Journal of Biomedical Informatics 64 (2016) 192–206

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Modeling nurse-patient assignments considering patient acuity and travel distance metrics

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ARTICLE INFO

Article history:
Received 13 May 2016
Revised 7 October 2016
Accepted 8 October 2016
Available online 11 October 2016

Keywords:
Workload metrics
Balancing workload
Nurse-patient assignments

ABSTRACT

Balancing workload among nurses on a hospital unit is important for the satisfaction and safety of nurses and patients. To balance nurse workloads, direct patient care activities, indirect patient care activities, and non-patient care activities that occur throughout a shift must be considered. The layout of a hospital unit and the location of a nurse's assigned patients relative to other resources on the unit are also important factors in achieving workload balance. In most hospitals, a unit charge nurse is responsible for the shift assignment of patients to nurses based on experience and past practices. The nurse-patient assignment process is also often a manual process in which the charge nurse must sort through multiple decision criteria in a limited amount of time. In this paper, a methodology for the construction of balanced nurse-patient workload assignments is proposed. Through the illustration of this methodology new scoring metrics are developed using measures currently available on, or from, the hospital unit. It was demonstrated that the complex scheduling problem can be captured. While the methodology was illustrated for a scheduling problem commonly encountered on a hospital unit, the approach can be adapted to other workforce scheduling problems in which measures of workload are required and composed of elements imposed by the work environment, variability within the required tasks, and a measurable perception of the relative intensity of the work elements.

1. Introduction and background

Professional and skilled labor within an organization is often a scarce resource and in some U.S. sectors there is potential for significant shortages. Thus, the appropriate allocation of these scarce resources are important for the efficiency and efficacy of the organization. While there are many organizations that contain sets of scarce employee groups, hospitals are organizations which have many levels of highly skilled professional staff. One of the most prevalent and important groups among the hospital professionals are the registered nurses.

The Registered Nurse (RN) population in the U.S. decreased from 3,063,162 in 2008 to 2,711,500 in 2012 [1]. The American Association of Colleges of Nursing (AACN) reported that the shortage of RNs in the U.S. is projected to grow to 260,000 by 2025 [2]. Nurses continue to express concerns over the consequences of staff shortages. Buerhaus et al. found that approximately 75% of the participating RNs assumed that shortages would present a major problem for the quality of their work life, the quality of patient care, and the time spent with patients [3]. To combat excessive workloads, researchers have looked at means to eliminate nonproductive movements and balance hospital unit activities among the nursing staff through better planning [4].

While the elements of nurse planning in a hospital can be defined in many ways, Punnakitikashem suggested that nurse planning (or nurse workforce planning) has four distinct stages: budgeting, scheduling, rescheduling, and assignment [4]. Punnakitikashem defines each of these four stages as follows. *Budgeting* consists of strategically planning for the number of nurses needed during a fiscal year based on the predicted needs of each hospital unit [4]. *Scheduling* is the process of assigning individual nurses to a set of shifts over a given time horizon, such as a 28-day period. This stage is what many define as nurse rostering. *Rescheduling* involves making revisions to the current schedule due to staffing and patient load changes on the unit. This activity is completed by a unit coordinator approximately ninety minutes before the shift begins. Finally, *assignment*, or *nurse-patient assignment*, is typically the responsibility of the unit charge nurse who has approximately thirty minutes to assign each nurse (as the primary caregiver) to a set of unit patients at the start of a shift. The focus

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http://dx.doi.org/10.1016/j.jbi.2016.10.006
1532-0464/

of this work is on this final stage of nurse planning. To date, nurse-patient assignments have received very little attention in the literature even though they have a direct and immediate impact on nurses' activities during a shift.

Nurse-patient assignments are typically allocated based on estimated direct patient care requirements with little consideration for other activities that must be completed throughout a shift. In an effort to improve upon previous assignment methodologies, new measures and metrics were considered in this study to reduce and balance demands placed on nurses through the assignment of required activities.

Although the literature has addressed nurse scheduling for more than 40 years, nurse-patient assignments have received little attention. Among the works published, Bostrom and Suter investigated the decision-making process surrounding nurse-patient assignment [5]. Shaha and Bush considered nurse-patient assignments under the condition that each nurse was assigned the same number of patients on a unit [6]. Rosenberger et al. developed an integer programming model with an objective function that minimized 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 one time epoch until the next time epoch [7]. Mullinax and Lawley developed a mathematical programming approach for achieving better workload balance based on patient acuity in a neonatal intensive care unit [8]. These researchers considered nursery environments that could be divided into zones, separated by aisles, walls, or floors. The objective was to minimize the sum of the range of acuities over all zones. Punnakitikashem et al. developed a stochastic integer-programming model to assign nurses to patients by attempting to balance direct patient care activities [9]. And finally, Sir et al. developed a model that considered patient acuity metrics and the nurses' perceived workload [10]. In their study, a survey was completed by 45 nurses from oncology and surgery units in which the nurses rated the impact of patient acuity indicators on their perceived workload.

Most nurse-patient assignment models have focused on balancing patient acuity measures. This focus on patient acuity concentrates workload measures on direct patient care activities. While this is very important for the care of the patient, it does not necessarily take into account all of the activities comprising a nurse's workload.

The objective of this research was to present a methodology for the construction of balanced nurse-patient assignments based on the specific characteristics of the hospital unit. The main elements of this methodology consist of: (1) identifying nurse workload measures specific to a hospital unit's unique characteristics, (2) measuring the perceived level of importance of each workload measure, and (3) developing mathematical models for the construction of balanced nurse-patient assignments. In the following sections, the elements of the methodology will be illustrated through the use of a real-world example of assigning workload to nurses for a specific hospital unit described in Section 2.

2. Methodology, data collection, analysis and modeling

2.1. Study hospital unit

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 used to make assignments, historical data on bed census, patient acuity, and applicable nurse-patient ratios. At the time of this study, GMU employed a total of 45 full-time nurses, 26 of which were chemo-certified nurses. Nurses typically work three 12-h 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.

GMU consists of one long hallway with 29 single patient rooms. Fig. 1 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 (450 to 478) on the periphery of the layout.

There are six nursing stations, referred to as Pods A, B, C, D, E, and F, and three medical/supply rooms located on this unit. Patient charts can be moved from station to station to accommodate a nurse's assignment, but they typically remain at one nursing station throughout a shift. To isolate chemo patients, the staff preferably locates these patients nearest to nursing station F, which has a medical cart, a nourishment room, and a supply room.

