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Optimisation de l'organisation en hémodialyse : étude de cas

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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Optimisation de l'organisation en hémodialyse : étude de cas

présenté par **Marie-Claude NORMAND**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DÉDICACE

*À mes parents,
qui m'ont accompagnée durant toutes les étapes de ma scolarité.
Merci de m'avoir guidée et inspirée.*

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RÉSUMÉ

Lorsque les reins d'un patient ne sont plus en mesure de filtrer efficacement les déchets et les liquides présents dans son sang, celui-ci pourrait se voir prescrire des traitements d'hémodialyse. Les traitements d'hémodialyse sont exigeants. En moyenne, les patients nécessitent 3 rendez-vous par semaine d'une durée de 4 heures. Ainsi, la qualité de l'organisation du centre d'hémodialyse lui procurant les traitements a un impact important sur sa qualité de vie.

Lors des rendez-vous d'hémodialyse, les patients sont affectés à une infirmière et à une chaise de traitement. Le rôle de l'infirmière est de brancher le patient à la machine d'hémodialyse, de surveiller la complétion du traitement et de le débrancher. Également, certains patients requièrent d'être affectés à des chaises correspondant à leurs besoins spécifiques, telles que des chaises basses, pour obèses, ou en isolation. L'affectation des infirmières aux patients dépend de leur niveau d'expérience, ainsi que du nombre maximal de patients auxquelles ces dernières peuvent être affectées par quart et par jour.

Les problèmes à résoudre dans un centre d'hémodialyse pour en optimiser l'efficacité sont nombreux. Nous pouvons citer, par exemple, l'horaire des infirmières, et plus particulièrement la longueur des quarts de travail affectés, le choix des jours de rendez-vous des patients (c'est-à-dire le triplet de jours lundi/mercredi/vendredi ou mardi/jeudi/samedi), la période de rendez-vous (matin, après-midi ou soir) ou l'affectation quotidienne infirmière-patient-chaise. Dans ce mémoire, bien que nous abordions les problèmes d'horaire et d'assignation à des périodes de rendez-vous, nous avons un intérêt particulier pour le problème d'affectation quotidien. C'est en effet la tâche administrative la plus lourde pour le personnel infirmier. Cela est notamment dû aux fréquentes modifications de la liste quotidienne de patients à affecter en raison de nombreux facteurs : les hospitalisations des patients actuels, les nouveaux patients nécessitant des traitements et les patients en vacances ayant besoin de visiter un centre d'hémodialyse durant leur séjour. Le nombre d'infirmières travaillant durant chaque quart de travail peut également être modifié selon les absences et le volontariat pour compléter du temps supplémentaire. De plus, la variation entre les niveaux d'acuité des patients complexifie la répartition équitable entre les infirmières.

Afin de répondre à ces enjeux, tout d'abord, nous proposons d'optimiser les horaires des infirmières et les périodes de rendez-vous des patients, en minimisant l'acuité affectée aux infirmières à chaque période de rendez-vous à l'aide d'un modèle d'optimisation. Ce modèle est utilisé pour évaluer la relation entre la qualité des affectations et les types d'horaires des patients et des infirmières.

Un modèle linéaire multi-objectifs est ensuite développé pour optimiser les assignations en hémodialyse. Grâce à la collaboration avec la clinique externe d'hémodialyse du Centre hospitalier de l'université de Montréal (CHUM), ce modèle est réaliste et adapté aux besoins pratiques. Son objectif est de minimiser la charge de travail des infirmières et de respecter les critères de qualité lors de l'affectation des patients aux chaises. La charge de travail d'une infirmière est définie par la distance entre les chaises de traitement qui lui sont affectées et par l'acuité des patients qu'elle traite. Les critères de qualité de l'affectation à une chaise incluent le respect du niveau d'autonomie du patient et la constance dans les affectations aux chaises d'un rendez-vous à l'autre. Ce modèle peut être résolu séquentiellement après le modèle d'optimisation des horaires.

Pour assurer l'utilisation à long terme du modèle d'affectation par le centre d'hémodialyse, nous avons développé une interface sur Excel. En un clic, le personnel peut optimiser les affectations en fonction des données fournies, facilitant ainsi une application quotidienne des résultats du modèle. Pour enrichir davantage le modèle, nous avons intégré une procédure pour suggérer des heures d'arrivée aux patients selon leur période de rendez-vous et l'affectation proposée par le modèle.

Afin de tester les modèles mathématiques, des instances représentant des semaines réelles au centre d'hémodialyse ont été bâties grâce aux données de la clinique d'hémodialyse. Des critères d'acuité chez les patients ont aussi été identifiés afin de pouvoir évaluer leur charge de travail respective. La principale conclusion de cette étude est que le modèle d'affectation développé permet d'obtenir des améliorations significatives en termes de qualité de répartition de l'acuité des patients entre les infirmières. De plus, l'utilisation de l'interface sur Excel permettra de limiter le temps passé par les infirmières à planifier les affectations. Par ailleurs, la qualité des résultats pour les affectations est améliorée lorsque les horaires de travail des infirmières et les périodes de rendez-vous des patients sont bâtis en considérant la charge de travail. Changer quelques patients d'un patron de rendez-vous à un autre peut significativement affecter la charge de travail des infirmières.

ABSTRACT

When a patient's kidneys can no longer effectively filter waste and fluids from their blood, they may require hemodialysis treatments. These treatments are demanding, typically involving three appointments per week, each lasting four hours on average. Therefore, the quality of organization at the hemodialysis center providing these treatments can significantly impact the patient's quality of life.

During hemodialysis appointments, patients are assigned to a nurse and a specific treatment chair. The nurse's responsibilities include connecting the patient to the hemodialysis machine, monitoring the treatment's progress, and disconnecting the patient afterward. Patients must be assigned a chair that meets their specific needs, such as a low chair, a chair for obese patients, or an isolation chair. Nurse assignments depend on their experience level and the maximum number of patients they can attend to per shift and per day.

Optimizing the efficiency of a hemodialysis center involves addressing several challenges. Key issues include scheduling nurses, particularly the length of their shifts, selecting patient appointment days (Monday/Wednesday/Friday or Tuesday/Thursday/Saturday), determining appointment periods (morning, afternoon, or evening), and the daily nurse-to-patient-to-chair assignments. In this study, we primarily focus on the daily assignment problem, but we also address nurse and patient scheduling. This daily assignment is the most administratively burdensome task for nursing staff, mainly due to frequent changes in the patient list caused by various factors: current patient hospitalizations, new patients requiring treatment, and vacationing patients needing temporary hemodialysis treatments. Additionally, the number of nurses per shift can fluctuate based on absences and voluntary overtime. The varying acuity levels of patients further complicates equitable assignment among nurses.

To address these challenges, we first propose optimizing nurse schedules and patient appointment periods by minimizing the acuity assigned to nurses during each appointment period using an optimization model. This model is employed to evaluate the relationship between the quality of assignments and the types of schedules for patients and nurses.

A multi-objective linear model is then developed to optimize dialysis assignments. Through collaboration with the outpatient dialysis clinic at CHUM, this model is realistic and tailored to practical needs. Its objective is to minimize nurse workload while meeting quality criteria for assigning patients to chairs. A nurse's workload is defined by the distance between the treatment chairs assigned to her and the acuity of the patients she treats. The quality criteria for chair assignments include respecting the patient's level of autonomy and maintaining

consistency in chair assignments from one appointment to the next. This model can be solved sequentially after the schedule optimization model.

To ensure long-term use of the assignment model at the hemodialysis center, we have developed an Excel interface. This interface allows staff to begin optimizing assignments with a single click based on provided data, facilitating daily application of model results. We've also integrated a procedure to suggest patient arrival times based on their appointment period and the assignment proposed by the model.

To validate the mathematical models, instances representing actual weeks at the hemodialysis center were constructed and patient acuity criteria were identified to assess their respective workload. The primary outcome of this study is that the developed model significantly improves assignment quality. Utilizing the Excel interface to generate assignments will also help decrease the time nurses spend on planning. Moreover, we observe that even minor changes in patient appointment patterns or nurse schedule types can have a significant impact on nurse workload.

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LISTE DES SIGLES ET ABRÉVIATIONS

CHUM	Centre hospitalier de l'Université de Montréal
NPC	Nurse-to-patient-to-chair assignment
PAT	Patient appointment time
PNS	Patient and nurse scheduling
VBA	Visual Basic for Applications

CHAPITRE 1 INTRODUCTION

La durée moyenne d'attente pour une greffe de rein est de 3 à 5 ans [1]. En attente de la greffe, lorsque les reins ne fonctionnent plus suffisamment pour répondre aux besoins du corps, deux options s'offrent aux patients : la dialyse péritonéale ou l'hémodialyse [2]. Pendant la dialyse péritonéale, une solution est introduite dans l'abdomen du patient via un cathéter. Après une durée déterminée, la solution, désormais chargée des déchets et de l'excès de liquide présents dans le corps, est retirée. D'autre part, l'hémodialyse est un traitement où une machine est utilisée pour filtrer le sang des patients. Dans cette machine, une membrane fine sépare les déchets du sang qui y circule [3]. L'hémodialyse est un traitement exigeant pour les patients, nécessitant en moyenne 3 séances par semaine, chacune durant environ 4 heures [1]. Ce nombre élevé de séances durant une période étendue rend prioritaire l'organisation optimale des soins lors des visites dans les centres d'hémodialyse pour garantir la qualité des traitements.

