum_{p=1}^{P} ST_p X_{np} + \sum_{p=1}^{P} K_p X_{np} \leq 3 \qquad \forall n \tag{33}$$

$$\sum_{p=1}^{P} X_{np} \leq U_n - \sum_{p=1}^{P} K_p X_{np} \qquad \forall n \tag{34}$$

$$\sum_{p=1}^{P} K_p X_{np} \leq 1 \qquad \forall n \tag{35}$$

$$X_{np} + X_{np_2} \leq 1 + Y_{np\,p_2} \qquad \forall n\,, \forall p, \forall p_2\,, p \neq p_2 \tag{36}$$

$$m_1 \sum_{p=1}^{P} s_p X_{np} + m_2 \sum_{p=1}^{P} sr_p X_{np} + m_3 \sum_{p=1}^{P} \sum_{p_2=p+1}^{P} v_{pp_2} Y_{np\,p_2} \leq M_n \qquad \forall n \tag{37}$$

$$A, D \geq 0 \tag{38}$$

$$X_{np} \geq 0{,}1 \qquad \forall n, p \tag{39}$$

$$Y_{np\,p_2} \geq 0{,}1 \qquad \forall n, p, p_2 \tag{40}$$

$$W_n\,, M_n \geq 0 \qquad \forall n \tag{41}$$

Objective function (27) minimizes the weighted sum of the maximum total patient acuity scores assigned to a single nurse and the maximum total distance scores assigned to a single nurse. The actual weighting values for q_1 and q_2 were based on the importance set by the CNs using AHP. Since the literature and the CNs stated that acuity was the most important assignment measure, a higher weight was placed on the acuity score, in a 5 to 1 ratio. The third component in the objective function sets a very small penalty, q_3, on each of the $Y_{np\,p_2}$ variables that is set to the value one. This third component is needed to enforce constraints (36) and (37). Constraint (28) ensures that every patient is assigned to one nurse. Constraint (29) gives the sum of the acuity scores of the patients assigned to nurse n. Constraint (30) sets the upper bound on the maximum assigned sum of acuity scores given to any nurse. Constraint (31) sets the upper bound on the maximum assigned distance score given to any nurse. Constraint (32) assures that a chemo patient and an isolation patient cannot be assigned to the same nurse. Constraint (33) ensures that the maximum number of Step-down patients and DKA patients assigned to a nurse is three. In constraint (34), if a nurse is assigned one DKA patients, her maximum patient load is reduced by one patient. Constraint (35) restricts the number of DKA patients assigned to a nurse to one. Constraint (36) identifies if patients p and p_2 are assigned to the same nurse. Constraint (37) sets the sum of distance scores for nurse n based on the patients assigned to nurse n. Constraint (37) sets the sum of distance scores for nurse n based on the patients assigned to nurse n. Implicitly constraints that ensure positive variables and binary variables in constraints (38, 39, 40, and 41)

Model 1 (Formulation 5) assumes that the two objective measures are optimized over all nurses. That is, in setting all of the patient assignments to the nurses, the maximum total acuity scores that are minimized could be associated with nurse 1 and the maximum total distance scores that are minimized could be associated with a different nurse, say nurse 5. Therefore, to consider the case in which the maximum weighted sum of the total acuity scores and the total distance scores for any one nurse (i.e., the total workload for any one nurse) is minimized, a second formulation was developed and is presented in Formulation 6 (Model 2). In addition to the change in the objective function, two constraints, (30) and (31), were removed from Model 1 and constraint (41) was added in their place in Model 2. The resulting formulation is found below. In this formulation, B is a variable which is equal to the upper bound on the total workload score for any nurse (i.e., the maximum total workload score assigned to any nurse). All other notation uses the same definition as in Formulation 5.

Formulation 6 (Model 2):

$$minimize\ Z = B + q_3 \left[\sum_{n=1}^{N} \sum_{p=1}^{P} \sum_{p_2=p+1}^{P} Y_{np\,p_2} \right] \tag{42}$$

Subject to

$$\sum_{n=1}^{N} X_{np} = 1 \qquad \forall p \tag{43}$$

$$\sum_{p=1}^{P} a_p X_{np} = W_n \qquad \forall n \tag{44}$$

$$q_1 * W_n + M_n \leq B \qquad \forall n \tag{45}$$

$$\sum_{p=1}^{P} C_p X_{np} + \sum_{p=1}^{P} I_p X_{np} \leq 1 \qquad \forall n \tag{46}$$

$$\sum_{p=1}^{P} ST_p X_{np} + \sum_{p=1}^{P} K_p X_{np} \leq 3 \qquad \forall n \tag{47}$$

$$\sum_{p=1}^{P} X_{np} \leq U_n - \sum_{p=1}^{P} K_p X_{np} \qquad \forall n \tag{48}$$

$$\sum_{p=1}^{P} K_p X_{np} \leq 1 \qquad \forall n \tag{49}$$

$$X_{np} + X_{np_2} \leq 1 + Y_{np\,p_2} \qquad \forall n, \forall p, \forall p_2, p \neq p_2 \tag{50}$$

$$m_1 \sum_{p=1}^{P} s_p X_{np} + m_2 \sum_{p=1}^{P} sr_p X_{np} + m_3 \sum_{p=1}^{P} \sum_{p_2=p+1}^{P} v_{pp_2} Y_{npp_2} \leq M_n \quad \forall n \tag{51}$$

$$A, D \geq 0 \tag{52}$$

$$X_{np} \geq 0,1 \qquad \forall n, p \tag{53}$$

$$Y_{npp_2} \geq 0,1 \qquad \forall n, p, p_2 \tag{54}$$

$$W_n, M_n \geq 0 \qquad \forall n \tag{55}$$

Objective function (42) minimizes the maximum total workload score assigned to any nurse. This second component of the objective function works to enforce constraints (50) and (51) and increase the objective function by a negligible value. Constraint (43) ensures that every patient is assigned to one nurse. Constraint (44) gives the sum of the acuity scores of the patients assigned to nurse n. Constraint (45) sets the upper bound on the total work score for nurse n. Constraint (46) assures that a chemo patient and an isolated patient cannot be assigned to the same nurse. Constraint (47) ensures that the maximum number of step-down patients and DKA patients assigned to a nurse is three. In constraint (48), if a nurse is assigned one DKA patients, her maximum patient load is reduced by one patient. Constraint (49) restricts the number of DKA patients assigned to a nurse to one. Constraint (50) identifies if patient p and p_2 are assigned to the same nurse. Constraint (51) sets the sum of distance scores for nurse n based on the patients assigned to nurse n. Implicitly constraints that ensure positive variables and binary variables in constraints (52, 53, 54, and 55)

In the next chapter, the use and comparison of these two formulations is presented. In addition, computational results and nurse-to-patient assignments developed from these models are presented and discussed in relation to actual assignments constructed by CNs.

CHAPTER V

RESULTS AND DISCUSSION

To investigate the efficacy of the two mixed-integer programming models proposed in Chapter 4, Formulation 5 (Model 1) and Formulation 6 (Model 2), several test problems were evaluated. The test problems were constructed based on shift data taken from the General Medical/Oncology unit (GMU). For each test problem, the actual nurse-to-patient assignments developed by the CN were also collected for comparison to the model results. In order to solve the problem instances collected from GMU, the General Algebraic Modeling System 23.3 (GAMS, 2009) was used to translate each of the models into a form which could be evaluated using a professional mixed-integer programming solver. GAMS has a compiler that converts a model into the appropriate form for input to a mathematical programming solver. GAMS is particularly useful for complex modeling applications in that the models can be written concisely and adapted quickly. GAMS has the ability to interface with many solvers. The solver chosen for this work was GAMS/XPRESSMP. This solver is an adaptation of the XPRESS-MP Optimization Subroutine Library from FICO™ (FICO, 2009). Once the models were coded in the GAMS language, the files were sent to the *NEOS Server for Optimization* (NEOS, 2010) for input to the GAMS/XPRESSMP solver through a webpage submission tool (http://www-neos.mcs.anl.gov/neos/solvers/milp:XpressMP/GAMS.html#webform). The NEOS project was developed in conjunction with Argonne National Laboratory and is a free service giving unlimited access to many optimization solvers through its network

(Czyzyk et al., 1998). Examples of the two proposed models written in the GAMS language can be found in Appendix A. The files were submitted to the GAMS/XPRESSMP solver and the solution process was stopped when the relative gap fell below 10% (relative gap = (best estimate – best integer)/best estimate)). The results of the optimization were then sent via e-mail to the researcher.