GMU runs at patient census capacity and rarely has an empty bed. Nurses on GMU are assigned three to five single patient rooms during a shift. Typically, this means that a nurse is assigned to four rooms on the day shift and five rooms on the night shift. Additionally, the charge nurse (CN) will often take a one-patient

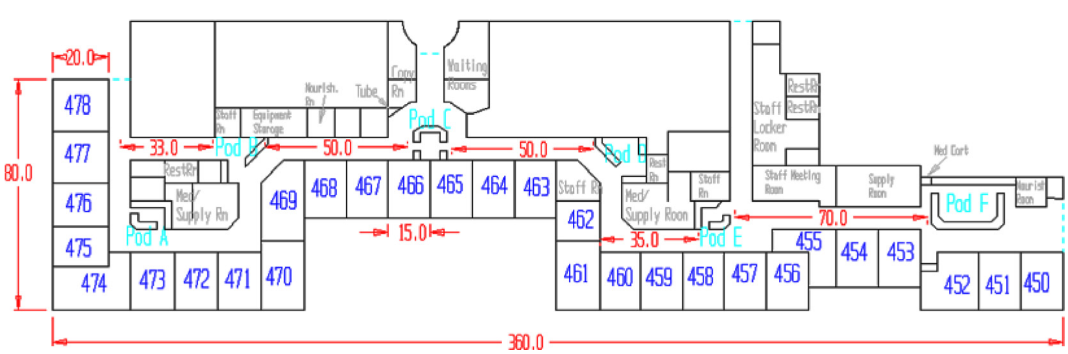

Fig. 1. Facility layout of GMU.

assignment on the day shift. At the beginning of each shift the CN assigns a set of patients to each RN. The CN has approximately 30 min to prepare these assignments prior to the shift start. Since there can be a large variation in patient needs on this unit, the assignment process can be complex and the manual development of balanced nurse-patient assignments can be difficult.

2.2. Identifying the important components of workload – work measurement and correlation

To identify the activities that comprise a nurse's workload during a shift, a direct observation work measurement study was completed on the GMU. In this study, data were collected through continuous direct observation via PDA devices equipped with customized work measurement software. With these devices a trained observer could time up to five simultaneous activities, record the location of each activity, and write additional notes, if needed. The nurse being followed and the observer both wore pedometers to record the distances traveled throughout a shift. Data collection commenced following approval of the study by the university and hospital Human Subjects Institutional Review Boards. In addition to the data collected through direct observation, historical unit data was collected 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 had been used in staffing/acuity determinations.

Through pilot testing of the direct observation data collection process over a 12-week period, 45 distinct nursing activities were defined and assigned to one of ten general categories. It was during this time that the observers were also trained. Following the pilot testing, direct measurement of the 45 nursing activities were collected by continuously following consenting nurses during their shift for a total of 276 h. During this time, over 45,000 individual nursing activities were observed. This data was exported and stored in spreadsheets where it was subsequently cleaned and then analyzed using statically software. With respect to each of the observations, the activity time and the location of the activity were recorded. Tables 1–3 summarize the relevant portion of the general category results of the work measurement study. Included in these tables are measures of the activity frequency by category, activity time, and common travel paths between activities that RNs encounter during their 12-h shifts.

In Table 1 it is shown that indirect nursing care activities take more time during a shift than do the direct nursing care activities. Indirect nursing care activities include patient care activities that do not require direct interaction with the patient. Examples include: planning and documenting, calls, and medicine preparation. Conversely, direct care activities require some degree of interaction with the patient. Examples of direct nursing care activities include: dispensing medication, hygiene, and IV care. In addition, there is a notable percentage of time that a RN is: (i) *In-Transit* (traveling between unit locations), (ii) completing non-patient *Unit-Related* activities, and (iii) searching for a missing or out-of-stock item (*Fetching*).

While the percentage of time associated with moving between locations on the unit (*In-Transit*) may not be as large as the direct and indirect care activities (see Table 1), Table 2 shows that the number of times that *In-Transit* activities occur constitutes a larger percentage of the total number activities during a shift than do *Direct Care* activities. *Fetching* is another example of an activity that may not take much time during a shift (Table 1), but *Fetching* does occur at a significant frequency during a shift (Table 2).

From Table 3, we see that the three top routes that a RN travels during a 12-h shift are (i) between a patient room and a nursing station, (ii) between a nursing station and a supply room, and (iii) between a patient room and a supply room. The table shows that there is some travel between patient rooms, but the more common occurrence is to travel to (from) a patient room from (to) a nursing station or a supply room.

In another study on this same hospital unit (GMU), Butt et al. showed that nurses were traveling between 3.0 and 10.5 miles per 12-h shift and that the distance traveled was correlated to their assigned patient load and location [11]. The authors identified key distances that were highly correlated to the total distance traveled by the nurses. These included the distances between a nurse's assigned patient room and: (i) the nearest nursing station; (ii) the nearest supply room; and (iii) another assigned patient room.

Information from these two studies was used in this work to identify key RN activities and movements that impact a RN's workload on this unit. The use of this information was incorporated into the resulting scoring metrics, which are described in subsequent sections.

Table 1
Percentage of RN time spent in activity category during a 12-h shift.

Activity Category	Percentage of 12-h shift spent on activities in category
Indirect Care	45.9%
Direct Care	19.3%
Personal Time	13.4%
In-Transit	6.3%
Unit-Related	6.2%
Fetching	1.8%
Other	7.1%

Table 2
Percentages of RN occurrences of activities by category.

Activity Category	Percentage of activity occurrences by category
Indirect Care	34.5%
In-Transit	24.9%
Direct Care	12.4%
Fetching	9.6%
Unit-Related	7.1%
Personal Time	5.5%
Other	6.0%

Table 3
Most frequently traveled paths by RNs during a 12-h shift.

Travel Path	Percentage of RN shift movements attributed to Travel Path
Between Patient Room and Nursing Station	34.5%
Between Nursing Station and Supply Room	15.3%
Between Patient Room and Supply Room	11.4%
Between Two Nursing Stations	10.3%
Between Nursing Station and Hall	5.7%
Between Two Patient Rooms	5.6%
Between Patient Room and Hall	4.5%
Other	12.7%

2.3. Collection of available workload measures and surrogates

The hospital in this study uses an electronic form to collect an extensive amount of patient information. From this information a standardized hospital-wide acuity level is calculated and logged. The acuity level calculation is the same for all units in the hospital. Since there is little differentiation between GMU patients based solely on their hospital-wide acuity levels, the CN's struggle to use the hospital acuity levels in making nurse-patient assignments. The current practice is to use specific acuity information that are recorded on two unit-specific patient information sheets. These sheets included special care needs of patients, including key items such as: Isolation, Specialty, High-Risk Medication (Chemo, Heparin, Morphine, etc), Diabetic Ketoacidosis (DKA), Lab Trending, and Step-Down. The term "Specialty" is used for several conditions including fall precautions, skin precautions, and remote telemetry. DKA is a state of inadequate insulin levels resulting in high blood sugar and the accumulation of organic acids and ketones in the blood. The "Lab Trending" category was used for several patient attributes such as: low red blood cell counts and platelets, patients with electrolyte imbalances, monitoring bleeding times, renal failure, dialysis and others. Step-Down patients on this unit require more nursing interactions than the average GMU patient. These patients are often being trained on how to care for their wounds once they leave the hospital. From this information, the CNs and unit coordinators compiled a list of important care measures needed to make useful nurse-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. Reconciling the opinions and the importance of each measure among the CNs in a consistent manner was imperative for the automation of the process.

Because the GMU CNs 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 Figs. 2a and 2b, 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.