Lors d'un traitement dans un centre d'hémodialyse, les patients sont généralement assignés à une chaise et à une ou plusieurs infirmières qui sont chargées du branchement et du débranchement à la machine d'hémodialyse. Ces dernières assurent également une surveillance durant le traitement et complètent des soins additionnels comme des changements de pansements. Lorsque l'hémodialyse est complétée, la machine est désinfectée avant de pouvoir être utilisée par un autre patient.

Dans le cadre de ce projet, nous avons travaillé en collaboration avec le Centre de services ambulatoires de dialyse de Gaspé, affilié au CHUM. Située à Montréal, ce centre accueille hebdomadairement 200 patients réguliers répartis durant trois périodes de rendez-vous distinctes : matin, après-midi et soirée. À chaque période, tous les patients arrivent à la même heure. Comme la plupart des patients reçoivent trois traitements par semaine, ils sont généralement affectés à la même période de rendez-vous les lundi/mercredi/vendredi ou les mardi/jeudi/samedi.

Les patients se distinguent par différentes caractéristiques :

- **Acuité** : Un patient peut augmenter la charge de travail d'une infirmière en raison de facteurs tels que le déplacement à l'aide d'un fauteuil roulant ou d'une canne, l'utilisation d'un cathéter ou le besoin d'injections.
- **Caractéristiques de la chaise** : Certains patients nécessitent d'être affectés à des chaises ayant des caractéristiques spécifiques. Dans les chaises présentes au centre d'hémodialyse du CHUM, on retrouve des chaises en isolement, des chaises pour pa-

tients obèses et des chaises basses.

- **Niveau d'autonomie** : Les patients sont évalués comme étant non-autonomes ou semi-autonomes. Les patients semi-autonomes sont capables de participer à leur branchement et à leur débranchement.

Le centre d'hémodialyse dispose de trois salles, chacune comportant en moyenne 15 chaises. Une salle est dédiée aux patients semi-autonomes et les deux autres aux patients non-autonomes. Généralement, les patients sont affectés à une chaise dans une salle correspondant à leur niveau d'autonomie. L'attribution de la même chaise d'une visite à l'autre est favorisée.

Quarante infirmières travaillent au centre d'hémodialyse. Ces dernières complètent des quarts de travail de 8 ou de 12 heures. Selon le quart de travail complété et le niveau d'expérience, les infirmières peuvent être affectées à un nombre maximal de patients par quart et par jour.

La principale problématique de notre centre d'hémodialyse partenaire réside dans l'élaboration des affectations des patients aux chaises et aux infirmières. La création manuelle de ces affectations demande un temps considérable au personnel infirmier, réduisant ainsi le temps disponible pour les patients. De plus, ces assignations nécessitent des adaptations quotidiennes. En effet, il arrive fréquemment que de nouveaux patients soient admis au centre d'hémodialyse pour une durée prolongée ou pour un nombre restreint de rendez-vous (par exemple, lorsqu'ils sont en voyage). Par ailleurs, des rendez-vous peuvent également être annulés lorsque les patients sont hospitalisés. Ainsi, la production des affectations devient une tâche administrative lourde et récurrente.

Afin de répondre à cette problématique, l'objectif de ce projet est d'optimiser l'assignation des patients aux infirmières et aux chaises durant les périodes de rendez-vous grâce à un modèle linéaire multi-objectifs. Le modèle développé vise à optimiser deux aspects principaux des assignations. Tout d'abord, la charge de travail des infirmières doit être minimisée. Cette charge de travail est représentée par l'acuité des patients assignés aux infirmières et la distance à parcourir entre les chaises des patients. Ensuite, les patients doivent être affectés à des chaises situées dans des salles correspondant à leur niveau d'autonomie, sans variation de chaise entre les rendez-vous. Pour que les résultats bénéficient au centre d'hémodialyse, un sous-objectif est de développer un outil intuitif et simple d'utilisation sur Excel permettant d'utiliser le modèle au quotidien.

Actuellement, les patients n'ont pas d'heure attitrée de rendez-vous. Nous proposons donc également une procédure pour déterminer les heures d'arrivée des patients selon les assignations planifiées. Enfin, comme le modèle d'assignation prend en compte les quarts de travail des infirmières et les périodes de rendez-vous des patients, nous proposons d'évaluer l'impact de la qualité de ces horaires sur les assignations proposées. Pour ce faire, nous développons

un modèle d'optimisation simultanée des périodes de rendez-vous des patients et des quarts de travail des infirmières, résolu sur une période de deux semaines. Les résultats de ce modèle d'horaire seront ensuite intégrés séquentiellement dans le modèle d'affectation afin d'étudier leur incidence.

Ce mémoire est organisé comme suit. Dans le chapitre 2, une revue de littérature est présentée sur les thèmes de l'affectation des infirmières aux patients, des horaires d'infirmières et de patients et du développement d'interfaces utilisateur sur Excel. Cette revue permet de positionner notre étude par rapport aux travaux de recherche antérieurs. Ensuite, dans le chapitre 3, la démarche suivie lors du projet de recherche est détaillée. Le chapitre 4 présente un article dans lequel on retrouve la méthodologie utilisée dans le cadre du projet, les modèles développés, les résultats, ainsi que le processus de développement de l'outil d'optimisation. Puis, dans le chapitre 5, une discussion générale est proposée sur les résultats de l'article et sur des pistes d'amélioration liées à l'organisation du centre d'hémodialyse. Enfin, le mémoire se conclut par le chapitre 6 avec une description des limitations de l'étude et des futures directions de recherche.

CHAPITRE 2 REVUE DE LITTÉRATURE

Cette section présente une revue de littérature ayant pour objectif de recenser et de synthétiser les travaux antérieurs. Tout d’abord, les problèmes d’affectations en hémodialyse, en oncologie et dans un contexte hospitalier plus général sont abordés dans la section 2.1. Ensuite, la section 2.2 détaille les problèmes d’horaire. Finalement, la section 2.3 résume différentes approches de développement d’une interface sur Excel permettant au personnel clinique d’utiliser un modèle mathématique.

2.1 Problèmes d’affectation

Les problèmes d’affectation des patients aux infirmières ou autres professionnels de la santé sont fréquemment étudiés dans la littérature et appliqués à divers domaines avec des méthodes de résolution variées. Selon le domaine d’application, les objectifs diffèrent. Toutefois, à notre connaissance, un seul article a été publié à ce sujet en hémodialyse. Farhadi et al. [4] proposent un modèle d’optimisation mixte pour l’affectation des patients aux techniciens et aux lits dans un centre d’hémodialyse. Ce modèle permet également l’optimisation quotidienne des horaires des techniciens, avec pour objectif principal la minimisation de leurs coûts d’opération. Ce modèle est résolu avec des instances comprenant jusqu’à 60 patients.

Dans le domaine de l’oncologie, Acar et Butt [5] proposent un modèle d’affectation des patients aux infirmières. L’objectif du modèle est de minimiser l’acuité des patients assignés aux infirmières et le score de distance total des infirmières durant un quart de travail. Le score de distance est calculé selon plusieurs facteurs : la distance entre la chambre du patient et la salle de fournitures et le poste infirmier les plus proches, ainsi que la distance entre chacune des chambres assignées à l’infirmière. Les analyses des résultats du modèle sont effectuées avec 28 patients et 8 infirmières. Liang et Turkcan [6] s’intéressent également aux affectations en oncologie, mais dans le contexte d’une clinique de chimiothérapie recevant des patients pour des rendez-vous. Ils développent un modèle d’affectation multi-objectifs visant à minimiser les temps d’attente, la charge de travail excédentaire des infirmières et la quantité d’heures supplémentaires effectuées. Le modèle est testé avec des instances comprenant de 40 à 68 patients et de 5 à 7 infirmières.

Dans un contexte hospitalier plus général, Rosenberger et al. [7] reprennent l’objectif de minimiser la charge de travail excédentaire des infirmières avec un modèle d’optimisation en nombres entiers. Ce modèle est évalué pour des instances de 14 à 23 patients et de 4 à 10

infirmières. Mullinax et Lawley [8], ainsi que Schaus et al. [9] s'intéressent aux affectations des patients aux infirmières dans le département de néonatalogie. Les modèles développés servent à assigner des infirmières à des patients, mais également à des zones. Les patients assignés à une infirmière doivent donc être situés dans la zone de cette dernière. Les deux modèles sont résolus pour des instances de 20 à 30 nourrissons et de 10 à 15 infirmières. Cependant, Mullinax et Lawley [8] modélisent le problème à l'aide d'un modèle linéaire en nombres entiers, tandis que Schaus et al. [9] développent un modèle de programmation par contraintes.