Prior to analysis, AHP was used to determine the weights that were used in the models, as discussed in Chapter 4. The following parameter values were chosen for the two models based on the prior AHP analysis:

$q_1 = 15$; $q_2 = 1$; $q_3 = 0.000001$; $m_1 = 0.637$; $m_2 = 0.258$; and $m_3 = 0.105$.

The values for m_1, m_2, and m_3, were taken directly from the AHP weights developed for the distance measures in Table 13. The value of q_3 was set to a small value (penalty) that would not affect the overall objective function optimization of the nurse-to-patient assignments, but yet it was set large enough to enforce the constraints that contained the Y_{npp_2} binary variables. (These variables must be set to zero when they were not active in the model.) The first two parameters above, q_1 and q_2, were set after pilot testing of the models was completed. It was found that the optimal acuity scores assigned to the RNs on this unit ranged between 4 and 6 and the optimal distance scores for the RNs ranged between approximately 10 and 20. From the AHP analysis discussed in Chapter 4, the weighting of the acuity and distance scores was found to be in a ratio of 5:1. Therefore, based on the midpoint of the two ranges above, q_1 was set to 15 and q_2 was set to 1 (i.e., 15*5 = 75 is 5 times larger than 1*15 = 15).

For the following analyses, it important to recall that in Model 1 the objective function was to minimize the weighted sum of the maximum nurse acuity score and the maximum nurse distance score (which can be written as: $\min z = q_1 \max_{n \in N}\{W_n\} + q_2 \max_{n \in N}\{M_n\}$). In Model 2, the objective function was to minimize the maximum total workload of any nurse, where total workload was defined as the sum of the weighted acuity score and the weighted distance score for any nurse (which can be written as: $\min_{n \in N} \max\{q_1 W_n + q_2 M_n\}$). Thus, in Model 1, the objective function focused on the maximum workload of a composite nurse made up of one or more nurses on the unit, and in Model 2, the objective function focused on the individual nurse on the unit with the maximum total workload.

For data input into both Model 1 and Model 2, a spreadsheet model (score sheet) was developed to translate the actual patient acuity measures collected from GMU into the appropriate scoring values for input into the models. (A description of the calculation of these measures was given in Chapter 4.) An example of a score sheet is given in Table 16. Table 16 also displays two of the three distance measures needed for the model. Recall that these two measures are defined as the number of standard width patient rooms from a specific patient room to the patient room located directly across the hallway from the nearest supply room (or nursing station), plus one additional standard width unit that accounted for crossing the hallway. These measures represented an approximate standardized rectilinear distance between the two locations. The third distance measure, the distance between two assigned patient rooms, was similarly defined as the number of standard width patient rooms between the two assigned patient rooms.

For the shift illustrated in Table 16, the resulting nurse-to-patient assignment scores for the Actual (manual) CN constructed assignments, and the Model 1 and Model 2 assignments, are given in Table 17. This data was taken from a GMU day shift (denoted

Table 16

Acuity Scores and Distance Scores for the 29 Patients on Day 1 (day shift) – No DKA

Patient Room	Base	DKA	Step-down	High risk Med.	Lab Trending	Isolation	Specialty	Acuity Score	Dist. to supply room	Dist. to pod
450	1.0						0.1	1.1	5	2
451	1.0				0.2			1.2	4	1
452	1.0				0.2		0.1	1.3	3	1
453	1.0						0.1	1.1	2	1
454	1.0				0.2		0.1	1.3	1	2
455	1.0							1	2	3
456	1.0					0.2		1.2	3	2
457	1.0					0.2	0.1	1.3	4	1
458	1.0			0.4	0.2		0.1	1.7	3	1
459	1.0						0.1	1.1	2	2
460	1.0				0.2		0.1	1.3	1	3
461	1.0				0.2		0.1	1.3	1	3
462	1.0				0.2		0.1	1.3	1	2
463	1.0				0.2			1.2	3	2
464	1.0						0.1	1.1	4	3
465	1.0				0.2			1.2	5	4
466	1.0			0.4		0.2		1.6	6	4
467	1.0				0.2	0.2	0.1	1.5	4	3
468	1.0					0.2		1.2	3	2
469	1.0						0.1	1.1	2	1
470	1.0				0.2		0.1	1.3	1	2
471	1.0							1	1	3
472	1.0					0.2		1.2	2	2
473	1.0							1	3	1
474	1.0							1	4	1
475	1.0						0.1	1.1	5	1
476	1.0						0.1	1.1	6	1
477	1.0							1	7	2
478	1.0				0.2		0.1	1.3	8	3

Day 1) in which there was 7 RNs and 1 CN scheduled. Please note that the CN was assigned to one patient on this shift; however, the information related to the CN was placed at the bottom of the table and was not included in the summary statistics. This is

true of all subsequent tables that include the CN, since the CN will traditionally not care for more than one patient during the shift.

Table 17

Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Workload Scores (Acuity Scores and Distance Scores)

Assignment	Acuity Scores			Distance Scores		
	Actual	Model 1	Model 2	Actual	Model 1	Model 2
RN1	4.7	4.9	4.8	17.5	13.5	13.8
RN2	4.8	5.0	4.7	16.8	13.5	18.0
RN3	5.4	5.0	5.0	16.1	11.3	11.3
RN4	4.8	4.8	5.0	17.9	15.9	13.7
RN5	5.5	4.8	5.0	22.2	17.0	13.8
RN6	4.2	4.5	4.3	16.7	13.4	23.4
RN7	4.5	4.5	4.6	20.8	13.8	19.0
Mean	***4.8***	***4.8***	***4.8***	***18.3***	***14.1***	***16.1***
Std. Dev.	0.5	0.2	0.3	2.3	1.9	4.2
Range	1.3	0.5	0.7	6.1	5.7	12.1
CN	1.2	1.6	1.7	1.0	2.0	0.9

For both Model 1 and Model 2, the resulting assignments have mean RN acuity scores that are the same as the mean acuity score of the Actual assignments developed by the CN. In the case of the distance scores, both models achieved mean RN assignment scores that were considerably lower than the mean Actual distance score (while still maintaining the same mean acuity score). The mean distance score reduction was approximately 23% in Model 1 with respect to the Actual and approximately 12% in Model 2 with respect to the Actual. More importantly, with Model 1 and Model 2, the ranges and standard deviations of the acuity and distance scores among the RNs were greatly reduced over the scores of the Actual assignments. This lower variability implies a better balancing of workloads among the nurses in addition to a reduction in the total distance traveled over a shift.

Table 17 compared the two workload scores (acuity and distance) individually by nurse for the three assignment methodologies. In Table 18, a comparison of the total work ($q_1 W_n + q_2 M_n$) for each RN is presented for this same shift. In this table, Model 1's maximum total workload score is shown to be slightly higher than that of Model 2, yet as with the individual workload scores in Table 17, Model 1 had the lowest mean total workload for all nurses. The difference in Figure 18 was that Model 2 had the lowest variability measures of total workload among the three methods; however, as will be seen

Table 18

Total Nurse Workload Results for Day 1

Assignment	**Total Workload**		
	Actual	**Model 1**	**Model 2**
RN1	88.0	87.0	85.8
RN2	88.8	88.5	88.5
RN3	97.1	86.3	86.3
RN4	89.9	87.9	88.7
RN5	104.7	92.0	88.8
RN6	79.7	80.9	87.9
RN7	88.3	81.3	88.0
Mean	*90.9*	*85.8*	*87.7*
Std. Dev.	7.9	3.4	1.2
Range	25.0	8.1	3.0
Max	104.7	89.0	88.8
Min	79.7	80.9	85.8
CN	19.0	26.0	26.4

in subsequent figures, this was at the expense of requiring distant room assignments within a nurse's patient assignment. Still, while Model 1 and Model 2 are somewhat different in their statistics for total workload, they both performed significantly better than the Actual assignments constructed by the CN.

As a final numerical comparison for Day 1, Model 1 and Model 2 objective functions were used to calculate representative objective function values for all three resulting nurse-to-patient assignments. The values of this analysis can be found in Table 19. From this table, observe that Model 1's nurse-to-patients assignments fair very well with respect to both objective functions, unlike the other two methods. This was a common theme throughout the remaining analysis indicating that Model 1's assignments are more robust to the workload measures than are the other two methods. It also indicated that the balance among the nurses in the Model 1 assignments was found in both workload measures (acuity and distance), and not in acuity alone.