2.4. Quantitative and perceived scores of workload – analytic hierarchy process

Measures for scoring nurse-patient assignments were developed through consultation with the CNs. In addition to acuity, the CNs were asked to consider the distance traveled to complete workload tasks during a shift when balancing the workload among nurses. Many Multi-Criteria Decision Making (MCDM) methods require the use of weights to distinguish between the importance of competing measures, such as in the case of acuity and distance traveled. The Analytic Hierarchy Process (AHP) is one of the MCDM techniques that can combine qualitative and quantitative factors into the overall evaluation of alternatives [12]. In AHP, the decision making criteria are structured as a hierarchy and then relative ratio scales are derived through pairwise comparisons of their importance. AHP uses a fundamental scale that captures an individual's preferences with respect to quantitative and qualitative values [12]. This scale ranges from 1 to 9 and is shown in Table 4.

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. 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) 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.

AHP was used in this study to obtain the relative weights (or importance) of the acuity measures and the distance measures considered when making specific nurse-patient assignments on the GMU [13]. CNs were asked to rank workload attributes and alternatives through pairwise comparisons using the AHP methodology. Expert Choice 11.5 was used to obtain the resulting ranked weightings [14]. Expert Choice is an easy-to-learn software which administers the steps of AHP. Expert Choice has a graphical tool input structure, which allows the novice user to quickly compare decision making criteria and scenarios. There are advantages of using this software. It aids the decision maker by quickly completing the tedious numerical computations required in AHP, checking for consistency within and between users with respect to pairwise comparisons, and allowing users to employ a sophisticated mathematical technique with no mathematical modeling background. Ishizaka and Labib [15], Barford [16] and Yunus et al. [17] gave additional examples of the use of this software in their work.

As stated earlier, total workload balance must consider activities beyond direct patient care activities, such as indirect patient care activities and unit-related activities. These latter activities are affected by the layout of the hospital unit. The previous study conducted on GMU [11] 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 using AHP. The three distances and their associated AHP weights are as follows: Distance traveled by nurses between a patient room and the nursing station, the supply room or another patient room were considered as surrogates' measures for these activities and were based on the previous unit studies, staff interviews, and the paper written by Hendrich [18]. AHP was used to compare and score patient room assignments with respect to two main criteria, acuity and travel distance. The distance measure had three sub-criteria:

- Distance between two patient rooms.
- Distance between a patient room and the nearest supply room.
- Distance between a patient room and the nearest nursing station.

Expert Choice 11.5 was again used to obtain the weights for these measures following the comparison of the patient rooms [14]. Overall weights of acuity and distance, including the sub-criteria weights, are given in Table 5. (The higher the weight, the higher the perceived workload importance associated with that criterion or sub-criterion.)

CNs' ranking process was done by the software Expert Choice 11.5. At the beginning of the process CN was introduced about AHP and the software. Three distance sub criteria under the main

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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478														

Fig. 2a. Patient chart sheet.

distance criterion (Table 5), which were found based on the pilot data findings, and five acuity sub criteria under the main acuity criterion (Table 5) were used in the AHP and each CN was asked to rank the attributes through pair-wise comparisons individually. We used a fundamental scale to capture individual preferences of CNs with respect to quantitative and qualitative values. When all the comparisons were done, CNs rated acuity approximately five times more important $(0.833/0.167 = 4.988)$ than the distance measure when constructing nurse-patient assignments. Within the distance sub-criteria, the CNs viewed the distance between patient rooms as the most important distance measure when assigning patients to nurses. Additionally, the distance between a patient room and the nearest supply room was considered by the CNs to be approximately three times $(0.26/0.10 = 2.6)$ more impactful on a nurse's workload than the distance between an assigned patient room and the nearest nursing station.

2.5. Scoring: standardizing AHP weights for use in workload modeling and comparing alternatives

Based on current practices in the GMU, the following items were considered in the development of the workload model:

- A CN determines which nurse is assigned to each patient on the unit at the beginning of the shift.
- During a shift, if a patient is admitted to a room from which a patient was discharged, the nurse assignment to that room will care for the newly admitted patient.
- 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.
- The patient care workload of a DKA patient is equivalent to caring for two non-DKA patients.

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

Fig. 2b. Staffing/acuity determination sheet.

In addition, current practices dictated the following constraints:

- A nurse can only be assigned one DKA patient on a shift.
- A nurse's maximum patient load should be reduced by one if the nurse is assigned a DKA patient.
- A nurse can be assigned to no more than three Step-Down patients on a shift; or no more than two Step-Down patients on a shift if the nurse is also assigned to a DKA patient.
- There are always a sufficient number of chemo-certified nurses on a shift. Therefore, a patient who requires a chemo-certified nurse can always be assigned a chemo-certified nurse.
- A chemo (High Risk Medication) patient and an isolated patient cannot be assigned to the same nurse.

When constructing assignments, the CNs work to balance the total workload by (1) distributing the acuity of the unit patients as uniformly as possible; and (2) minimizing the effect of other

Table 4
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

Table 5
Overall AHP weights of *Acuity* and *Distance* measures and sub-criteria measures.

Acuity	0.833
DKA	0.39
Step-down	0.35
High Risk Medication	0.13
Lab Trending	0.06
Isolation	0.04
Specialty	0.03
Distance	0.167
Patient room to patient room	0.64
Patient room to supply room	0.26
Patient room to nursing station	0.10

required duties that occur on the unit. To achieve this goal, the objective function considered in the proposed model was to minimize the maximum sum of patient acuity scores assigned to any nurse during a shift and to minimize the maximum sum of weighted distance scores assigned to any nurse during a shift. The weighting of acuity and distance in the objective function were based on the AHP findings. In addition, the AHP sub-criteria acuity scores in Table 5 were standardized relative to the largest attribute weight (DKA) for use in the GMU acuity scoring system as shown in Table 6. (Each acuity weight was divided by 0.39).

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 6 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 1.90, which is the base score of 1 plus the additional acuity score of 0.90. 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 0.39. The resulting additional acuity scores are listed in Table 6.

Table 6
AHP weights and standardized acuity attribute scores (above base-level) by patient attribute.

Attribute	AHP Acuity Weight	Standardized Attribute Score
DKA	0.39	1.00
Step-Down	0.35	0.90
High Risk Medication	0.13	0.33
Lab Trending	0.06	0.15
Isolation	0.04	0.10
Specialty	0.03	0.08

The scoring of a patient's acuity was completed as follows. A GMU patient that had no additional acuity attribute given in Table 6 was assigned a base acuity score of 1, which is considered equal to caring for one "base-score" GMU patient. The additional scores for the remaining acuity attributes are taken from the standardized scores in Table 6. An example of the patient scores for a single shift on GMU is given in Table 7. The resulting scores were used as a parameter input for the objective function in the model with respect to acuity.

A GMU patient is never designated as both a DKA and Step-Down patient, which implies that the maximum acuity score that can be accumulated by a single patient is

$$1 + 0.90 + 0.33 + 0.15 + 0.1 + 0.08 = 2.56$$

That is, if a patient is assigned the attributes of *DKA*, *High Risk Medication*, *Lab Trending*, *Isolation*, and *Specialty*, the patient's acuity score will be equal to the base-level score plus the sum of all additional attribute acuity scores.