La lecture des articles dédiés à l'affectation des infirmières aux patients permet de constater que la taille des problèmes étudiés demeure modérée. Le nombre maximal de patients dans un problème d'assignation est de 68, tandis que le nombre maximal de professionnels de la santé est de 15. De plus, peu d'articles considèrent la distance parcourue par les infirmières ou intègrent l'affectation des patients à des chaises et à des lits. Pour les problèmes résolus dans des cliniques accueillant les patients pour des rendez-vous, la constance des chaises entre les rendez-vous n'est également pas prise en compte. Toutefois, le point commun entre ces articles est l'optimisation de la charge de travail des infirmières.

La définition de la charge de travail dans les problèmes d'affectation varie selon les articles. Plusieurs décrivent la charge de travail comme étant l'acuité des patients affectés à une infirmière, c'est-à-dire la quantité de soins requis par ces patients [5,7–9]. Liang et Turkcan [6] affinent la description de la charge de travail en la définissant comme le produit de l'acuité et de la durée du traitement d'un patient. Farhadi et al. [4] utilisent plutôt le concept des tâches afin d'évaluer la charge de travail. Une contrainte est ajoutée dans le modèle développé pour limiter la différence entre le nombre total de tâches complétées par les techniciens, avec une durée de tâche variant selon les patients. D'autres définitions de la charge de travail sont également proposées pour des modèles d'affectation de patients à des infirmières dans des contextes différents des hôpitaux et des cliniques. Par exemple, la charge de travail pour les infirmières complétant des soins à domicile peut être calculée en additionnant différents temps : le temps de déplacement, le temps dédié aux soins et le temps d'attente [10,11].

2.2 Problèmes d'horaire

Dans la littérature, la majorité des articles en hémodialyse sont dédiés aux problèmes de rendez-vous des patients. Liu et al. [12] s'intéressent à l'assignation des rendez-vous des patients durant une période de deux semaines. Plusieurs facteurs sont optimisés : les coûts d'utilisation et l'usage équitable des équipements, le nombre de traitements durant la nuit et la satisfaction des préférences des patients. Reihaneh et al. [13] modélisent les rendez-vous

des patients grâce à un modèle de partitionnement. Le problème est résolu à une fréquence hebdomadaire grâce à un algorithme de séparation et d'évaluation. Les travaux de Fleming et al. [14] sont davantage axés sur la minimisation des temps d'attente et la réduction des retards par rapport à l'heure de fin planifiée. Le modèle analytique développé est résolu quotidiennement. Peña [15] propose également une résolution quotidienne, mais dans un contexte d'hémodialyse hospitalière plutôt qu'en clinique. L'objectif du modèle développé est d'optimiser l'utilisation des stations d'hémodialyse, les heures de fonctionnement de l'unité étudiée et les délais pour les autres procédures susceptibles de prolonger la durée d'hospitalisation des patients. Toutefois, aucun des modèles d'optimisation des rendez-vous des patients en hémodialyse ne considère également l'optimisation des horaires des infirmières.

Plusieurs similarités sont constatées entre l'organisation d'un centre d'hémodialyse et celle d'un centre d'oncologie. En effet, pour chacun des rendez-vous des patients, ces derniers sont assignés à une ou plusieurs infirmières, ainsi qu'à une chaise ou un lit. De plus, les patients doivent se présenter à leur centre pour une série de rendez-vous. En oncologie, une résolution séquentielle est proposée afin de générer les horaires des patients, ainsi que les affectations des patients aux infirmières. Tout d'abord, Turkcan et al. [16] propose un algorithme en deux phases. La première phase est dédiée à la planification de la première journée des traitements des patients. Cette planification est basée sur l'acuité du patient, ainsi que ses besoins en ressources. La deuxième phase est plutôt axée sur l'affectation des patients aux infirmières et aux chaises. Cette phase permet également d'assigner des heures d'arrivée aux patients. L'approche en 2 phases est également utilisée par Benzaid et al. [17] avec, en première phase, l'assignation des rendez-vous de nouveaux patients. Cette première phase est également utilisée pour estimer le nombre d'infirmières requises pour les traitements des patients. Dans la deuxième phase, l'affectation aux infirmières est complétée tout en minimisant le nombre d'infirmières requises. Turkcan et al. [16] incluent l'affectation aux chaises dans leur deuxième phase, tandis que Benzaid et al. [17] se concentrent davantage sur la minimisation des besoins en personnel infirmier.

Un article propose également l'optimisation simultanée des horaires de personnel et de patient en oncologie. Ce type d'optimisation est peu souvent abordée dans la littérature compte tenu des objectifs souvent conflictuels de ces deux problèmes. Sadki et al. [18] développent un modèle de planification quotidien des rendez-vous de patient et des heures de début des quarts de travail des oncologues. L'objectif du modèle est de minimiser les temps d'attente des patients, ainsi que l'heure de fermeture de la clinique. Afin de résoudre ce problème, une heuristique basée sur la relaxation lagrangienne est proposée, ainsi qu'une heuristique de recherche locale.

2.3 Développement d'une interface sur Excel

Afin de permettre aux professionnels de la santé de bénéficier à long terme des modèles mathématiques développés, plusieurs articles abordent le développement d'interfaces. L'utilisation d'Excel est fréquemment mentionnée puisque cet outil est souvent bien connu du milieu de la santé. Son utilisation permet de faciliter l'adaptation au changement et assure la pérennité des outils.

Dans le domaine de l'oncologie, Liang et Turkcan [6] proposent un fichier Excel permettant d'afficher les résultats de leur modèle d'horaire et d'affectation. Dans le fichier, l'utilisateur peut spécifier le niveau d'acuité des patients, leurs durées de rendez-vous, le niveau de compétence des infirmières, leurs horaires de travail et les heures d'ouverture du centre. L'utilisateur n'a qu'à appuyer sur un bouton pour que l'optimisation débute. La résolution est effectuée avec OpenSolver, un complément de Visual Basic for Applications (VBA). OpenSolver est également utilisé par Fleming et al. [14] dans un outil développé sur Excel, axé sur l'optimisation des assignations en hémodialyse. Finalement, Punnakitikashem et Rosenberger [19] proposent une interface sur Excel dédiée à la résolution de problèmes d'affectation. Grâce aux données fournies sur Excel par l'utilisateur concernant les chambres des patients, leur diagnostic, ainsi que les types d'infirmières, l'optimisation peut commencer. Le fichier est transféré de l'ordinateur personnel de l'utilisateur à un ordinateur plus performant. Le modèle est alors résolu grâce au solveur CPLEX 9.1. Ensuite, grâce à VBA, les résultats des assignations sont affichés pour l'utilisateur.

CHAPITRE 3 DÉMARCHE DU TRAVAIL DE RECHERCHE

Le projet de recherche est centré sur un objectif principal : l'optimisation des affectations des patients aux infirmières et aux chaises en hémodialyse. Cet objectif est divisé en trois sous-objectifs. Tout d'abord, nous cherchons à modéliser le processus d'assignation en hémodialyse grâce à un modèle mathématique multi-objectifs. Puis, nous souhaitons étudier la relation entre la qualité des affectation et les horaires des patients et des infirmières. Enfin, nous avons pour but de concevoir une interface permettant au personnel d'une clinique d'hémodialyse de générer des affectations quotidiennes.

Pour améliorer le fonctionnement du centre d'hémodialyse, nous avons également comme objectif secondaire le développement d'une procédure permettant de proposer des heures d'arrivée pour les patients à leur rendez-vous.

Afin d'atteindre ces objectifs, une démarche rigoureuse a été adoptée. Les étapes suivantes résument la méthodologie suivie :

1. **Séances d'observation et de consultation :** Afin de mieux comprendre le fonctionnement du centre d'hémodialyse, nous avons complété plusieurs séances d'observation et de consultation. Nous avons accompagné des infirmières lors de de quarts de travail, assisté à une séance de planification des assignations et été présents durant une période de développement des horaires du personnel. En discutant avec le personnel planifiant les assignations, nous avons pu cibler les critères de qualité des assignations complétées. Une infirmière cheffe nous a épaulé afin de gagner une meilleure compréhension des quarts de travail, de la charge de travail des infirmières et de l'organisation des salles d'hémodialyse
2. **Collecte de données :** Nous avons ensuite recueilli des données sur les caractéristiques des patients, des infirmières et des chaises au centre d'hémodialyse. En évaluant les horaires précédents de rendez-vous des patients et de travail des infirmières, nous avons pu créer diverses instances.
3. **Conception d'un système de mesure de l'acuité :** Une des parties centrales du modèle d'assignation est la répartition équitable de la charge de travail entre les infirmières. Cette charge de travail est représentée par la distance à parcourir par une infirmière, ainsi que par l'acuité des patients qui lui sont affectés. Toutefois, le centre d'hémodialyse n'utilisait pas de système d'évaluation de l'acuité des patients. Nous avons collaboré avec une infirmière cheffe et son assistante pour identifier les facteurs d'acuité influençant la quantité de travail associée à un patient. Ensuite,

pour chacun des facteurs, nous avons estimé le temps supplémentaire à accorder à un patient présentant ce facteur. Cela nous a permis d'estimer des scores utilisés dans un système de mesure de l'acuité des patients.