Table 19

Model 1 and Model 2 Objective Function Comparisons for Day 1

	Model 1 $z = 15\max(W_n) + \max(M_n)$	**Model 2** $z = \max(15W_n + M_n)$
Actual	104.7	104.7
Model 1	92.0	89.0
Model 2	98.4	88.8

To compare the physical layout of the nurse-to-patient assignments generated by the three methods for Day 1, each set of assignments was superimposed on the unit layout of GMU. The results are found in Figures 12 – 14. In these figures, the patient assignments for each nurse are identified with a different color. The colors also correspond to the color coding of assignments in Tables 17 and 18. Furthermore, note that the RN assignments are numbered sequentially in Tables 17 and 18, moving from right to left on the unit layout.

The Actual assignments constructed by the CN, and displayed in Figure 12, contained adjacent room assignments for all RNs. The CN’s assignment on this shift was room number 468, which is circled in red in Figure 12.

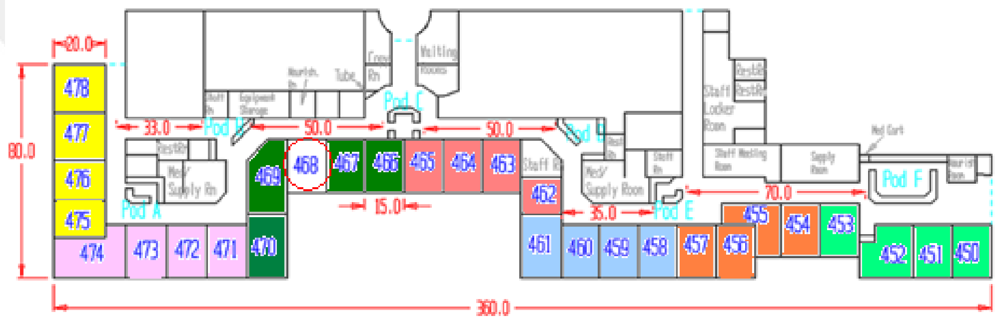

Figure 12. GMU Layout of Actual Patient Assignments Based on Day 1.

In the initial interviews with the GMU Unit Coordinator and CNs, it was indicated that adjacent room assignments for a nurse were most preferable. In subsequent interviews, following the presentation of the model assignments in comparison to the Actual assignments, the Unit Coordinator and CNs indicated that it was reasonable to assume that some non-adjacent room assignments could be considered to be as good as adjacent assignments. In their words, any assignment could be acceptable if rooms were close to each other and also close to the nearest supply room and nursing station. For example, in Figure 13, the RN5 patient assignment (rooms 465, 467, 469, 471) was deemed to be a desirable RN assignment since the patient rooms are relatively close together and close to both a supply room and a nursing station. Therefore, it was interesting to learn from the GMU staff that the Model 1 assignments could in fact outperform the assignments that were currently being generated by the CNs. Model 1's biggest advantage was its ability to balance the distance traveled by the RNs over the course of the shift while maintaining the balance of the assigned patient acuities.

In Figure 13, observe that the CN's room assignment for Model 1 was room number 466. This room is not located adjacent to a supply room or a nursing station. (Recall that pod C was not used for nursing activities and was located at the entrance to the unit.) Thus, based on the objective function of Model 1, it is easy to reason why this room was assigned to the CN (who was only assigned one patient during the shift).

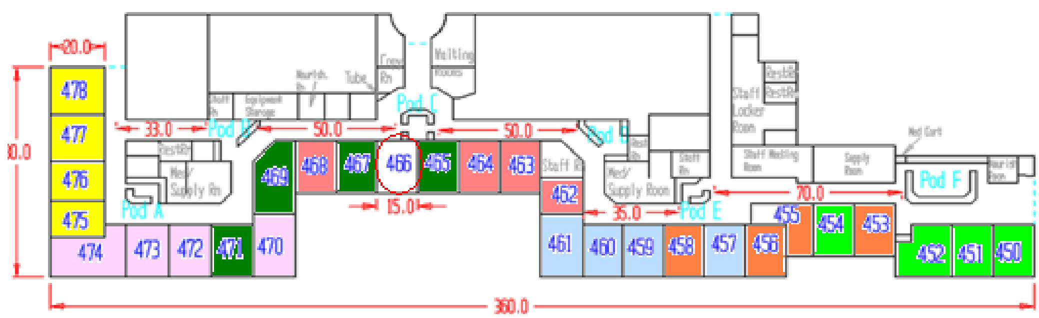

Figure 13. GMU Layout of Model 1 Patient Assignments Based on Day 1.

Figure 14 shows the RN assignments constructed by Model 2. The CN's assigned room was room 458. With the exception of the third RN assignment (RN3) which consisted of adjacent rooms (room numbers 459 to 462), many of the RN assignments had rooms that were significantly more spread out from one another than with the other two methods. Recall that the average RN acuity scores resulting from Model 2 was the same as for the other two methods (see Table 17) in this example. Yet, the variability of the RN distance scores approximately doubled that of the other two methods, in terms of both the range and the standard deviation (see Table 17). So while the total workload measures recorded for the three methods displayed in Table 18 indicate that Model 2 may perform as well or better than the other two methods, many of the resulting assignments were undesirable from an implementation standpoint. This implies that while the RN assignments generated by Model 2 may be balanced overall for total workload, the appearance of assignments that will require higher total travel distances during a shift may not be perceived as balanced by the nursing staff; even though these nurses are carrying a much lower total patient acuity load to balance the total workload.

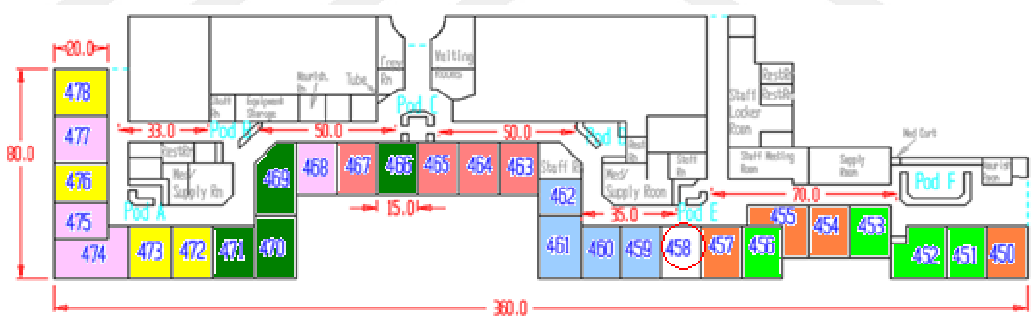

Figure 14. GMU Layout of Model 2 Patient Assignments Based on Day 1.

Acuity Scores for a second day shift (denoted Day 2) gathered from GMU are presented in Table 20. The patients on this shift included one patient that was designated as a DKA patient.

As with the data from the previous shift, the resulting nurse-to-patient assignments for Day 2 were compared based on nurse total acuity scores, nurse total distance scores, and nurse total workload scores. Results of the two models and the Actual assignments constructed by the CN are given in Tables 21 and 22.

Table 20

Acuity Scores and Distance Scores for the 29 Patients on Day 2 (day shift) – One DKA

Patient Room	Base	DKA	Step-down	High risk Med.	Lab Trending	Isolation	Specialty	Acuity Score	Dist. to supply room	Dist. to pod
450	1.0							1.0	5	2
451	1.0				0.2			1.2	4	1
452	1.0				0.2		0.1	1.3	3	1
453	1.0						0.1	1.1	2	1
454	1.0							1.0	1	2
455	1.0						0.1	1.1	2	3
456	1.0					0.2		1.2	3	2
457	1.0						0.1	1.1	4	1
458	1.0			0.4	0.2	0.2	0.1	1.9	3	1
459	1.0				0.2			1.2	2	2
460	1.0							1.0	1	3
461	1.0	1.0			0.2		0.1	2.3	1	3
462	1.0					0.2	0.1	1.3	1	2
463	1.0				0.2		0.1	1.3	3	2
464	1.0						0.1	1.1	4	3
465	1.0							1.0	5	4
466	1.0				0.2			1.2	6	4
467	1.0					0.2		1.2	4	3
468	1.0						0.1	1.1	3	2
469	1.0							1.0	2	1
470	1.0				0.2		0.1	1.3	1	2
471	1.0				0.2		0.1	1.3	1	3
472	1.0							1.0	2	2
473	1.0							1.0	3	1
474	1.0							1.0	4	1
475	1.0			0.4	0.2		0.1	1.7	5	1
476	1.0				0.2		0.1	1.3	6	1
477	1.0				0.2	0.2	0.1	1.5	7	2
478	1.0				0.2		0.1	1.3	8	3