In addition to acuity scoring, distance scores were also developed for the proposed models based on a standardized distance score with a unit length equal to the distance between two adjacent patient rooms. For example, going from room 450 to room 452 is equal to two standard widths or a distance score of 2 (See Fig. 1). A from-to matrix of distances (scores) was developed for use in this work. The resulting symmetric matrix contained the distance scores between all patient rooms, supply rooms, and nursing stations on the unit. These same standardized distances were used by Butt et al. in their development of regression models to predict the distance traveled by nurses and the energy expended by nurses over a 12-h shift [10].

2.6. Model formulation

Based on the acuity and distance scores previously discussed, mathematical models were developed to construct equitable assignments of patients to nurses for the GMU. The decision variables, parameters, and formulations follow.

Indices

$P = total\ number\ of\ patients\ on\ the\ unit\ during\ the\ shift$
$p = patient\ index,\ \ p = 1, 2, 3, \ldots, P$
$r = alias\ of\ patient\ index,\ \ r = 1, 2, 3, \ldots, P$
$N = total\ number\ of\ nurses\ working\ on\ the\ unit\ during\ the\ shift$
$(NincludestheChargeNurse)$
$n = nurse\ index,\ \ n = 1, 2, 3, \ldots, \mathrm{N}$

Decision variables

$$x_{np} = \begin{cases} 1\ if\ patient\ p\ is\ assigned\ to\ nurse\ n \\ 0\ otherwise \end{cases}$$

$$y_{npr} = \begin{cases} 1\ if\ patients\ p\ and\ r\ are\ assigned\ to\ nurse\ n \\ 0\ otherwise \end{cases}$$

$W_n = total\ acuity\ score\ assigned\ to\ nurse\ n\ during\ the\ shift$
$M_n = total\ distance\ score\ assigned\ to\ nurse\ n\ during\ the\ shift$

(*continued*)

Indices
A = maximum total acuity score assigned to any nurse during the shift
D = maximum total distance score assigned to any nurse during the shift
B=maximum total work load score (total acuity score + total distance score) assigned to any nurse during a shift
Parameters
Q_1 = weight of acuity score in objective function
Q_2 = weight of distance score in objective function
R_1 = weight of supply room measure in distance score
R_2 = weight of nursing station measure in distance score
R_3 = weight of patient room measure in distance score
A_p = acuity score of patient p
$C_p = \begin{cases} 1 \text{ if patient } p \text{ is a chemo patient} \\ 0 \text{ otherwise} \end{cases}$
$I_p = \begin{cases} 1 \text{ if patient } p \text{ is an isolation patient} \\ 0 \text{ otherwise} \end{cases}$
$K_p = \begin{cases} 1 \text{ if patient } p \text{ is a DKA patient} \\ 0 \text{otherwise} \end{cases}$
$S_p = \begin{cases} 1 \text{ if patient } p \text{ is a Step} - \text{Down patient} \\ 0 \text{ otherwise} \end{cases}$
U_n = upper bound on the number of patients that can be assigned to nurse n
SR_p = distance score from patient room p to nearest supply room
NS_p = distance score from patient room p to nearest nursing station
PT_{pr} = distance score between patient rooms p and r

Model 1:

$$\text{Minimize } Z = Q_1 A + Q_2 D \tag{1}$$

Subject to

$$\sum_{n=1}^{N} x_{np} = 1 \quad \forall p \tag{2}$$

$$\sum_{p=1}^{P} A_p x_{np} = W_n \quad \forall n \tag{3}$$

$$W_n \leqslant A \quad \forall n \tag{4}$$

$$M_n \leqslant D \quad \forall n \tag{5}$$

$$\sum_{p=1}^{P} C_p x_{np} + \sum_{p=1}^{P} I_p x_{np} \leqslant 1 \quad \forall n \tag{6}$$

$$\sum_{p=1}^{P} x_{np} \leqslant U_n - \sum_{p=1}^{P} K_p x_{np} \quad \forall n \tag{7}$$

$$\sum_{p=1}^{P} K_p x_{np} \leqslant 1 \quad \forall n \tag{8}$$

$$\sum_{p=1}^{P} S_p x_{np} + \sum_{p=1}^{P} K_p x_{np} \leqslant 3 \quad \forall n \tag{9}$$

$$x_{np} + x_{nr} \leqslant 1 + y_{npr} \quad \forall n, \forall p, \forall r, p \neq r \tag{10}$$

$$R_1 \sum_{p=1}^{P} NS_p x_{np} + R_2 \sum_{p=1}^{P} SR_p x_{np} + R_3 \sum_{p=1}^{P} \sum_{r=p+1}^{P} PT_{pr} y_{npr} = M_n \quad \forall n \tag{11}$$

$$x_{np} \in 0,1 \quad \forall n, p \tag{12}$$

$$y_{npr} \in 0,1 \quad \forall n, \forall p, \forall r, p \neq r \tag{13}$$

$$W_n, M_n \geqslant 0 \quad \forall n \tag{14}$$

Table 7
Acuity score sheet.

Patient (Room)	Base Acuity score (1.00)	Acuity Attribute Scores						TOTAL Patient Acuity score
		DKA (1.00)	Step-down (0.90)	High-risk Medication (0.33)	Lab Trending (0.15)	Isolation (0.10)	Specialty (0.08)	
450	1.00						0.08	1.08
451	1.00				0.15			1.15
452	1.00				0.15		0.08	1.23
453	1.00	1.00					0.08	2.08
454	1.00				0.15		0.08	1.23
455	1.00							1.00
456	1.00					0.10		1.10
457	1.00					0.10	0.08	1.18
458	1.00			0.33	0.15		0.08	1.56
459	1.00						0.08	1.08
460	1.00		0.90		0.15		0.08	2.13
461	1.00				0.15		0.08	1.23
462	1.00				0.15		0.08	1.23
463	1.00				0.15			1.15
464	1.00						0.08	1.08
465	1.00						0.08	1.08
466	1.00			0.33				1.33
467	1.00				0.15	0.10	0.08	1.33
468	1.00					0.10		1.10
469	1.00			0.33	0.15		0.08	1.56
470	1.00				0.15		0.08	1.23
471	1.00							1.00
472	1.00	1.00				0.10		2.10
473	1.00							1.00
474	1.00							1.00
475	1.00						0.08	1.08
476	1.00						0.08	1.08
477	1.00							1.00
478	1.00				0.15		0.08	1.23

The objective function (1) of *Model 1* minimizes the weighted sum of the maximum total patient acuity scores assigned to a nurse and the maximum total distance scores assigned to a nurse. The actual weighting values for Q_1 and Q_2 were based on the importance set by the CNs using AHP. Constraint (2) ensures that every patient is assigned to one nurse. Constraint (3) calculates the sum of the acuity scores of the patients assigned to nurse n. Constraint (4) sets the upper bound on the maximum assigned sum of acuity scores given to any nurse. Constraint (5) sets the upper bound on the maximum assigned distance score given to any nurse. Constraint (6) ensures that a chemo patient and an isolation patient are not assigned to the same nurse. In constraint (7), if a nurse is assigned one DKA patient, her maximum patient load is reduced by one patient. Constraint (8) restricts the number of DKA patients assigned to a nurse to one. Constraint (9) sets the maximum number of Step-Down patients assigned to a nurse to three. If the nurse is assigned to a DKA patient, then this constraint only allows up to two Step Down patients to be assigned to the nurse (i.e., one DKA patient + two Step Down patients = three patients in total). Constraint (10) sets y_{npr} to one if patients p and r are assigned to nurse n. Constraint (11) calculates the sum of weighted distance scores for nurse n based on the patients assigned to nurse n. (From the AHP analysis, $R_1 = 0.10$, $R_2 = 0.26$, and $R_3 = 0.64$). Constraints (12) and (13) identify variables x_{np} and y_{npr} as binary, and constraint (14) restricts variables W_n and M_n to non-negative values.