4. **Développement d'un modèle mathématique d'assignation :** Une fois les contraintes du centre d'hémodialyse comprises et les objectifs identifiés, nous avons modélisé le problème d'assignation de deux manières distinctes. Nous avons implanté les deux modèles sur Julia. Comme il était essentiel que le temps de résolution du modèle soit minimisé pour qu'il puisse être utilisé au quotidien par le centre d'hémodialyse, nous avons évalué les temps de résolution des deux formulations avec diverses instances. Cette évaluation nous a permis de sélectionner la modélisation désirée.
5. **Analyse de sensibilité et validation du modèle :** Pour déterminer les poids à attribuer aux différentes composantes de la fonction objectif, nous avons réalisé une analyse de sensibilité. Ensuite, en présentant des exemples d'affectation aux représentants du centre d'hémodialyse et en discutant des compromis entre les différents indicateurs de qualité, nous avons identifié les poids à intégrer dans la fonction objectif. De plus, nous avons mis en place un groupe de travail afin d'identifier les points forts et les lacunes du modèle développé. Cela nous a permis d'adapter le modèle pour qu'il soit en adéquation avec la réalité quotidienne du centre d'hémodialyse.
6. **Évaluation de l'impact de la qualité des horaires :** Afin d'enrichir l'étude, nous nous sommes interrogés sur l'influence de la qualité des horaires des infirmières et des patients sur les affectations. Pour ce faire, nous avons développé un modèle d'optimisation simultanée des périodes de rendez-vous des patients et des horaires de travail des infirmières. Les résultats de ce modèle ont été intégrés comme paramètres dans le modèle d'affectation afin d'en quantifier l'impact.
7. **Développement d'une interface :** Nous avons développé une interface sur Excel permettant de lancer l'optimisation selon les données et les paramètres spécifiés par l'utilisateur. Après l'optimisation, les affectations sont affichées grâce à l'utilisation de VBA. Le modèle est résolu avec HiGHS, un solveur *open source*, afin de faciliter le transfert technologique.
8. **Formation :** Enfin, nous avons formé le personnel du centre d'hémodialyse sur l'utilisation de l'outil développé.

La démarche décrite est reprise dans l'article présenté au chapitre 4.

CHAPITRE 4 ARTICLE 1: OPTIMIZATION OF THE ORGANIZATION OF A HEMODIALYSIS CENTER

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Abstract : Hemodialysis treatments necessitate multiple weekly hospital visits, each lasting several hours. Planning these treatments is challenging and demands efficient staffing and patient scheduling and assignment. Patients are assigned an appointment day and time, and on the day of treatment, a chair for their treatment, and a nurse to supervise their care. Nurses are scheduled typically two weeks in advance. Solving these problems is complex, mainly due to the variety of patients' acuity, and chair requirement which often conflict with the goal of ensuring equitable workload among nurses. In collaboration with the hemodialysis center from the Centre Hospitalier de l'Université de Montréal, a large teaching hospital in Montreal, we propose a sequential optimization approach that first addresses staffing and scheduling nurses alongside patient scheduling, followed by a multi-objective nurse-to-patient-to-chair assignment, to improve the center's overall organization. The key takeaways are that the shift patterns offered to nurses are crucial for balancing workloads, which is expected to enhance their job satisfaction and the quality of care provided to patients. While the timing of patient appointments does not significantly impact overall operations, substantial improvements are observed through better chair and nurse assignments. To support this, we developed an interface that enables hemodialysis center managers to generate weekly patient assignments and arrival times. This tool also helps mitigate personnel shortages by freeing assistant head nurses from the administrative task of scheduling and assignment planning, allowing them to focus more on effectively managing the center.

Keywords : Hemodialysis organization, Patient assignment to nurse and chair, Scheduling, Workload balancing, Multi-objective optimization

4.1 Introduction

In 2022, more than 48,000 Canadians (excluding Quebec), were living with End Stage Renal Disease. At this stage, the permanent and irreversible loss of kidney function requires renal

replacement therapy by kidney transplantation or dialysis to keep the patient alive [20]. There are two types of dialysis : peritoneal dialysis and hemodialysis [2]. During peritoneal dialysis, a solution circulates in the patient’s abdomen via a catheter, remains there for a predetermined period, and is then removed [3]. Hemodialysis, on the other hand, involves using a dialysis machine and a special filter called a dialyzer to clean the blood. The patient’s blood passes through the machine where a fine membrane filters out waste products like urea and excess fluid, which are then removed. Larger components such as blood cells and proteins remain in the bloodstream. Although a minority of patients start renal replacement therapy with a kidney transplant or an autonomous home dialysis treatment (home hemodialysis or peritoneal dialysis), in-center hemodialysis is the initial modality for over 75% of patients [21]. In-center hemodialysis is generally continued for several years, unless the patient can be transferred to an autonomous dialysis modality, or receive a kidney transplant. Despite the development of living-donor transplantation, cadaveric transplantation remains largely predominant, and is generally associated with a waiting period of 3 to 5 years. Hemodialysis treatments typically last 4 hours and are scheduled three times a week [1].

For in-center treatments, patients are typically assigned to a chair and one (or more) nurse(s) during their appointment. The nurse’s role involves connecting and disconnecting the patient from the hemodialysis machine. They also oversee the hemodialysis treatment, deliver care, and provide supplementary education to the patients. Once a patient’s treatment is completed, the hemodialysis machine must be cleaned before another patient can begin their treatment again. Numerous challenges are encountered in hemodialysis centers to plan these treatments efficiently. For example, several constraints need to be considered. Nurses have a limited capacity regarding the number of patients they can simultaneously attend to. Additionally, the chairs assigned to a nurse need to be close together throughout the day, and for comfort, efforts are made to allocate the same chair to a patient across appointments. The major challenge lies in the need to modify daily assignments for the coming days and sometimes even for the same day due to regular changes in the list of patients requiring appointments. Indeed, some patients need hemodialysis for an extended period of time, while others may only require a few appointments, such as those traveling to a new city who need the services of a new hemodialysis center. Additionally, during the same day, chairs may sometimes be occupied longer than expected, necessitating a reorganization of assignments to find places for waiting patients.

In the literature, most related work in hemodialysis planning primarily focus on optimizing either patient appointment scheduling, which refers to the planning of treatment periods, or on nurse shift scheduling, which may or may not include workload balancing. Some study patient to chair assignment. More generally in a healthcare facility setting, to our

knowledge, no study have addressed the assignment of patients to nurses and chairs while simultaneously considering acuity, the distance between nurses' chairs, and the consistency of chair assignments to patients.

In this paper, we fill this gap. First, we propose a model that simultaneously optimizes nurses' shifts and patients' appointment periods over a two-week period. Next, we develop a mathematical model for the daily assignment of patients to nurses and chairs. We evaluate this approach on a practical case from the teaching hospital University of Montreal Health Centre (CHUM) and provide various analysis on the impact of the staff schedule or patient appointment periods on the overall organization.

Our contribution is threefold :

1. To the best of our knowledge, this is the first study to investigate patient assignment to nurses and chairs using both the consistency of patients' chairs between appointments and a novel equity measure. This measure includes the proximity of chairs assigned to each nurse. The instances used to test the model's outcomes are also larger in terms of the number of patients and nurses.
2. We extend the assignment model to include the optimization of nurse and patient schedules in hemodialysis. We propose a sequential resolution approach, first addressing the scheduling problem followed by the assignment problem.
3. At last, we have developed an intuitive and user-friendly Excel interface to generate daily assignments between chairs, nurses, and patients. Various parameters can be adjusted by the staff of the hemodialysis center to accommodate evolving needs.

This paper is organized as follows. In section 4.2, we present a literature review, followed by a description and a analysis of the problem in section 4.3. The methodology and the mathematical models are described in section 4.4. Furthermore, we analyze the results in section 4.5. Next, we describe the development process of the Excel interface in section 4.6. We conclude with managerial insights in section 4.7 and future directions for research.

4.2 Literature review

Our literature review begins by presenting related work specific to optimizing operations in hemodialysis centers. These are usually related to scheduling patient appointment. We then focus on related work on assignment problems, followed by the integration of nurse and patient scheduling problems. We finally expand our focus to present work that combine scheduling and patient assignment problems.