Table 21

Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Workload Scores (Acuity Scores and Distance Scores)

Assignment	Acuity Scores			Distance Scores		
	Actual	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**
RN1	4.6	4.6	4.5	17.5	14.4	22.0
RN2	4.4	5.2	5.3	16.8	20.3	18.1
RN3	6.4	5.6	5.9	17.2	11.3	8.4
RN4	4.7	4.7	4.4	17.9	10.9	31.3
RN5	4.9	5.2	4.5	21.2	13.3	35.9
RN6	4.0	4.4	4.7	23.7	13.4	32.9
RN7	5.8	5.5	5.1	20.8	12.6	26.2
mean	***5.0***	***5.0***	***4.9***	***19.3***	***13.7***	***25.0***
std dev	0.8	0.5	0.6	2.6	3.1	9.6
range	2.4	1.2	1.5	7.0	9.4	27.5
CN	1.2	1.7	1.7	2.0	2.4	1.4

The nurse-to-patient assignments for Day 2 indicated similar trends among the three assignment methods when compared to Day 1, even with the addition of one DKA patient. The average acuity scores for the three methods were again almost the same, with the range and standard deviation of the acuity scores for Models 1 and 2 being lower than the scores for the Actual assignments. This is expected since the objective functions in both models places a much higher weight on optimizing the acuity scores. With respect to distance scores, Model 1 again had the lowest mean and standard deviation scores and Model 2 had the largest standard deviation. The largest noticeable changes going from Day 1 to Day 2 were the large distance scores and the range of scores that resulted from Model 2. This gives additional evidence to the superiority of Model 1 with respect to balancing the distances traveled by nurses over a shift. In comparison to the Actual assignments on this shift, the mean distance score was reduced by approximately 30% by Model 1 and was increased by approximately 30% by Model 2.

Table 22

Total Nurse Workload Results for Day 2

Total Workload			
Assignment	**Actual**	**Model 1**	**Model 2**
RN1	86.5	97.6	89.5
RN2	82.8	98.3	97.6
RN3	113.2	95.3	96.9
RN4	88.4	81.4	97.3
RN5	94.7	83.8	101.9
RN6	83.7	79.4	103.4
RN7	107.8	95.1	102.7
Mean	93.9	88.1	98.5
Std. Dev.	12.1	7.8	4.8
Range	30.4	18.9	13.8
Max	113.2	98.3	103.4
Min	82.8	79.4	89.5
CN	20.0	27.9	26.9

The total workload of each nurse was also compared and the results are presented in Table 22. For Day 2, Model 1 was shown to have a much lower mean total nurse workload. And while Model 2 had the lowest standard deviation in total workload, indicating a better balance between the nurses, Model 2's minimum total workload was higher than Model 1's mean total workload. Thus, the slight improvement in the standard deviation with Model 2 was again at the expense of all nurses on the unit.

A final numerical comparison was completed on Day 2 by using the Model 1 and Model 2 objective functions to calculate the objective function values for each of the three resulting nurse-to-patient assignments. The values of this analysis are found in Table 23. From this table, observe that Model 1's nurse-to-patients assignments had the lowest values for both objective functions. This again indicates that Model 1's assignments were more robust than the others, and by looking at a composite nurse rather than an individual nurse, overall workload can be driven down further for all nurses.

Table 23

Model 1 and Model 2 Objective Function Comparisons for Day 1

	Model 1 $z = 15\max(W_n) + \max(M_n)$	**Model 2** $z = \max(15W_n + M_n)$
Actual	119.7	113.2
Model 1	104.3	98.3
Model 2	124.4	103.4

For comparison of the physical layout of the nurse-to-patient assignments generated by the three methods on Day 2, each set of assignments was superimposed on the unit layout of GMU. The results are found in Figures 15 – 17. In these figures, the patient assignments for each nurse are identified with a different color. The colors also correspond to the color coding of assignments in Tables 21 and 22, as described previously for Day 1.

The Actual assignments constructed by the CN are displayed in Figure 15. The nurse assignments were very similar to those seen on Day 1. With the expectation of the assignments for RN6 (rooms 469, 472, 473, and 474) and RN5 (rooms 467, 468, 470, and 471), all nurse assignments contained adjacent rooms. With the exchange of one room, observe that RN5 and RN6 would also consist of adjacent rooms. So it appears that during this shift the CN attempted to keep each nurses assigned patient rooms as close to one another as possible. (The CN's assignment on this shift was room number 466, which is different from Day 1 (room 468).)

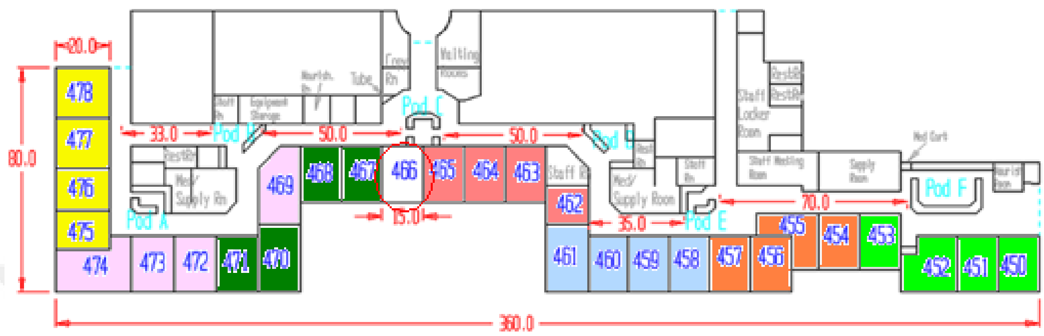

Figure 15. GMU Layout of the Actual Patient Assignments Based on Day 2.

In Figure 16, two of the RN assignments are adjacent room assignments (RN1 and RN4). Additionally, assignment RN6 (rooms 468, 471, 472, and 473) and RN5 (rooms 466, 467, 469, and 470) would be adjacent assignments with the exchange of one room and assignment RN5 is an adjacent room assignment with the exception of one room (room 458). Assignments RN2 (rooms 450, 452, 454, and 458) and RN1 (rooms 451, 453, 455, and 456) do have rooms that are spread farther apart than the other nurse assignments; however the rooms at the ends of both assignments are close to a nursing station and a supply room or supply cart. (In the cases of RN1 and RN2, the nurse may choose to keep their patient charts at different nursing stations.) The CN's room assignment was room number 478.

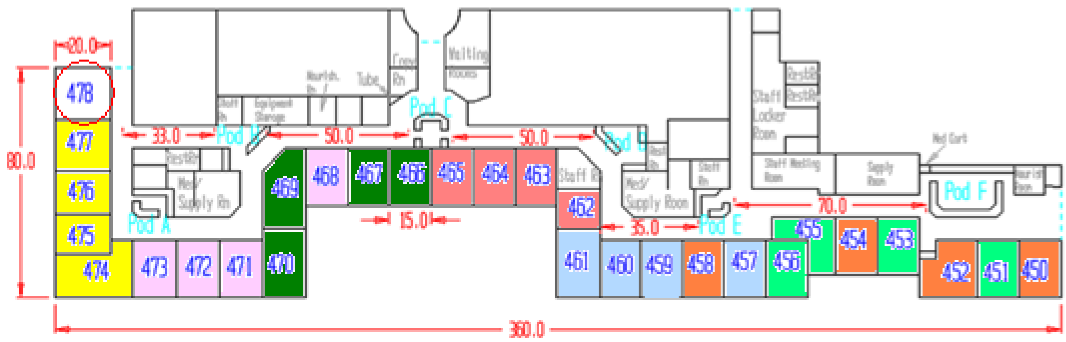

Figure 16. GMU Layout of Model 1 Patient Assignments Based on Day 2.

Figure 17 is the depiction of the Day 2 nurse assignments constructed by Model 2. Except for the adjacent room assignments for RN3 (rooms 460, 461, 462, and 463), all other assignments were widely spread over the unit. This includes one assignment in which two patient rooms are 15 standard width units away from each other (RN5). Upon review by the GMU CNs, it was noted that this set of assignments would be very difficult to implement on the unit.