Model 1 assumes that the two objective measures are optimized over all nurses. In setting the patient assignments in Model 1, the maximum total acuity score that is minimized could be associated with one nurse and the maximum total distance score that is minimized could be associated with a different nurse. Therefore, to consider the case in which the maximum total weighted workload for any one nurse is minimized, a second formulation was developed (Model 2). Model 2 is the same as Model 1 with the following exceptions. In Model 2, the objective function was changed to minimize the maximum total weighted workload score assigned to any nurse, B:

$$\text{Minimize } Z = B. \tag{15}$$

In addition, constraints (4) and (5) are removed and the following constraint, regarding total workload for a nurse, was added:

$$Q_1 W_n + Q_2 M_n \leqslant B. \quad \forall n \tag{16}$$

This constraint sets the upper bound on the total workload score for any nurse n to B.

3. Results and discussion

To investigate the efficacy of the two mixed-integer programming models proposed, test problems were evaluated. The test problems were constructed based on actual shift data taken from the GMU. For each test problem, the actual nurse-patient

Table 8
(Day 1) comparison of actual assignments versus Model 1 and Model 2 assignments by 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	4.8	4.4	17.9	17.6	14.8
RN2	5.4	4.7	4.7	22.2	20.3	21.3
RN3	4.4	4.6	4.9	17.5	21.6	18.5
RN4	4.3	4.6	4.2	16.7	11.4	27.8
RN5	5.0	4.6	4.5	16.1	19.0	26.0
RN6	4.7	4.4	4.9	20.8	10.5	11.1
RN7	4.0	4.6	4.7	16.8	18.3	17.6
Mean	4.6	4.6	4.6	18.3	17.0	19.6
Std. Dev.	0.5	0.1	0.3	2.3	4.3	5.9
Range	1.4	0.4	0.7	6.1	11.1	16.7
Max	5.4	4.8	4.9	22.2	21.6	27.8
Min	4.0	4.4	4.2	16.1	10.5	11.1
CN	1.2	1.3	1.3	1.3	1.3	2.0

Table 9
Total workload by nurse for Day 1.

Assignment	Total Workload		
	Actual	Model 1	Model 2
RN1	87.2	89.6	80.8
RN2	103.2	90.8	91.8
RN3	83.5	90.6	92.0
RN4	81.2	80.4	90.8
RN5	91.1	88.0	93.5
RN6	91.3	76.5	84.6
RN7	76.8	87.3	88.1
Mean	87.7	86.2	88.8
Std. Dev.	8.6	5.5	4.6
Range	26.4	14.3	12.7
Max	103.2	90.8	93.5
Min	76.8	76.5	80.8
CN	19.3	20.8	21.5

Table 10
Comparison of assignments versus objective functions for Day 1.

Assignments	*Model 1 Objective Function* $Z = 15\max(W_n) + \max(M_n)$	*Model 2 Objective Function* $Z = \max(15W_n + M_n)$
Actual	103.2	103.2
Model 1	93.6	90.8
Model 2	101.3	93.5

assignments developed by the CN were also collected for comparison to the model results. To solve the problem instances, the General Algebraic Modeling System 23.3.3 (GAMS) was used and the optimal solution was obtained in seconds with XPRESS Solver on a SONY VAIO laptop with an Intel (R) Core 2 Duo CPU 2.10 GHz [19].

Before discussing the results of the test problems, the model differences observed on GMU will be demonstrated by using data from one day shift (Day 1). It is important to recall that the Model 1 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 weighted workload of any nurse, where total weighted workload was defined as the sum of the weighted acuity score and the weighted distance score for any one nurse. This can be written as: $\min_{n\in N}(\max\{Q_1 W_n + Q_2 M_n\})$. Through experimentation it was found that based on the current scoring systems, the average magnitude of the distance scores assigned to a nurse on GMU were approximately three times larger than the magnitude of the average assigned acuity scores ($\sim$ 15 versus 5). Therefore, Q_1 and Q_2 were scaled appropriately to maintain the required weighting acquired using AHP, in which the CNs placed five times more weight on acuity versus distance. As a result, Q_1 was set to 15 and Q_2 was set to 1. (This implies that the average weighted scores are approximately 75 and 15 for acuity and distance, respectively, which is a 5 to 1 ratio.)

For Day 1, there were seven RNs and one CN scheduled. The resulting nurse-patient assignment scores are given in Table 8, by nurse, for the manually constructed assignments (*Actual*) and the Model 1 and Model 2 constructed assignments. In this table, 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.

For both Model 1 and Model 2, the resulting assignments have mean RN acuity scores that are equal to the mean acuity score of the *Actual* assignments developed by the CN. Model 1 had the lowest mean distance score in comparison to both the *Actual* and Model 2 assignments. With respect to variability measures (standard deviation and range), the lowest values of these statistics occurred with Model 1 for acuity and with *Actual* for distance. These lower values for the *Actual* assignments is most likely due to the CNs assigning contiguous patient rooms to the nurses regardless of patient acuity.

Table 8 compared the two workload scores (acuity and distance) by nurse for the three assignment methodologies. In Table 9, a comparison of the total workload ($Q_1 W_n + Q_2 M_n$) for each individual RN is presented for this same shift. For this shift, Model 1 had the lowest mean total workload and Model 2 had the lowest standard deviation and range for the total workload. Note that even with the lower variability in total workload, the Model 2 assignments do not necessarily reduce the workload of the individual RN in comparison to the Model 1. This is seen through comparison of the Mean, and Max Total Workload values.

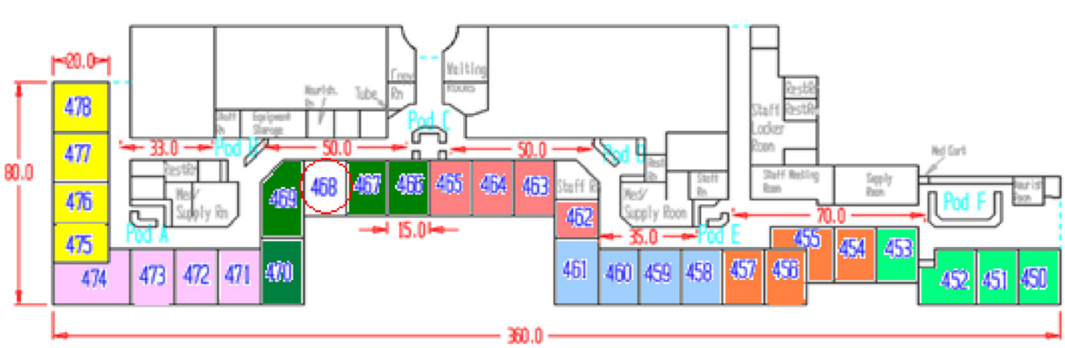

Fig. 3. GMU layout of actual patient assignments based on Day 1.