Most studies in hemodialysis clinics focus on the *patient appointment problem*, either the

daily problem or over a longer period such as two weeks. The problem usually consists of determining the treatment appointment start times, and the objective is to minimize wait time and sometimes overtime. In [15], a link between patient appointment and other procedures is highlighted, suggesting a better appointment system should improve patient hospital stays. In Reihaneh et al. [13], the problem is modeled as a weekly partitioning problem and a Branch and Price algorithm is used to solve it. When solving the problem over a two weeks period, Liu et al. [12] include minimizing equipment usage costs and patients' number of overnight treatments. The aim is to satisfy patient preferences and maintain a balance equipment usage. Finally, [14] develop an analytical model and provide a decision support tool for healthcare staff.

While no study focuses solely on patient assignment problems in hemodialysis context, the literature shows that many studies tackle this problem in other contexts. Usually, it focuses on the *daily assignment of nurses to patients* with the goal of minimizing excessive nurse workload or balancing workload. Workload is generally defined as the amount of care required by the patient, it may include the patient acuity (based on complexity) and the average duration of treatment [6], it could also vary in time [7], or include specifics such as isolation [5]. Mullinax and Lawley [8] for example develop a sophisticated system to measure patient acuity in neonatal intensive care unit, identifying fourteen factors such as the frequency of weighing, the frequency and number of medications, and the infant stability score. Liang and Turkcan [6] propose a multi-objective assignment model in oncology and include minimizing patient wait times and nurses' overtime. The instances range from 40 to 68 patients and 5 to 7 nurses. In [7], the size of the problem varies between 14 to 23 patients, and 4 to 10 nurses. In [8] and [9], the instances are characterized by 10 to 15 nurses, and 20 to 30 infants. Only Schaus et al. [9] use constraint programming to solve the problem. Note that in Mullinax and Lawley [8] and Schaus et al. [9], nurses need also to be assigned to zones, but no notion of distance is considered. Only Acar and Butt [5] include the total distance score of nurses during a shift. This score depends on the proximity of each of their patient room to the nearest supply room and the nearest nursing station, and the distances between the rooms of all their assigned patients. They consider at most 28 patients and 8 nurses. The AHP approach is used to determine the compromise between acuity and distance in the objective function.

Scheduling patients and staff consist generally of assigning them to time slots. Yinusa and Faezipour [22] develop an integer linear model for emergency rooms that simultaneously tackles patient assignment to nurses and patient and staff scheduling while minimizing costs. To prevent an excessive workload for any single nurse, a maximum allowable difference between the hours worked by nurses is enforced. The model is solved for 30 patients and 20 staff

members. Furthermore, Sadki et al. [18] focus on oncology patient appointment scheduling while scheduling the start time of each oncologist's shift. The goal is to minimize patient wait times and the oncology center closing time. To solve this optimization problem, a heuristic based on Lagrange relaxation and a local optimization heuristic are proposed. The number of patients in the instances varies from 16 to 48, with a maximum of 5 oncologists. We observe that these two problems are solved over a one-day period.

To our knowledge, only Farhadi et al. [4] address both the *technician-to-patient assignments and the scheduling problems for technicians and patients simultaneously* in hemodialysis, but from a daily perspective. They also consider patient assignment to beds. They develop a mixed optimization model aiming to minimize technician operation costs by optimizing staffing levels, assignments, and patient arrival times. In the model, workload is measured by the difference in the number of jobs assigned to technicians. The duration of jobs varies according to the patients. The model is solved with a maximum of 60 patients over three appointment periods and two work shifts for the technicians. Note that the model does not consider the distance between the beds assigned to a technician and that the beds, as well as the technicians, are considered identical.

Turkcan et al. [16] and Benzaid et al. [17] solve a similar problem (i.e. patient assignment and scheduling problems), but in an oncology setting. These two contexts are in fact very similar. In oncology, patients need regular appointments, and treatments consist of injection requiring a set-up time followed by the the injection per se. Both use a two-phase approach to address the problem. This is mainly due to the size and the complexity of the problems. In [16], the first phase plans the start day of patient treatment considering patient acuity and treatment resource needs, and the second phase solves the daily assignment problem by assigning each patient a nurse, a chair, and an appointment time. Similarly, Benzaid et al. [17] utilize a two-phase approach in an oncology center. At the end of each day in the first phase, appointments are assigned to new patients, nurse requirements are estimated, and a waitlist is generated in case of cancellations. In the second phase, patients are assigned to nurses while minimizing the number of required nurses. With the approach of [17], constraints verify that the capacity of chairs and beds are sufficient to accommodate patients in the first phase, but patients are not assigned to specific chairs in the second phase.

This literature shows that : 1) the majority of the daily assignment studies do not include the assignment of patients to chairs or beds; 2) the few studies that focus on patient assignment to chairs and nurses do not consider that the chairs need to be close to each other. This is a complicating addition; 3) the largest number of patients in the solved instances is 68, and the maximum number of nurses is 15. In this work, we propose to fill these gaps.

4.3 The practical case of CHUM

In this section, we first describe the characteristics and the processes of the CHUM hemodialysis center, followed by an analysis of their current scheduling and assignment processes.

4.3.1 Organization of the center

The CHUM is a major Montreal-based hospital that offers both an in-hospital hemodialysis center and an outpatient hemodialysis center, the latter being the focus of our case study. This outpatient center serves approximately 200 regular patients, and includes three treatment rooms, each offering an average of 15 treatment chairs arranged in a circular layout. Nursing stations are centrally positioned within each room. Various chair types cater to specific patient needs, including low-seating, bariatric chairs, and those located in isolation rooms, which can be assigned to patients with specific conditions such as contagious infections. Two rooms are dedicated for non-autonomous patients, while the third accommodates semi-autonomous individuals capable of self-managing specific dialysis procedures as connection and disconnection from the hemodialysis machine, thereby reducing nursing workload. Figure 4.1 illustrates the arrangement of chairs across the three rooms of the hemodialysis center.

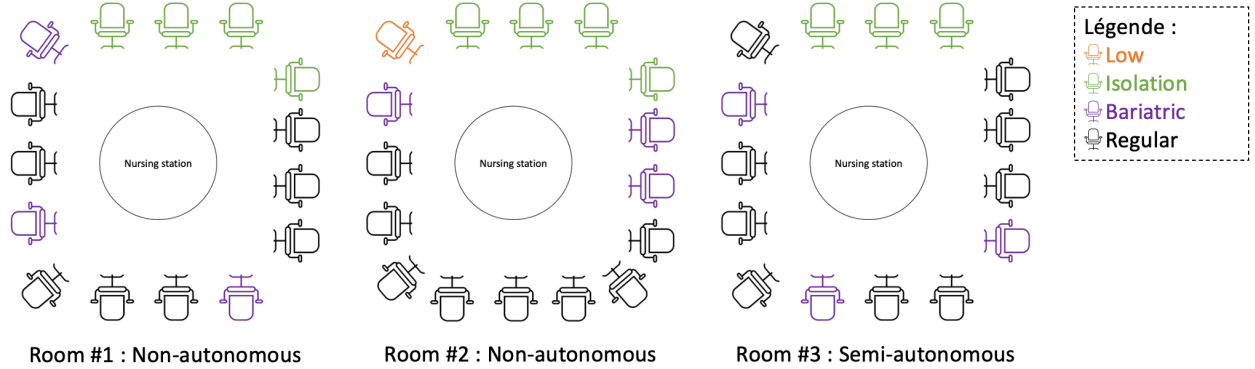


Figure 4.1 Layout of the rooms in the hemodialysis center

A patient can only be assigned to a chair if it meets their specific requirements. For example, an obese patient would not be assigned to a regular chair. However, if necessary, a regular patient could be assigned to a bariatric chair. Most patients do not have specific requirements for their chair assignments (91%), the others require either isolation, bariatric or low chair. Figure 4.2a illustrates the distribution of chair requirements among patients.

Next, we describe the four most important characteristics for planning the center's operations

: appointment periods and times, patient assignment to chairs, nurse schedules and nurse assignments to patients, chairs, and tasks.

Appointment periods The majority of the patients attend three hemodialysis appointments per week. For some individuals, this frequency may be reduced to two sessions, while others may only require intermittent visits, such as during travel to Montreal. Operating six days a week, from Monday to Saturday, between 7:30am and 11:30pm, the center divides its appointments into three distinct periods: morning, afternoon, and evening. Patients are assigned to specific appointment periods which typically remain constant each week. Those receiving three treatments per week are allocated either to the triplet Monday/Wednesday/Friday or Tuesday/Thursday/Saturday. During appointment periods, the majority of patients (84%) undergo hemodialysis treatments lasting 4 hours. A smaller portion of patients receive shorter hemodialysis treatments (between 3 and 3.75 hours) or longer treatments (from 4.25 to 5 hours) (see Figure 4.2b).

Appointment times In the current organization, all patients are assigned the same appointment time, which refers to the start of each appointment period; they all arrive simultaneously. This synchronized schedule aims for efficiency for the hemodialysis center. If a patient is late or a chair is occupied longer than expected, the start order of treatments can easily be adjusted, as there are multiple patients waiting to begin their treatment. However, it occasionally leads to patient frustration due to long waiting times.