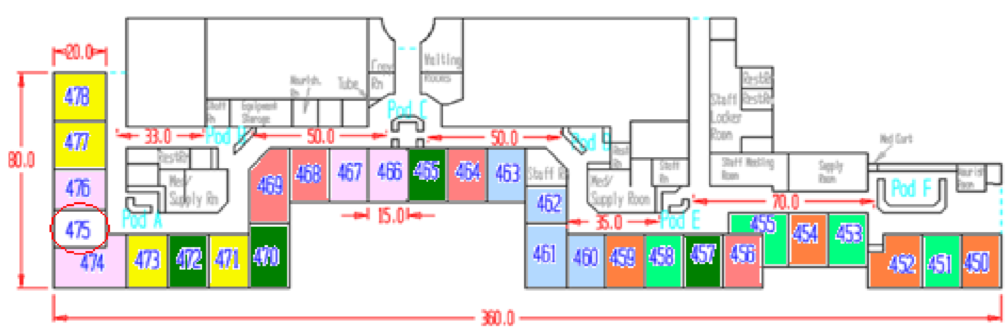

Figure 17. GMU Layout of Model 2 Patient Assignments Based on Day 2.

As a further means of comparing the three assignment methods, nurse-to-patient assignments for 7 day shifts were constructed using Models 1 and 2, and the Actual assignments for these shifts were recorded. The results of these 7 days are displayed in terms of acuity scores in two tables, Tables 24 and 25, and in terms of distance scores in the Tables 26 and 27.

Table 24

(Days 1-3: Day Shifts) Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Acuity Scores

	Day 1			Day 2			Day 3		
	Acuity Scores			**Acuity Scores**			**Acuity Scores**		
Assignment	**Actual**	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**
RN1	4.7	5.0	4.3	4.9	5.1	4.2	5.0	5.2	4.7
RN2	4.8	4.5	4.7	5.9	4.4	4.8	5.4	5.2	5.3
RN3	5.4	4.8	5.0	4.5	5.0	4.7	4.8	5.3	5.4
RN4	4.8	5.0	4.8	4.5	5.1	5.0	4.3	5.0	5.0
RN5	5.5	4.5	4.6	5.3	4.7	5.0	4.7	4.8	4.7
RN6	4.2	4.9	5.0	5.0	4.8	5.1	5.5	4.8	4.7
RN7	4.5	4.8	5.0	4.0	5.0	5.0	5.8	4.9	5.4
Mean	4.8	4.8	4.8	4.9	4.9	4.8	5.1	5.0	5.0
Std. Dev.	0.5	0.2	0.3	0.6	0.3	0.3	0.5	0.2	0.3
Range	1.3	0.5	0.7	1.9	0.7	0.9	1.5	0.5	0.7

Statistical analyses were performed on the data in Tables 24 and 25 (acuity scores) and then Tables 26 and 27 (distance scores) using the statistical software MINITAB, Version 15 (Minitab, 2009). An ANOVA analysis based on a randomized block design was performed in each case. In these analyses, the acuity scores and then the distance scores were set as the response variable, and days (shifts) were used as the

Table 25

(Days 4-7: Day Shifts) Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Acuity Scores

Assig.	Day 4			Day 5			Day 6			Day 7		
	Acuity Scores			Acuity Scores			Acuity Scores			Acuity Scores		
	Act.	Model 1	Model 2	Act.	Model 1	Model 2	Act.	Model 1	Model 2	Act.	Model 1	Model 2
RN1	4.5	5.4	4.4	6.4	5.6	5.9	4.8	5.1	4.8	4.8	5.1	4.7
RN2	3.6	4.3	4.9	4.6	4.4	4.7	4.9	4.9	4.7	4.8	4.8	5.0
RN3	4.3	4.4	4.6	5.8	4.6	5.3	4.1	4.9	5.1	5.0	5.2	4.8
RN4	5.4	4.3	4.2	4.0	4.7	4.5	5.3	5.0	4.8	4.8	4.8	4.8
RN5	4.4	4.9	5.3	4.9	5.2	5.1	4.7	4.9	4.9	4.7	5.0	4.9
RN6	4.2	4.7	4.7	4.7	4.7	4.4	5.1	5.1	5.3	5.4	5.0	5.1
RN7	3.3	4.8	4.5	4.4	5.5	4.4	5.3	4.8	5.1	5.1	4.5	5.1
Mean	4.2	4.7	4.7	5.0	5.0	4.9	4.9	5.0	5.0	4.9	4.9	4.9
Std. Dev.	0.7	0.4	0.4	0.8	0.5	0.6	0.4	0.1	0.2	0.2	0.2	0.2
Range	2.1	1.1	1.1	2.4	1.2	1.5	1.2	0.3	0.6	0.7	0.7	0.4

Table 26

(Days 1-3: Day Shifts) Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Distance Scores

Assignment	Day 1			Day 2			Day 3		
	Distance Measures			Distance Measures			Distance Measures		
	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2
RN1	17.5	11.3	23.4	17.9	17.5	19.8	21.3	18.3	24.8
RN2	16.8	13.4	18.0	22.2	17.6	20.4	16.8	13.8	15.3
RN3	16.1	15.9	13.7	17.5	17.1	19.0	16.7	17.5	13.8
RN4	17.9	13.5	13.8	16.7	13.6	16.5	17.5	13.8	11.6
RN5	22.2	13.8	19.0	16.1	16.2	15.2	16.1	13.7	13.4
RN6	16.7	13.5	11.3	20.8	17.1	13.6	16.8	18.0	23.7
RN7	20.8	17.0	13.8	16.8	13.8	13.8	20.8	14.5	14.8
Mean	18.3	14.1	16.1	18.3	16.1	16.9	18.0	15.7	16.8
Std. Dev.	2.3	1.9	4.2	2.3	1.7	2.8	2.1	2.1	5.2
Range	6.1	5.7	12.1	6.1	4.0	6.8	5.2	4.5	13.2

Table 27

(Days 4-7: Day Shifts) Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Distance Scores

	Day 4			**Day 5**			**Day 6**			**Day 7**		
	Distance Measures			**Distance Measures**			**Distance Measures**			**Distance Measures**		
Assign.	**Act.**	**Model 1**	**Model 2**	**Act.**	**Model 1**	**Model 2**	**Act.**	**Model 1**	**Model 2**	**Act.**	**Model 1**	**Model 2**
RN1	21.1	12.1	14.0	17.2	11.3	8.4	16.1	11.4	16.5	17.5	11.1	18.7
RN2	7.4	12.4	19.2	17.5	13.4	32.9	17.5	11.3	14.0	16.8	10.5	13.8
RN3	16.7	11.4	12.9	20.8	14.4	18.1	20.8	9.0	13.7	20.8	13.8	18.5
RN4	20.8	8.8	14.0	23.7	10.9	22.0	23.7	13.0	18.2	16.7	9.8	9.7
RN5	17.5	11.7	17.8	21.2	20.3	26.2	21.2	12.9	18.5	16.8	13.8	11.7
RN6	16.7	12.3	11.5	17.9	13.3	35.9	17.9	15.5	9.1	16.1	11.8	11.1
RN7	10.1	10.2	15.2	16.8	12.6	31.3	16.8	10.5	15.5	17.9	11.5	12.7
Mean	15.8	11.3	14.9	19.3	13.7	25.0	19.2	12.0	15.1	17.5	11.8	13.8
Std. Dev.	5.2	1.3	2.7	2.6	3.1	9.6	2.8	2.1	3.2	1.6	1.5	3.5
Range	13.7	3.6	7.6	7.0	9.4	27.5	7.6	6.5	9.3	4.7	4.0	9.1

blocks. (A 5% significance level was assumed for all tests.) The ANOVA results are presented in Table 28 for the acuity scores and Table 29 for the distance scores. Each figure also includes the results of Post Hoc analysis using Tukey Tests. Tukey Test results are reported in the form of homogenous subsets in these figures.

At a 5% significance level, evidence of a statistical difference was not found between the mean acuity scores assigned to the nurses by Method 1, Method 2 and the Actual assignments set by the CN ($p = 0.818$; see Table 28). This finding was consistent with the previous findings.