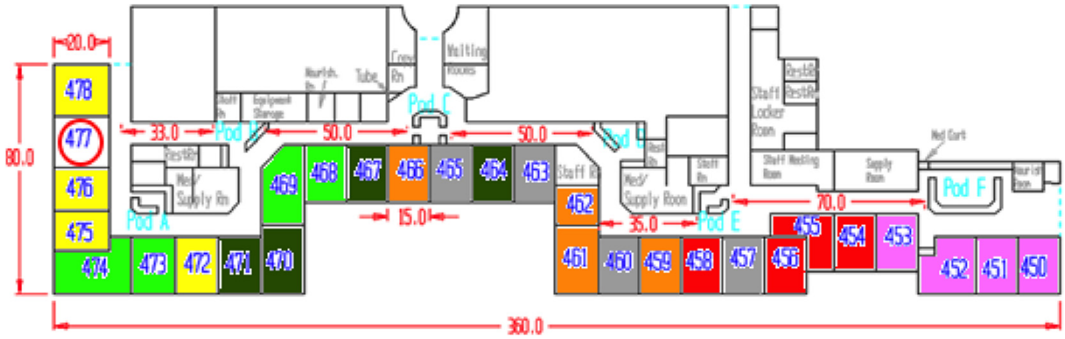

Fig. 4. GMU layout of Model 1 patient assignments based on Day 1.

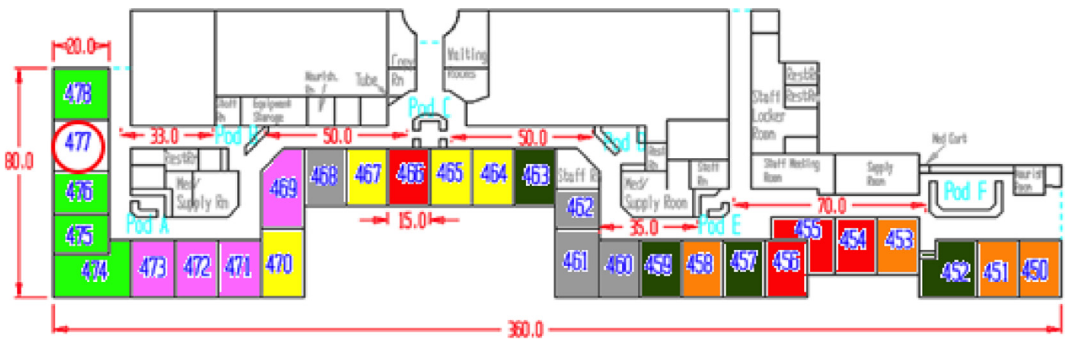

Fig. 5. GMU layout of Model 2 patient assignments based on Day 1.

As a final numerical comparison of Day 1, the nurse-patient assignments constructed with the three methods were subjected to the objective functions of Model 1 and Model 2. The objective function comparisons for Day 1 are located in Table 10. Observe that Model 1's nurse-patient assignments perform 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 may be 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 of the workload measures and not in acuity or distance alone.

To compare the proximity of the nurse-patient assignments generated for Day 1, each set of assignments was superimposed onto the unit layout. The results of *Actual*, Model 1 and Model 2 patient assignments are shown in Figs. 3–5, respectively. In these figures, the patient assignments for each nurse are identified with a different color. The colors correspond to the color-coding of assignments in Tables 8 and 9. The red circle indicates the CN's patient assignment.

In the initial interviews with the GMU CNs, the CNs indicated that adjacent room assignments for a nurse were most preferable. In subsequent interviews and following the presentation of the model assignments in comparison to the *Actual* assignments, the CNs indicated that it was reasonable to assume that non-adjacent room assignments could be considered as acceptable as long as the RNs perceived their rooms to be close to each other and also close to the nearest supply room and nursing station. For example, in Fig. 4, the RN5 patient assignment (rooms 464, 467, 470, 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 nursing station. It was interesting to learn from the GMU staff that the Model 1 assignments could in fact outperform the assignments 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.

Fig. 5 shows the RN assignments constructed by Model 2. Many of the RN assignments have rooms that are significantly farther apart from one another than with the other two methods. So while the total workload variability measures recorded for the three methods indicates that Model 2 may outperform the other two methods, many of the resulting assignments are undesirable because they consist of higher travel distance scores that are compensated for by lower weighted acuity scores.

Access to data for seven day shifts was granted by the hospital through their Institutional Review Board. The assignments and results with respect to acuity, distance, and total workload measures for the seven day shifts are displayed in Tables 11–13, respectively.

From Table 13 and the boxplots in Fig. 6, it is apparent that Model 2 has the lowest variability among the nursing assignments during a shift. These lower values in the range and standard deviation may suggest a better balance in the assignments among the nurses on a shift, but please note that in order to achieve this lower variability, the workload on the assignments are higher on average than those of Model 1.

Using Tables 11–13, statistical analyses were performed on the acuity scores, distance scores, and total workload scores using MINITAB, Version 17 (Minitab, 2016). Assuming a randomized block design, an ANOVA was performed in each case. In these analyses, the acuity scores, the distance scores, and the total workload scores were set as the response variable, and days (shifts) were used as the blocking variable. A 5% significance level was assumed for all tests. The ANOVA results are presented in Table 14 for acuity, Table 15 for distance, and Table 16 for total workload. Each table also includes the results of Post Hoc analysis using a Tukey Test. Tukey Test results are reported in the form of homogenous subsets in these tables.

Table 11
Comparison of *Actual* assignment versus Model 1 and Model 2 assignments with respect to *Acuity Scores*– day shifts.