Chair assignment After being called by their assigned nurse to start their treatment, patients are directed to their assigned treatment chairs, with efforts made to maintain consistency in chair allocation between appointments. When assignment to their usual chair is not possible, patients are assigned to a chair within their usual treatment room. This procedure helps optimize comfort and familiarity, as well as efficiency since patients are familiar with their treatment environment, including the operation of TV screens and chair adjustments. Additionally, specific procedures, such as blood tests are occasionally conducted within rooms, simplifying the tracking of testing frequency through consistent patient room assignments.

Nurse scheduling Nurses work either 8 or 12-hours shifts. There are three 8-hour shifts per day: morning, afternoon, and evening shifts. Nurses on the morning shift can only be assigned to patients scheduled for the morning appointment period, and the same logic applies to nurses on the afternoon and evening shifts. For the 12-hour shifts, there are

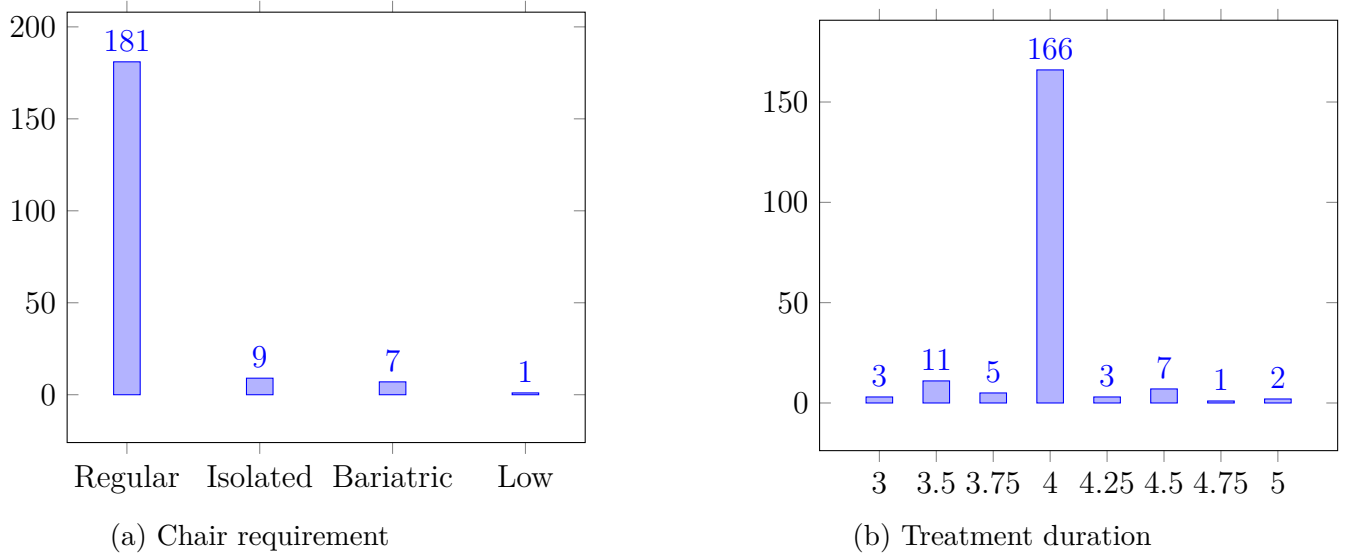


Figure 4.2 Distribution of patients

morning and afternoon shifts. A nurse working a 12-hour morning shift can be assigned to patients scheduled for both morning and afternoon appointments, while nurses on the 12-hour afternoon shift can be assigned to patients scheduled for afternoon and evening appointments. Overall, nurses work 75 hours over 2 weeks : 10 shifts of 8 hours for the 8-hour schedule type or 6 shifts of 12 hours plus one 8-hours shift for the 12-hour schedule type. There is a 45-minute break for every 8 hours worked. Figure 4.3 summarizes the nurses' shifts and the appointment periods to which they may be assigned to patients.

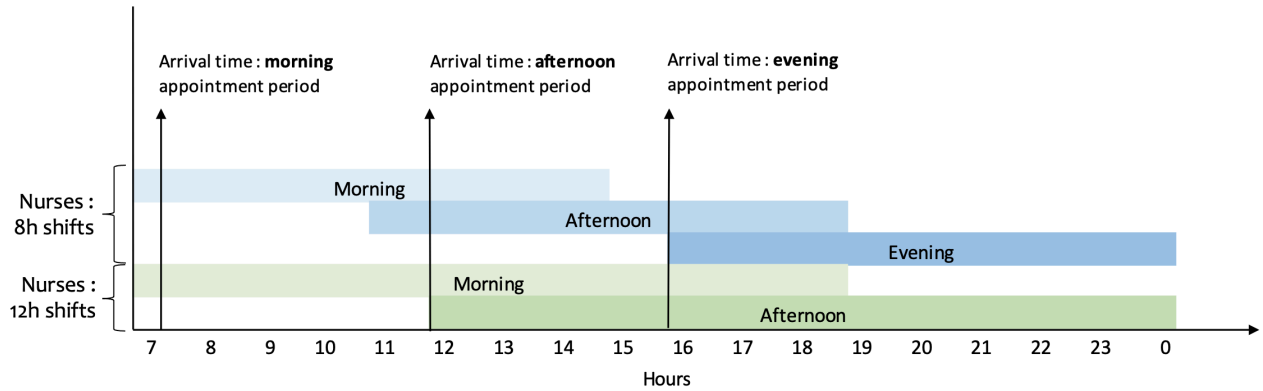


Figure 4.3 Organization of the nurses' shifts and the patients' appointment periods

Nurse assignment Once settled, patients begins their hemodialysis treatment with their respective nurse, who connect them or help them connect to their assigned hemodialysis

machines. Throughout the session, nurses closely monitor treatment progress and may undertake additional tasks such as dressing changes or administering antibiotics.

Nurses are generally assigned to the same section of chairs in the same room during the day. There are approximately 40 nurses at the hemodialysis center. Occasionally some nurses cannot be assigned to patients as they do not have the level of experience. Note that some nurses may not be assigned to specific patients but will instead assist other nurses with tasks such as cleaning stations or completing patient records. The number of patients that can be assigned to a nurse during a shift and during a day varies according to the nurse's level of experience and training. The patients are also distributed equitably between the nurses depending on their acuities. The acuity of each patient perceived by nurses varies based on their characteristics and needs.

Task assignment Each treatment is divided into three parts : connecting the patient to the machine, the hemodialysis process, and the disconnection. Typically, assigning a patient to a nurse means that the nurse will perform all three tasks for the patient. Note that the hemodialysis process mainly requires surveillance, so nurse are typically assigned to more than one patient and may be connecting or disconnecting other patients. In the current organization, 8-hour shifts are usually assigned to a complete treatment, thus they will be assigned to all three tasks. This is not the case for the 12-hour shifts. Nurses working morning 12-hour shift often do not have sufficient time to disconnect patients during the afternoon period or must rush to complete this task. Nurses working 12-hour afternoon shifts face the same issue with connecting patients from the afternoon appointment period.

4.3.2 Scheduling and assignment strategies at the CHUM

At the hemodialysis center, nurses create their schedules through a self-scheduling process for two-week periods. These schedules are then reviewed by a scheduling clerk to ensure fair distribution of shifts among the nurses and that the covering constraints (enough nurses for each appointment periods) are met. If there are insufficient nurses to cover specific shifts and overtime is necessary, a sign-up sheet is posted to request volunteers. Additionally, the scheduling clerk may call nurses to solicit overtime. Regarding patient schedules, patients are assigned to an appointment pattern when they begin their treatments. The assigned pattern depends on the center's capacity for each appointment period but also considers patient preferences.

Once nurse schedules are finalized, they are used to define nurse assignments to patients and chairs for each appointment period. Initially, an assignment plan for the entire week is created

by assistant head nurses using an Excel file. Since the hemodialysis center receives weekly calls to temporarily accommodate new patients or to cancel regular patients' appointments, frequent reviews of assignments are necessary. On average, each week, one non-regular patient at the hemodialysis center requires appointments, while 15 regular patients are absent. Additionally, on the same day, treatments may take longer than expected. Consequently, assignments must be adjusted throughout the day based on chair and nurse availability. Thus, on average, nurses spend 30 minutes each day reviewing the initial assignments.

4.3.3 Discussion

Our field observations and preliminary analysis reveal four key findings.

- Impact of Nurse Scheduling : Nurse scheduling significantly affects the daily assignment of patients to chairs and nurses. For instance, staffing levels during certain shifts may not be adequate to achieve a balanced workload.
- Workload Measurement: While crucial, the center currently lacks a formal measure for assessing workload, which hinders the ability to make meaningful comparisons.
- Patient Allocation to Appointment Periods : Contrary to existing literature on appointment scheduling, allocating patients to appointment periods does not appear to pose significant challenges. The literature often emphasizes the difficulty of setting precise appointment times due to varying treatment durations and strict deadlines for starting treatment. However, in the context of hemodialysis, treatment durations are relatively consistent across patients, simplifying these challenges. This confirms that the appointment periods themselves do not need revision; instead, the focus should be on optimizing patient arrival times within their respective appointment periods.
- Challenge of Daily Assignments : The daily assignment of patients to chairs and nurses is a significant operational challenge for the hemodialysis center and has been identified as an area urgently needing improvement.