Table 28

ANOVA and Tukey Homogeneous Subsets for Comparison of Assignment Methods for Acuity Scores

c	*df*	*SS*	*MS*	*F*	*p*
Model	2	0.0702	0.0351	0.21	0.809
Day	6	3.4271	0.5712	3.45	0.003
Error	138	22.8317	0.1654		
Total	146	26.3290			
Means: *Actual = 4.8 Model 1 = 4.9 Model 2 = 4.9*					
Tukey Homogeneous Subsets: (Actual, Model 1, Model 2)					

Table 29

ANOVA and Tukey Homogeneous Subsets for Comparison of Assignment Methods for Distance Scores

Source	*df*	*SS*	*MS*	*F*	*P*
Model	2	549.58	274.79	19.34	0.000
Day	6	420.93	70.15	4.94	0.000
Error	138	1961.00	14.21		
Total	146	2931.50			
Means: *Actual = 18.0 Model 1 = 13.5 Model 2 = 16.9*					
Tukey Homogeneous Subsets: (Model 1) (Model 2, Actual)					

At a 5% significance level, there was a statistical difference (p = 0.000) found between the mean distance scores assigned to the nurses by Method 1, Method 2 and the

Actual assignments set by the CN. The Tukey homogeneous subsets indicate that Model 1 assignments have a significantly lower mean distance score than both Model 2 assignments and the Actual assignments. Therefore, it can be inferred from these findings, and the illustrative examples discussed above, that the set of nurse-to-patient assignments generated by Model 1 are more desirable to both the Model 2 assignments and the Actual CN assignments in terms of the magnitude of the workload assigned to each nurse and in the balancing of the total workload among the nurses on a shift.

As discussed earlier in this document, a CN typically takes approximately 30 minutes prior to the start of each shift to construct nurse-to-patient assignments. Thus, the amount of time it takes to construct assignments with either Model 1 or Model 2 was of great concern. From the log files generated by GAMS during the optimization of the nurse-to-patient assignments, it was possible to monitor the changes in the best integer solutions over time through termination of the solution process. From these logs, the objective function values associated with three specific times were recorded. The times considered were 5 minutes or less, 10 minutes or less, and termination. The reason for the "or less" statement in the first two times was to cover the cases when the program reaches the 10% relative gap criterion and halts the program prior to reaching the 5 and/or 10 minute recording times. The results for this analysis are found in Table 30 for Model 1 and in Table 31 for Model 2.

From Tables 26 and 27, it can be seen that at the 10 minute mark, both Model 1 and Model 2 reached the optimum value, or within 5% of the optimal value, in all cases. Therefore, it is plausible that a CN would have sufficient time to use either methodology to make nurse-to-patient assignments at the start of a shift. Therefore, not only do the models produce feasible solutions, but they also produce the needed solutions in a reasonable amount of time.

Table 30

Best Integer Objective Function Value by Time for Model 1 over 7 Day Shifts.

Day	Model 1 Objective Function Values				
	Optimal (10% gap)	**At 5 min and less**	**At 10 min and less**	**% difference between optimal and at 5 min or less**	**% difference between optimal and at 10 min or less**
1	92.0	98.1	93.9	6.2%	2.0%
2	94.1	99.0	94.1	5.0%	0.0%
3	97.8	108.1	99.1	9.5%	1.4%
4	81.4	97.6	81.4	16.6%	0.0%
5	104.3	104.3	104.3	0.0%	0.0%
6	92.0	96.4	92.0	4.6%	0.0%
7	91.8	108.4	94.6	15.3%	3.0%

Table 31

Best Integer Objective Function Value by Time for Model 2 over 7 Day Shifts.

Day	Model 2 Objective Function Values				
	Optimal (10% gap)	**At 5 min and less**	**At 10 min and less**	**% difference between optimal and at 5 min or less**	**% difference between optimal and at 10 min or less**
1	88.8	93.6	88.8	5.1%	0.0%
2	88.0	100.5	92.4	12.4%	4.8%
3	95.8	96.1	95.8	0.3%	0.0%
4	88.3	100.6	90.0	12.2%	1.8%
5	103.4	103.4	103.4	0.0%	0.0%
6	92.0	94.9	92.0	3.1%	0.0%
7	90.5	93.8	90.5	3.5%	0.0%

The results discussed to this point in the document have considered GMU day shifts only. Since the night shifts typically have either five RNs and one CN or six RNs working during this shift, additional analysis was performed to determine if the Model 1 assignment methodology would continue to outperform the other two methods. Because there may be as few as five RNs on the unit during the night shift, it is necessary, and unit practice, to change the restriction in which *a nurse can have no more than one isolation or chemo patient assigned to them during a shift* to *a nurse can have no more than two isolation or chemo patients assigned to them during a shift.*

The data for three night shifts was collected. As with the day shift, comparisons of the Actual assignments set by the CN, Model 1 assignments, and Model 2 assignments were completed in terms of total acuity scores and total distance scores. The data for the acuity scores and the distance scores are summarized in Tables 32 and 33, respectively. In these tables, there were six RNs on the unit for Days 1 and 2 and only five RNs on the unit for Day 3.

Table 32

(3 Night Shifts) Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Acuity Scores

	Day 1			**Day 2**			**Day 3**		
	Acuity Scores			**Acuity Scores**			**Acuity Scores**		
Assignment	**Actual**	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**
RN1	5.4	6	6.2	5.8	5.4	5.9	6	7.2	7.5
RN2	6.7	5.6	6.4	5.1	6.3	6.1	8.1	7.5	7.2
RN3	6.6	6	5.2	6.1	5.8	5.8	7.5	7.3	7.1
RN4	6.1	5.5	5.8	5.6	5.6	6.1	7.5	7.5	7.2
RN5	4.4	5.9	5.8	5.9	5.8	5.1	7.2	6.8	7.3
RN6	6.7	6.2	5.8	6.6	6.2	6.1			
Average	6.0	5.9	5.9	5.9	5.9	5.9	7.3	7.3	7.3
Std. Dev.	0.9	0.3	0.4	0.5	0.3	0.4	0.8	0.3	0.2
Range	2.3	0.7	1.2	1.5	0.9	1.0	2.1	0.7	0.4

Table 33

(3 Night Shifts) Comparison of Actual Assignment Versus Model 1 and Model 2 Assignments in Terms of Distance Scores

	Day 1			**Day 2**			**Day 3**		
	Distance Measures			**Distance Measures**			**Distance Measures**		
Assignment	**Actual**	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**	**Actual**	**Model 1**	**Model 2**
RN1	20.9	24.5	24.4	23.7	22.7	24.6	23.7	31.8	27.0
RN2	23.7	9.0	19.8	17.2	24.4	23.1	49.7	29.3	31.8
RN3	23.1	22.3	30.2	23.1	20.1	25.7	51.6	34.4	33.3
RN4	25.7	20.3	31.9	25.7	23.0	22.8	49.3	34.0	32.5
RN5	16.0	19.5	33.2	16.0	20.3	31.7	54.0	33.3	26.9
RN6	27.7	24.6	26.5	27.7	24.4	22.2			
Average	22.8	20.0	27.7	22.2	22.5	25.0	45.7	32.6	30.3
Std. Dev.	4.1	5.8	5.1	4.7	1.9	3.5	12.4	2.1	3.1
Range	11.7	15.7	13.3	11.7	4.3	9.5	30.3	5.1	6.4

In general, because of the larger patient loads imposed on the nurses during the night shift (due to fewer nurses being scheduled on the unit), the acuity and distance scores for the nurses were higher than for the day shift. Fortunately, during the night shift many patients sleep and fewer non-patient care activities typically occur in the patient rooms. Also, during these patient rest periods, some nurses try to bundle their direct patient care activities into fewer episodes in the patients' rooms, in an effort to disturb the patient less often during sleep. If patient care activities do not slow down on the unit during the night shift, then one or more float nurses can be called to the unit.

From Tables 32 and 33, there appears to be less disparity in the workload measures between the three methods on the night shift. In part, this may be a result of fewer available feasible assignments due to fewer nurses being scheduled on the unit. While there is less disparity in general, it is important to note that Method 1 always had either the lowest mean distance score or the smallest standard deviation for the distance scores. Thus, Model 1 is again shown to outperform the other two methods with respect to distance traveled by the nurses on the unit. More interesting are the acuity scores. With the night shift, both Model 1 and Model 2 assignments have smaller standard deviations than those of the Actual assignments. This highlights the difficulty of optimizing even one workload measure manually and supports the need for a decision tool to aid in this nurse-to-patient assignment process.

After modeling all of the above shifts, the resulting nurse-to-patient assignments were shown to the CNs and the unit coordinator on GMU to enlist their expert judgments into the validation process. It was concluded that although both Model 1 and Model 2 developed feasible assignments which when compared to the Actual assignments were always better in the case of Model 1 and sometimes better in the case of Model 2, Model 1 gave “very good” results in terms of both acuity scores and distance measures. Model 1 also presented nurse-to-patient assignments that were reasonable and very easy to implement. In conclusion, they felt that Model 1 results would be perceived as equitable among the staff. These findings gave further proof that the developed models were able to capture the true nurse-to-patient assignment problem on this unit. It also showed that this extremely complex health care problem can be captured mathematically and gives hope for reproducing similar work on other hospital units in the future.