Nurses	Day 1			Day 2			Day 3			Day 4			Day 5			Day 6			Day 7		
	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2
RN1	4.6	4.8	4.4	4.5	4.7	4.6	4.8	4.9	4.6	4.4	4.3	4.2	6.0	5.6	5.3	4.5	4.9	4.6	4.6	4.8	5.0
RN2	5.4	4.7	4.7	4.5	4.7	4.2	5.0	4.9	5.0	3.4	3.8	3.6	4.5	4.8	4.5	4.7	4.8	4.8	4.6	4.9	4.6
RN3	4.4	4.6	4.9	5.1	4.6	4.5	4.5	4.7	4.6	4.2	3.3	4.5	5.3	4.3	4.8	3.8	4.7	4.6	4.8	4.9	4.7
RN4	4.3	4.6	4.2	4.6	4.4	4.6	4.2	4.8	5.0	5.0	4.1	4.4	4.0	4.5	5.0	5.0	4.5	4.3	4.6	4.7	4.7
RN5	5.0	4.6	4.5	5.1	4.6	4.9	4.6	4.6	5.1	4.3	4.5	3.3	4.6	4.5	4.4	4.5	4.8	5.1	4.5	4.2	4.5
RN6	4.7	4.4	4.9	4.1	4.7	4.4	5.1	5.0	4.4	4.2	4.2	4.3	4.5	4.9	4.8	4.8	4.9	4.8	4.9	4.7	4.8
RN7	4.0	4.6	4.7	4.4	4.2	4.7	5.3	4.6	4.6	3.2	4.5	4.3	4.3	4.8	4.2	5.0	4.7	4.6	4.8	4.5	4.9
Mean	4.6	4.6	4.6	4.6	4.6	4.6	4.8	4.8	4.8	4.1	4.1	4.1	4.7	4.8	4.7	4.6	4.8	4.7	4.7	4.7	4.7
Std. Dev.	0.5	0.1	0.3	0.4	0.2	0.2	0.4	0.2	0.3	0.6	0.4	0.5	0.7	0.4	0.4	0.4	0.1	0.2	0.1	0.2	0.2
Range	1.4	0.4	0.7	1.0	0.5	0.7	1.1	0.4	0.7	1.8	1.2	1.2	2.0	1.3	1.1	1.2	0.4	0.8	0.4	0.7	0.5
Max	5.4	4.8	4.9	5.1	4.7	4.9	5.3	5.0	5.1	5.0	4.5	4.5	6.0	5.6	5.3	5.0	4.9	5.1	4.9	4.9	5.0
Min	4.0	4.4	4.2	4.1	4.2	4.2	4.2	4.6	4.4	3.2	3.3	3.3	4.0	4.3	4.2	3.8	4.5	4.3	4.5	4.2	4.5

As shown in Table 14, there is no evidence of a statistical difference between the mean acuity scores assigned to the nurses by the three models ($p = 0.975$). However, Tables 15 and 16 identify a statistical difference between the mean distance scores ($p = 0.000$) and total workload scores ($p = 0.021$), respectively, for the nurse-patient assignment models. The Post Hoc tests indicate Model 1 assignments have a significantly lower mean distance score than both Model 2 and the Actual assignments. While the mean total workload scores of Model 1 are the lowest of all three models, there is not a statistical difference between Model 1 and the Actual Assignments based on the Post Hoc analysis. It can be inferred from these findings, that the set of nurse-patient assignments generated by Model 1 are more equitable in terms of the balancing of the travel distance scores among the nurses on a shift.

After analyzing the seven day shifts, the resulting nurse-patient assignments were shown to the three CNs on GMU individually to enlist their expert judgment in terms of the feasibility and balance of the assignments. It was suggested by all three CN's that Model 1 constructed assignments that were feasible and there was a perception of balance in terms of both mean acuity and mean distance scores. In terms of Model 2 assignments, on some days the CNs noted that one or more of the assignments appeared to be out of balance in terms of the distance between the locations of the assigned rooms. Following the individual interviews of the three CNs, the CNs were brought together to further compare Model 1 assignments to the Actual assignments for the same day. The consensus of the CNs was that Model 1 assignments were feasible, easy to implement, and would be perceived as equitable by the nursing staff. In addition, the RNs would perceive the Model 1 assignments to be unbiased since they were not created by a CN.

These findings gave further evidence that the proposed methodology was able to capture the true nurse-patient assignment problem on this unit. It also showed that this extremely complex health care problem can be captured mathematically and has the potential to be reproduced on other hospital units.

4. Conclusions

In this paper, a methodology was presented for the development of balanced nurse-patient assignments on a hospital unit using workload scoring metrics. The process included using work measurement techniques to identify the components of workload and correlation analysis to identify measures or surrogate measures which best represent workload components. Once the workload measures were identified, AHP was used to combine, scale, and resolve inconsistencies among the perceived importance and intensity of the workload measures and form the basis for the workload scoring metrics. Finally, the use of the resulting scoring metrics for the creation of balanced workload assignments via mathematical programming techniques was successfully demonstrated.

The proposed methodology is adaptable to many workforce scheduling problems in which one or more measures of workload are required. It is particularly applicable to situations in which the workload is composed of elements imposed by the work environment, variability within the required tasks, and a measurable perception of the relative intensity of the work elements.

Through the illustration of the use of the scoring systems, this work was the first to define a component of nurse workload based on key distances traveled by a nurse during a shift. Additionally, the scoring systems that were developed for acuity and distance measures were intuitive to the nursing staff and could be adapted to other units within the hospital. This work is particularly impor-

Table 12
Comparison of *Actual* assignment versus Model 1 and Model 2 assignments with respect to *Distance Scores* – day shifts.

Nurses	Day 1			Day 2			Day 3			Day 4			Day 5			Day 6			Day 7		
	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2
RN1	17.9	17.6	14.8	17.5	17.3	17.6	21.3	18.9	20.6	21.1	12.0	13.9	17.2	8.7	16.8	16.1	17.7	21.0	17.5	13.8	12.9
RN2	22.2	20.3	21.3	16.8	14.2	24.4	16.8	13.8	15.8	7.4	8.6	21.9	17.5	13.0	21.8	17.5	17.2	19.2	16.8	16.0	17.6
RN3	17.5	21.6	18.5	16.1	19.6	18.6	16.7	18.4	18.2	16.7	10.7	13.2	20.8	13.4	23.5	20.8	17.3	20.6	20.8	13.4	15.0
RN4	16.7	11.4	27.8	17.9	18.9	17.6	17.5	17.4	15.8	20.8	11.7	13.7	23.7	16.6	21.0	23.7	14.5	19.7	16.7	16.2	17.1
RN5	16.1	19.0	26.0	22.2	20.1	13.0	16.1	19.2	14.3	17.5	12.3	21.7	21.2	12.4	25.9	21.2	17.4	14.6	16.8	16.8	20.3
RN6	20.8	10.5	11.1	16.7	17.4	21.3	16.8	16.5	25.3	16.7	11.1	10.7	17.9	18.5	23.6	17.9	16.7	18.1	16.1	14.7	16.1
RN7	16.8	18.3	17.6	20.8	18.4	15.7	20.8	14.5	23.1	10.1	11.4	14.9	16.8	15.5	29.4	16.8	15.7	22.8	17.9	11.7	14.6
Mean	18.3	17.0	19.6	18.3	18.0	18.3	18.0	17.0	19.0	15.8	11.1	15.7	19.3	14.0	23.1	19.1	16.6	19.4	17.5	14.7	16.2
Std. Dev.	2.3	4.3	5.9	2.3	2.0	3.7	2.1	2.1	4.1	5.2	1.2	4.4	2.6	3.2	4.0	2.8	1.1	2.6	1.6	1.8	2.4
Range	6.1	11.1	16.7	6.1	5.9	11.3	5.2	5.4	11.0	13.7	3.7	11.2	6.9	9.8	12.6	7.6	3.2	8.2	4.7	5.1	7.4
Max	22.2	21.6	27.8	22.2	20.1	27.8	21.3	19.2	25.3	21.1	12.3	21.9	23.7	18.5	29.4	23.7	17.7	22.8	20.8	16.8	20.3
Min	16.1	10.5	11.1	16.1	14.2	13.0	16.1	13.8	14.3	7.4	8.6	10.7	16.8	8.7	16.8	16.1	14.5	14.6	16.1	11.7	12.9

Table 13
Comparison of *Actual* assignment versus Model 1 and Model 2 assignments with respect to *Total Workload Scores* – day shifts.