To address these issues, we propose the following steps:

- 1) Develop a model for optimal staffing and scheduling.
- 2) Develop a model to solve the daily assignment of patients to chairs and nurses.
- 3) Design a procedure to determine patient arrival times within their appointment periods. This procedure adjusts arrival times based on the patients assigned to each nurse, thereby reducing patient wait times. Figure 4.4 illustrates a potential sequence for patient connections by a nurse, aligned with their arrival times, to ensure that the last treatment concludes as early as possible.

We will evaluate the quality of the current staffing and scheduling configurations through extensive comparison and analysis. This will enable us to provide recommendations and

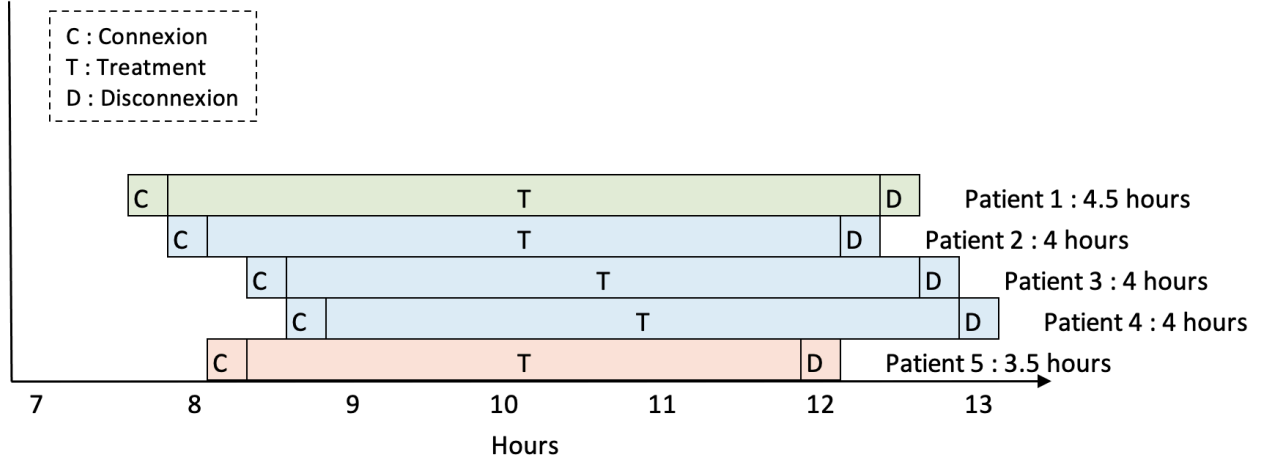


Figure 4.4 Example of a sequence for patient arrival times

identify potential areas for improvement.

4.4 Mathematical Models and Methodology

In this section, we first describe the formal method to calculate patients' acuity. Next, we present two interrelated linear optimization models and the procedure designed for the hemodialysis center : the patient and nurse scheduling model (PNS), the nurse-to-patient-to-chair assignment model (NPC), and the patient appointment time procedure (PAT). We develop the PNS to optimize the staffing and the scheduling of patients. Subsequently, the NPC is utilized to determine the optimal allocation of nurses to patients and chairs, serving as a foundation for scheduling patient arrival times. Finally, the PAT optimize the timing of patient appointments.

4.4.1 Acuity calculation

To build an optimization model for assignments, we developed a model to numerically evaluate a patient's acuity. To quantify the acuity associated with each patient, we collaborated with the hemodialysis center staff to identify the factors that influence the time a nurse dedicates to a patient during their hemodialysis session. An acuity factor is defined as any element that impacts the duration of care a nurse provides, thereby affecting the overall workload. The head nurse of the hemodialysis center initially collected information from the nurses regarding the acuity factors. Subsequently, we held a first meeting with the head nurse to identify these factors, followed by a second meeting to determine the associated times. Through this collaborative process, we identified eight distinct acuity factors and

their corresponding times. These times were then used to assign scores to each factor. For final validation, we confirmed the accuracy of these scores in consultation with the head nurse's assistants. Table 4.1 presents the scores allocated to each acuity factors.

Table 4.1 Scores of acuity factors

Acuity factors	Score
Cane or walker	1
Subcutaneous injections	1
Catheter	2
Confusion	2
Wheelchair	2
Isolation	2
Regular intravenous	3
Antibiotic intravenous	5

To calculate a patient's acuity, we sum all the relevant factor scores for each patient and add them to a base score of 1. The maximum possible acuity score is set at 6, with fewer than 5% of patients exceeding this threshold.

Figure 4.5 represents the distribution of acuities for regular patients at the hemodialysis center. It is observed that patient acuity varies significantly : around 30% have a score of 1, over 35% have a score of 3, and the remaining patients are fairly evenly distributed across scores 2, 4, 5 and 6.

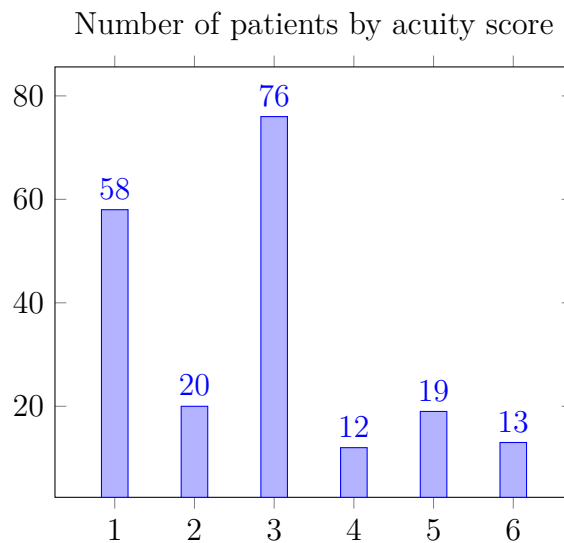


Figure 4.5 Distribution of acuity scores

4.4.2 Patient and nurse scheduling model (PNS)

We first present the PNS model that optimizes both the patient appointment periods and the nurse schedules simultaneously. The schedules generated will then be integrated into the assignment model.

In the model, patients are assigned to appointment patterns, where a pattern corresponds to the patient's appointment periods within a week. Concurrently, we complete the nurses' two-week work schedule. The model is solved for the same period. To construct the nurses' schedules, they are assigned to shifts for each day. Thus, based on the designated nurse schedules and shifts, the proportion of nurses completing 8-hour and 12-hour shifts may vary from day to day. The objective of the model is to minimize the maximum ratio of the total acuity during a shift out of the number of nurses working during that shift. Note that patients and nurses are identified in this model to allow for the incorporation of their preferences, availability, and specific needs when necessary.

Notation used in the PNS model is detailed in table 4.2.

There are two main binary variables in the model : f_{pi} and m_{nqj} that respectively assign appointment patterns and working shifts to patients and nurses. Each nurse is also assigned to a schedule type with the variable k_{ns} . The schedule types are the 8-hour schedules and the 12-hour schedules.

In the objective function, we also introduce the variable ω that represents the maximum acuity-to-nurse ratio during an appointment period. The acuity-to-nurse ratio is defined by the division of the total patient acuity during an appointment period by the number of nurses working during that period. The objective of the model is to minimize the acuity-to-nurse ratio (ω) which is represented with the objective function (4.1).

$$\text{Minimize } \omega \tag{4.1}$$

Note that we can easily include preferences of patients and nurses in the objective function. Indeed, patients often express preferred day or period to have their treatment depending on their schedule. Nurses can also prefer to work during certain days or favour specific types of schedules.