CHAPTER VI

CONCLUSION AND FUTURE DIRECTIONS

Summary of Study

The work in this study investigated the task of constructing nurse-to-patient assignments on a single hospital unit. This task requires the charge nurse (CN) on the unit to estimate the total nursing work requirements that must be covered by the scheduled nursing staff, and then divide this work equably among the nurses. The division of work comes through the specific assignment of individual patients to individual nurses. Work completed by the nurses is comprised of unit-related activities in addition to direct and indirect patient care activities. It was observed that as the number of required patient assignments on a unit increased, the more difficult it was to resolve competing workload measures manually. Thus, the CNs responsible for setting nurse-to-patient assignments typically focused their assignment efforts on what was recognized as the most important workload measure, patient acuity. Other measures of workload were resolved through broad efforts. For example, to reduce shift travel distance, the CN may attempt to build nurse assignments consisting of adjacent rooms. And with respect to meeting nurse preferences for patients, the CN may try to assign patients to the nurses who have cared for them on their previous shift. While this may be a very good practice from a continuity of care standpoint, it can lead to very heavy workloads and an imbalance of work among the nurses.

In this study, two models were created which captured the rules and restrictions of the nurse-to-patient assignment problem. Further, these models incorporated the logic and measures used by CNs when setting nurse-to-patient assignments on the unit. To construct the resulting models, two workload measurement scoring systems were developed. The first measured workload with respect to direct and indirect patient care activities completed by a nurse during a shift. The second measured workload in terms of the distance traveled by a nurse on a shift, given the location of the nurse's assigned patient rooms. The distance measures were developed based on a single patient room environment and leveraged finding regarding frequently traveled paths from a direct observation study of nurses on this unit. The total workload scoring system used in this study was a composite score developed from the weighted sum of the acuity and distance scores for each nurse. The weighting schemes for the total workload system was developed using an Analytical Hierarchy Process methodology through consultation with the CNs. To balance nurse-to-patient assignment workloads among the nursing staff, the objective functions of the two models developed were based on either minimizing the weighted sum of the maximum total patient acuity scores assigned to any nurse and the maximum total distance scores assigned to any single nurse (Model 1) or minimizing the maximum total workload score assigned to any nurse (Model 2). Here, total workload for a nurse was calculated as a weighted sum of the nurse's total acuity score and total distance score. The constraint sets for both models were nearly identical and consisted of several restrictions which defined feasible nurse-to-patient assignments, such as ensuring that each patient was assigned to exactly one nurse and that the nurses were not assigned to more patients than were allowed by their unit and hospital policies.

One of the two models (Model 1) was shown to have the capability to build assignments that were both subjectively and objectively rated as good as, or better than, those developed manually by the charge nurses (CNs) on the same unit. In addition, the developed acuity scoring system and the distance scoring systems showed promise for use in other scheduling and patient care activities on this unit. In conclusion, the methodologies used to construct the workload measurement system and the nurse-to-patient assignment solution process can be used to develop similar tools for other hospital units.

Key Findings

1. The models presented in this work were shown to accommodate for workload within a nurses assignment in terms of total assigned patient acuity and distance traveled over a shift. This work was the first to define a component of nurse workload based on key distances traveled by a nurse during a shift and which are defined by the nurse’s patient room assignments. The resulting measures used in the innovative distance scoring system were consistent with studies that had investigated the total distance traveled by nurses during a shift (Butt et al, 2004; Hendrich et al, 2008). This work is particularly important for hospitals that are adopting the single patient room (private room) care environment. This type of layout is becoming more popular nation-wide with new hospital construction and renovation. The basis for this type of layout comes out of research that has focused on patient healing environments and on the reduction of nosocomial infections rates within hospitals. (A recent literature

review concerning this research area was written by Glind et al. (2007)). While single patient rooms may be a step forward for patient care, it poses another question as to their affect on the nurse. That is, with a ward or a semi-private room environment, the patients to whom a nurse is assigned are often more closely located, and thus, less time and energy needs to be expended to complete movements between patients. In past studies, nursing workload considerations for assigning nurses to patients have concentrated on direct and indirect patient care needs with little consideration for the other activities performed by a nurse during a shift. With single patient rooms, these other activities may be placed even farther away from a nurse's patient care areas than were seen in the ward and the semi-private environments. Thus, the distance traveled, or energy expended, over a shift is a very important factor to consider when setting a nurse's workload and could impact the safety of both the nurse and the patient.

2. Acuity systems can be used for many planning and recording purposes, but unfortunately they do not always focus on the specific activities that drive a nurse's workload during a shift. A new acuity scoring system customized to reflect the direct and indirect patient care needs required for making nurse-to-patient assignments was developed for the unit under investigation in this study. Specifically, an AHP methodology was used to construct an acuity system for a General/Oncology Unit through consultation and input from those responsible for the making the nurse-to-patient assignments. The measures used in the system were existing measures currently collected by the nurses on the unit and which had been used in one form or another in the nurse-to-patient assignment process. In some respects, this approach

removed the researcher from the determination of what constituted representative measures of workload, since the chosen measures had been previously validated through years of nursing practice on this unit. The main benefit that this methodology offered was in the determination of the relative and consistent importance of each measure in making the final assignment determinations. The resulting measurement system helped to remove the subjectivity of an individual CN's interpretation of the importance of a measure in making the nurse-to-patient assignments. It also quantified the diverse components of the acuity of a patient and combined them into one intuitive score. This last piece was crucial to the ability to combine the optimization of the acuity measures and the distance measures into a single solution process. Furthermore, the developed methodology for the construction of the acuity scoring system can be repeated on other units in an effort to capture unit-specific workload measures and their corresponding importance in making nurse-to-patient assignments.

3. The model developed in this study balanced total workload of the nurses through two competing objectives, total patient acuity assigned to a nurse during a shift and the sum of key distances assigned to a nurse during a shift. Two approaches to balancing the total workload were considered. The first approach minimized the weighted sum of the maximum total patient acuity scores assigned to any nurse and the maximum total distance scores assigned to any nurse. And the second approach considered the minimization of the maximum total workload score assigned to any nurse, where total workload was defined by the weighted sum of the total acuity scores and the total distances scores assigned to the nurse. While the total workload of all nurses was

equal to or below the objective function measure in Model 2, it was found that the quality and variability of total work load was better balanced using the Model 1's approach. And while the acuity and distance measures are not independent in Model 1, the model has the flexibility to build a composite nurse workload which minimizes the average workload assigned to all nurses and which reduces the variability between the workload of all nurses. In fact, the standard deviation of the total workload of the nurses using Model 1 was shown to be drastically lower than that of Model 2 and the actual assignments created by the CNs on the unit.

4. As noted above, the resulting schedules produced by Model 1 always found solutions which had acuity and distance measures lower than those constructed manually by the CNs responsible for nurse-to-patient assignment. More importantly, the lower variability among the two objective measures indicated a better balance of workload among all nurses. This could also lead to a sense of fair treatment among the staff. It is hoped that this would in turn lead to higher job satisfaction among the nurses. And with the introduction of similar specialized assignment models for other units, this may lead to higher retention rates of nursing staff within the hospital and ultimately marketing opportunities and strategies for the recruitment of future nursing staff.
5. Model 1 and Model 2 have additional features which can be exploited.
    a. *Fulfill nurse preferences for specific patients*. Since the models solve for N sets of nurse-to-patient assignments, nurse preferences for certain patients can be met for at least one and possible all patients. This can be accomplished since the nurse-to-patient assignments are constructed without knowledge of which nurse will be assigned to a resulting set of patients.

Thus a particular assignment generated by the models which contains the patients that a nurse has requested can be assigned to that nurse.

b. *Pre-assignment of a set of patients to the same nurse*. If an RN requests a set of patients which does not comprise a complete shift assignment for that nurse, then prior to running the models the appropriate X_{np} and Y_{npp_2} variables are fixed to the value of one to force that set of patients to be assigned to the same nurse *n*. The remaining assignments would then be optimized among the *N-1* available nurses, with consideration for the fixed assignments and their fixed workload scores. The pre-assignments are particularly useful for specifying the patient(s) that will be cared for by the CN. If a complete nurse assignment is pre-assigned prior to running the models, then the assigned patients and patient rooms are removed from the model input and *N* is reduced by one unit. The remaining assignments are optimized among the *N-1* available nurses.