Nurses	Day 1			Day 2			Day 3			Day 4			Day 5			Day 6			Day 7		
	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2	Actual	Model 1	Model 2
RN1	86.9	89.6	80.8	85.0	87.8	86.6	93.3	92.4	89.6	87.1	76.5	76.9	107.2	92.7	96.3	83.6	91.2	90.0	86.5	85.8	87.9
RN2	103.2	90.8	91.8	84.3	84.7	87.4	91.8	87.3	90.8	58.4	65.6	75.9	85.0	85.0	89.3	88.0	89.2	91.2	85.8	89.5	86.6
RN3	83.5	90.6	92.0	92.6	88.6	86.1	84.2	88.9	87.2	79.7	60.2	80.7	100.3	77.9	95.5	77.8	87.8	89.6	92.8	86.9	85.5
RN4	81.2	80.4	90.8	86.9	84.9	86.6	80.5	89.4	90.8	95.8	73.2	79.7	83.7	84.1	96.0	98.7	82.0	84.2	85.7	86.7	87.6
RN5	91.1	88.0	93.5	98.7	89.1	86.5	85.1	88.2	90.8	82.0	79.8	71.2	90.2	79.9	91.9	88.7	89.4	91.1	84.3	79.8	87.8
RN6	91.3	76.5	84.6	78.2	87.9	87.3	93.3	91.5	91.3	79.7	74.1	75.2	85.4	92.0	95.6	89.9	90.2	90.1	89.6	85.2	88.1
RN7	76.8	87.3	88.1	86.8	81.4	86.2	100.3	83.5	92.1	58.1	78.9	79.4	81.3	87.5	92.4	91.8	86.2	91.8	89.9	79.2	88.1
Mean	87.7	86.2	88.8	87.5	86.3	86.7	89.8	88.7	90.4	77.3	72.6	77.0	90.4	85.6	93.9	88.4	88.0	89.7	87.8	84.7	87.4
Std. Dev.	8.6	5.5	4.6	6.5	2.8	0.5	6.8	2.9	1.6	14.1	7.2	3.3	9.7	5.6	2.7	6.5	3.1	2.6	3.0	3.8	1.0
Range	26.4	14.3	12.7	20.5	7.7	1.3	19.8	8.9	4.9	37.7	19.6	9.5	25.9	14.8	7.0	20.9	9.2	7.6	8.5	10.3	2.6
Max	103.2	90.8	93.5	98.7	89.1	87.4	100.3	92.4	92.1	95.8	79.8	80.7	107.2	92.7	96.3	98.7	91.2	91.8	92.8	89.5	88.1
Min	76.8	76.5	80.8	78.2	81.4	86.1	80.5	83.5	87.2	58.1	60.2	71.2	81.3	77.9	89.3	77.8	82	84.2	84.3	79.2	85.5

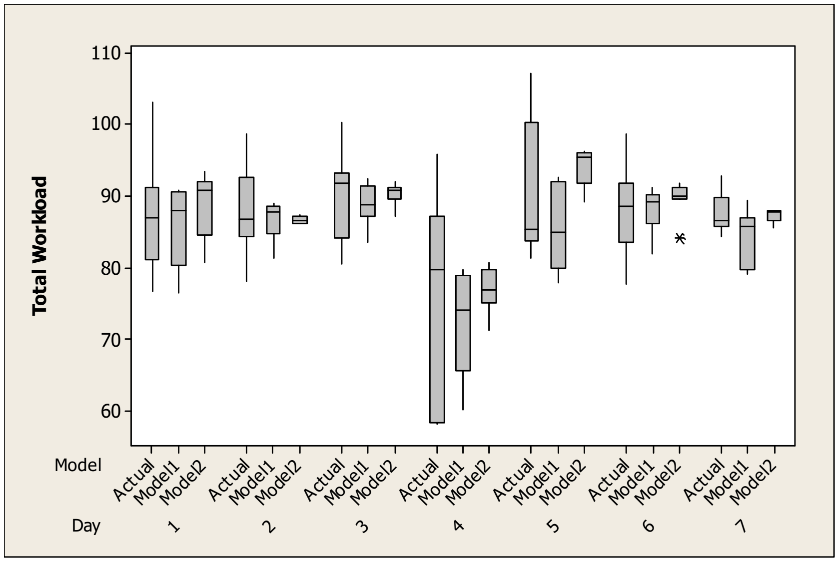

Fig. 6. Boxplots of total workload by day by nurse-assignment model.

Table 14
ANOVA and Turkey homogeneous subsets for comparison of assignment methods for acuity scores.

Source	df	SS	MS	F	p
Model	2	0.0059	0.0029	0.02	0.975
Day	6	6.8147	1.1358	9.69	0.000
Error	138	16.1694	0.1172		
Total	146	22.9899			
Means: Actual = 4.60 Model 1 = 4.60 Model 2 = 4.59					
Tukey Homogeneous Subsets: (Actual, Model 1, Model 2)					

Table 15
ANOVA and Turkey homogeneous subsets for comparison of assignment methods for distance scores.

Source	df	SS	MS	F	P
Model	2	294.17	147.09	13.59	0.000
Day	6	349.45	58.24	5.38	0.000
Error	138	1493.17	10.82		
Total	146	2136.79			
Means: Actual = 18.78 Model 1 = 15.48 Model 2 = 18.04					
Tukey Homogeneous Subsets: (Model 1) (Model 2, Actual)					

Table 16
ANOVA and Turkey homogeneous subsets for comparison of assignment methods for total workload.

Source	df	SS	MS	F	P
Model	2	256.26	128.13	3.98	0.021
Day	6	3068.26	511.38	15.88	0.000
Error	138	4444.10	32.20		
Total	146	7768.62			
Means: Actual = 86.98 Model 1 = 84.60 Model 2 = 87.68					
Tukey Homogeneous Subsets: (Model 1, Actual) (Actual, Model 2)					

tant for hospitals that are adopting the single patient room (private room) care environment. This type of layout is becoming more popular with new hospital construction and renovation. And while single patient rooms may be a step forward for patient care, it poses another question as to its effect on the additional physical demands placed on hospital unit nurse.

While the proposed methodology to construct nurse-patient assignments is generalizable to other hospital units, not all measures developed for one unit may be relevant to other units. Therefore, one limitation of this methodology is that it does take time and resources to implement all elements on a new unit. In addition, the methodology requires that charge nurses and registered nurses are willing to participate and have an understanding of how their activities affect their workload throughout a shift. Even with these potential issues, this methodology was able to show the feasibility to automate nurse-patient assignments that were perceived as feasible, balanced, and potentially less biased, in comparison to a charge nurse creating assignments on the same unit.

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