Future Work and Possible Research Directions

The following recommendations for future work are made based on the results and the conclusion of the study.

1. The methodology used to optimize nurse-to-patient assignments in this study was shown to be quite successful and produced excellent results that can be implemented on the GMU. The next proposed step for this work is to develop a better interface for Model 1, which will aid a CN in the nurse-to-patient

assignment process. To begin, discussions with the GMU staff will be needed to determine the required interface features for successful implementation on the unit. Possible features may include an acuity scoring tool that is integrated into the input and submission module and a graphical or tabular output for the display of the resulting patient assignments. And to illustrate the balance in the assignments to the nursing staff, it is envisioned that the acuity, distance and total workload scores would be displayed with the associated assignments.

2. With the development of the acuity scoring system and the distance scoring system in this work, it may be possible to develop one or more constructive heuristic methods based on the additive objective function of the optimization model. This in turn may lead to a methodology that is easier for all CN to understand and use on the unit. For example, the initial nurse assignments for all nurses on the unit may begin with adjacent room assignments. The associated acuity scores could then be calculated for each nurse assignment. From this point on, swaps between nurse assignments could be completed to remove violations in patient and unit constraints and to improve the balance of the acuity scores.
3. With the success on the studied unit, an investigation to determine whether there are other units similar to GMU in the hospital that could benefit directly from this work will be considered. In particular, the identification of units in which the nurse-to-patient assignments are the responsibility of one individual, such as a charge nurse, will be the first units considered.
4. AHP, as implemented in this work, was extremely important to the success of the resulting methodologies. AHP played three distinctive roles in differentiating and

defining nurse workload. It was used to identify the importance placed on the two identified workload measures (acuity and distance) on a single patient room unit in defining total nurse workload. It was used to build an acuity scoring system by identifying the importance of several quantitative and qualitative patient care activities and patient characteristics in defining workload in terms of indirect and direct patient activities. And finally, AHP was used to combine key distances that are correlated with the total distance a nurse will travel over the duration of a shift and then predict a nurse's workload due to movements on the unit given the nurse's assigned patient rooms. In each case, AHP needed the input of the decision makers on the unit to be successful. While these three tasks could be repeated on other units, AHP may also be successful as an approach to other unit related tasks. For example, AHP can possibly be used to determine the appropriate staffing ratios of a unit by looking at the importance of the state and federal regulations, financial impact, and nurse retention factors. AHP can possibly be used in hospital-wide supply chain decisions. And finally, AHP can possibly be used to decide upon the amenities that are available to a patient in a patient room.

5. While AHP was used to derive the weights used in the models in this work, other methods may also be of benefit and will be investigated for further refinement of Model 1 and its associated workload measurement systems. One very promising method that will be considered is a conic scalarization method. Conic scalarization methods for combining many complementary and conflicting objectives have been used with success in the past (Gasimov et al., 2007).

Scalarization methods combine several objectives into a single objective such that the resulting optimization problem is able to find Pareto or properly efficient solutions of an multi-objective problem (Gasimov et al.,2007).

6. Since the work in this study focused on a single patient room environment, it is uncertain as to whether the distance traveled by a nurse has a similar impact on a nurse's total workload in a ward or semi-private room environment. For example, since a nurse's patients may be located closer together on a ward than on a single patient room unit, acuity scoring alone may be sufficient to predict nurse workload during a shift. And if not, by how much do the various types of units differ in terms of the importance of distance as a measure of nurse workload. The researcher is also extremely interested in how the impact of distance traveled by a nurse during a shift may differ in hospitals in other countries, such as Turkey. Therefore, future work will include a comparison of this work to unit layouts in hospitals in Turkey. This will begin with making appropriate changes to Model 1 for application in a general medical unit in a Turkish Hospitals with a similar nursing staff and patient care environment.

Appendix A

GAMS Code For Model 1

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   p patients  / 450*478 /
   n nurses    / RN1*RN7, CN / ;

alias (p, p2);

sets pairs(p,p2)
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a(p) acuity weight of patient p
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452 1.3
453 1.1
454 1
455 1.1
456 1.2
457 1.1
458 1.9
459 1.2
460 1
461 2.3
462 1.3

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k(p) patient p is DKA patient
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457 0
458 0
459 0
460 0
461 0
462 0
463 0
464 0
465 0
466 0
467 0
468 0
469 0
470 0
471 0
472 0
473 0
474 0
475 0
476 0
477 0
478 0 /

u(n) upper bound of nurses' workload
/ RN1 5
RN2 4
RN3 4
RN4 4
RN5 4
RN6 4
RN7 4
CN 1 /

sr(p) distance traveled from patient room to nearest supply room
/ 450 5
451 4
452 3
453 2
454 1
455 2
456 3
457 4
458 3
459 2
460 1
461 1
462 1
463 3
464 4
465 5
466 6
467 4
468 3
469 2
470 1
471 1
472 2
473 3
474 4
475 5
476 6
477 7
478 8 /

s(p) distance traveled from patient room to pod
/ 450 2
451 1
452 1
453 1

```
      454  2
      455  3
      456  2
      457  1
      458  1
      459  2
      460  3
      461  3
      462  2
      463  2
      464  3
      465  4
      466  4
      467  3
      468  2
      469  1
      470  2
      471  3
      472  2
      473  1
      474  1
      475  1
      476  1
      477  2
      478  3  / ;

Parameter v(p,p2) distance traveled between patient p & p2 ;

        loop(p,
          loop(p2,
              v(p,p2) = sqrt((value(p)-value(p2))*(value(p)-value(p2)))
               )
           );


Binary Variables
        x(n,p)  !=1  patient p is assigned to nurse n and pod q & = 0 otherwise
        y(n,p,p2) !=1  patient p and patient p2 assigned to nurse n & = 0 otherwise ;
*         d(p,q)    !=1  patient p is assigned to pod q & = 0 otherwise ;
Variables
        W(n) ! = actual workload of nurse n
        M(n) ! = assigned traveled distance
        A ! = maximum assigned acuity
        D ! = maximum distance traveled
        Z ! = workload;
Positive variables W,M;
```

```
Equations
assign(p)        Every patient is assigned to one nurse
workload(n)      The sum of the acuity scores of the patients assigned to nurse n
workload3(n)     The upper bound on the maximum assigned sum of acuity scores given
                   to any nurse.
distance(n)      The upper bound on the maximum assigned distance score given to any
                 nurse
chemo(n)         Chemo patient and isolated patient cannot be assigned to a nurse at the
                 same time
dka(n)           If a nurse has one DKA patient her load will be reduced one
stepdown(n)      If a nurse has one step-down pt and 1 dka pt her max load is 3
dkaload(n)       Maximum 1 DKA patient can be assigned to a nurse
twopt(n,p,p2)    Identify if patients p & p2 are assigned to the same nurse
dist3(n)         Limit the distance traveled by nurse from patient room to pod
objfunc          Composite Objective function;

assign(p)..      sum(n, x(n,p))  =e= 1 ;
workload(n)..    sum(p, a(p)*x(n,p)) =e= W(n);
workload3(n)..   W(n) =l= A;
distance(n)..    M(n) =l= D;
chemo(n)..       sum(p, c(p)*x(n,p))+ sum(p, i(p)*x(n,p)) =l= 1;
dka(n)..         sum(p, x(n,p)) =l= u(n) - sum(p, k(p)*x(n,p));
stepdown(n)..    sum(p, st(p)*x(n,p))+ sum(p,k(p)*x(n,p))=l= 3;
dkaload(n)..     sum(p, k(p)*x(n,p)) =l= 1;
twopt(n,p,p2)$pairs(p,p2)..  x(n,p) + x(n,p2) =l= 1 + y(n,p,p2);
dist3(n)..       0.105*sum(p, s(p)*x(n,p))
                  + 0.258*sum(p, sr(p)*x(n,p))
                  + 0.637*(sum((p,p2)$pairs(p,p2), v(p,p2)*y(n,p,p2)))
                  =e= M(n);

objfunc..         Z =e= 15*A + D +0.000001*sum((n,p,p2)$pairs(p,p2), y(n,p,p2));

Model Assignment /all/;
option Iterlim = 1000000000;
option Reslim = 6000000;
option optcr= 0.1;
Solve Assignment using mip minimizing  Z ;
display x.l;
display y.l;
```

Appendix B

Letter For HSIRB

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