Table 4.2 Sets, parameters and variables of the PNS model

Sets	Description
P	Set of patients
A	Set of appointment periods for patients
N	Set of nurses
I	Set of appointment patterns
Q	Set of nurses' shifts
S	Set of nurse schedule types
D	Set of shift durations
J	Set of days
Π_n	Set of possible values for the total number of nurses working during an appointment period
Π_r	Set of possible values for the acuity-to-nurse ratio
O	Set of needs for chair characteristics (regular, bariatric, low, bariatric with isolation, etc)
Parameters	
w_p	The acuity of patient p
κ_{ij}^a	Equals 1 if pattern i schedules an appointment during period a and day j
κ_{ij}	Equals 1 if pattern i schedules an appointment during day j
Λ_{pi}	Equals 1 if patient p can be assigned to appointment pattern i
ϑ_{aq}	Equals 1 if a nurse working during shift q can be assigned to patients in the appointment period a
ω_n^a	The maximum number of patients that can be assigned to nurse n during an appointment period
ϱ_{nq}	The maximum number of patients that can be assigned to nurse n during shift q
ρ_s	The maximum proportion of nurses that can be assigned to schedule type s
ν_{sd}	The number of shift with a duration of d that a nurse has to complete if they are assigned to schedule type s
φ_{nqj}	Equals 1 if nurse n can be assigned to shift q during day j
τ_{qd}	Equals 1 if the duration of shift q is d
Υ_{ajo}	The number of chairs that can accommodate patients requiring a chair with characteristic o during appointment period a and day j
ψ_{ajo}^o	Equals 1 if patient p requires a chair with characteristic o
Variables	
f_{pi}	Equals 1 if patient p is assigned to appointment pattern i
m_{nqj}	Equals 1 if nurse n is assigned to shift q during day j
k_{ns}	Equals 1 if nurse n is assigned to schedule type s
ω	The maximum acuity-to-nurse ratio during an appointment period
$g_{\pi_n \pi_r a j}$	Equals 1 if the number of working nurses is π_n and the acuity-to-nurse ratio is π_r during appointment period a and day j
v_{aj}	The maximum total acuity during appointment period a and day j

We divide the model in 4 main categories of constraints :

1. Acuity-to-nurse ratio
2. Patient scheduling constraints
3. PNS constraints
4. Capacity constraints

Acuity-to-nurse ratio The main objective of the model is to minimize the maximum acuity-to-nurse ratio during an appointment period. The following constraints are introduced to calculate the highest ratio between patient total acuity during an appointment period and the number of nurses working during that period :

$$\sum_{p \in P} \sum_{i \in I} \frac{w_p \kappa_{ij}^a f_{pi}}{\vartheta_{aq} m_{nqj}} \leq \omega \quad \forall a \in A, \forall j \in J \quad (4.2)$$

Since constraints (4.2) is not linear, we linearize it with the following constraints (4.3)-(4.7):

$$\sum_{p \in P} \sum_{i \in I} w_p \kappa_{ij}^a f_{pi} \leq v_{aj} \quad \forall a \in A, \forall j \in J \quad (4.3)$$

$$v_{aj} = \sum_{\pi_n \in \Pi_n} \sum_{\pi_r \in \Pi_r} \pi_n \pi_r g_{\pi_n \pi_r a j} \quad \forall a \in A, \forall j \in J \quad (4.4)$$

$$\sum_{n \in N} \sum_{q \in Q} \vartheta_{aq} m_{nqj} = \sum_{\pi_n \in \Pi_n} \sum_{\pi_r \in \Pi_r} \pi_n g_{\pi_n \pi_r a j} \quad \forall a \in A, \forall j \in J \quad (4.5)$$

$$\omega = \sum_{\pi_n \in \Pi_n} \sum_{\pi_r \in \Pi_r} \pi_r g_{\pi_n \pi_r a j} \quad \forall a \in A, \forall j \in J \quad (4.6)$$

$$\sum_{\pi_n \in \Pi_n} \sum_{\pi_r \in \Pi_r} g_{\pi_n \pi_r a j} = 1 \quad \forall a \in A, \forall j \in J \quad (4.7)$$

Patient scheduling constraints The scheduling constraints for the patients are based on the definition of the appointment pattern of each patient.

$$\sum_{i \in I} f_{pi} = 1 \quad \forall p \in P \quad (4.8)$$

$$f_{pi} \leq \Lambda_{pi} \quad \forall p \in P, \forall i \in I \quad (4.9)$$

Constraints (4.8) assign each patient to an appointment pattern while constraints (4.9) verify that the patient can be assigned to each of the patterns with the parameter Λ_{pi} depending

on their availability and the number of appointment periods in the patterns.

PNS constraints The role of the PNS is to assign nurses to shifts and schedule types. The following constraints pertain to this category :

$$\sum_{s \in S} k_{ns} = 1 \quad \forall n \in N \quad (4.10)$$

$$\sum_{n \in N} k_{ns} \leq \rho_s |N| \quad \forall s \in S \quad (4.11)$$

$$\sum_{q \in Q} \sum_{j \in J} \tau_{qd} m_{nqj} = \sum_{s \in S} \nu_{sd} k_{ns} \quad \forall n \in N, \forall d \in D \quad (4.12)$$

$$\sum_{q \in Q} m_{nqj} \leq 1 \quad \forall n \in N, \forall j \in J \quad (4.13)$$

$$m_{nqj} \leq \varphi_{nqj} \quad \forall n \in N, \forall q \in Q, \forall j \in J \quad (4.14)$$

First, constraints (4.10) assign each of the nurses to a schedule type. Since, the hemodialysis center does not wish that all the nurses are assigned to 12-hour shift schedules, constraints (4.11) specify the maximum proportion of nurses ρ_s that can be assigned to different schedule types. Constraints (4.12) ensure that the correct number of shifts of each duration ν_{sd} is completed by the nurses according to the type of schedule they are assigned to. Furthermore, the role of constraints (4.13) is to ensure that a nurse is assigned to a maximum of one shift per day. Additionally, constraints (4.14) prevent nurses from being assigned to certain shifts with the parameter φ_{nqj} if, for example, they have a day off.

Capacity constraints The hemodialysis center has a limited capacity for patients that can be assigned to each appointment period. This limitation is determined not only by the number of chairs available in the center but also by the number of nurses on staff. The following constraints reflect these capacity challenges:

$$\sum_{p \in P} \sum_{i \in I} \kappa_{ij}^a \psi_{po}^o f_{pi} \leq \Upsilon_{ajo} \quad \forall a \in A, \forall j \in J \quad (4.15)$$

$$\sum_{p \in P} \sum_{i \in I} \kappa_{ij}^a f_{pi} \leq \sum_{n \in N} \sum_{q \in Q} \omega_n^a \vartheta_{aq} m_{njq} \quad \forall a \in A, \forall j \in J \quad (4.16)$$

$$\sum_{p \in P} \sum_{i \in I} \kappa_{ij}^a f_{pi} \geq \sum_{n \in N} \sum_{q \in Q} \vartheta_{aq} m_{nqj} \quad \forall a \in A, \forall j \in J \quad (4.17)$$

$$\sum_{p \in P} \sum_{i \in I} \kappa_{ij}^a f_{pi} \leq \sum_{n \in N} \sum_{q \in Q} \varrho_{nq} m_{njq} \quad \forall a \in A, \forall j \in J \quad (4.18)$$

Constraints (4.15) ensure that there are enough chairs to accommodate all patients, taking into account the days when certain rooms are closed. They also ensure that there are enough chairs meeting the patients' specific requirements (ψ_{po}^o). Constraints (4.16) and (4.17) ensure the respect of the capacity of the nurses f_n during an appointment period but also verifies that a nurse must be assigned to a minimum number of patients if they are working. Similarly, constraints (4.18) verify that the maximum daily capacity of the nurses ϱ_{nq} is respected depending on their assigned shifts. Each nurse has a specific capacity for the number of assignments during one appointment period but also during each type of shifts.

Constraints (4.19)-(4.24) define the domain of the variables.

$$f_{pi} \in \{0, 1\} \quad \forall p \in P, \forall i \in I \quad (4.19)$$

$$m_{nqj} \in \{0, 1\} \quad \forall n \in N, \forall q \in Q, \forall j \in J \quad (4.20)$$

$$k_{ns} \in \{0, 1\} \quad \forall n \in N, \forall s \in S \quad (4.21)$$

$$\omega \geq 0 \quad (4.22)$$

$$g_{\pi_n \pi_r a j} \in \{0, 1\} \quad \forall \pi_n \in \Pi_n, \forall \pi_r \in \Pi_r, \forall a \in A, \forall j \in J \quad (4.23)$$

$$v_{aj} \geq 0 \quad \forall a \in A, \forall j \in J \quad (4.24)$$

Note that constraints could also be incorporated into the model to ensure an even distribution of shifts across weeks, fairness among the nurses, or a specific sequencing of the nurses' shifts.

There is one important comment about the PNS model. We do not need to consider explicitly the chair assignment in the model to account for the workload related to distance between chairs. In fact, the equitable distribution of acuity across appointment periods implicitly considers this allocation of patients with specific needs to chairs. Indeed, one of the factors influencing acuity, as well as a characteristic for chair assignments, is the need for isolation (see Figure 4.1). This need is the only one that may impact the distance between chairs. Regardless of the scheduling model's outcome, i.e. number of nurses and patients per appointment period, consecutive chair assignments can still be achieved when solving the patient-to-nurse-to-chair assignment model considering the current layout of the hemodialysis center.

4.4.3 Nurse-to-patient-to-chair assignment problem (NPC)

The NPC problem consists of assigning patients to nurses and chairs. The problem is solved daily. Patient appointment periods and nurse shifts are fixed and known in advance. While chair consistency is easily measured through the assignment variable x_{pnc} of chair c and nurse

n to patient p , the workload of nurses has two components : the acuity of patients and the distance covered to care for the patients. Indeed, to optimize nurses' efficiency, patients assigned to the same nurse must be placed in chairs close to each other, minimizing nurses' movements. Let's introduce pairs of chairs in the following.¹ A pair of chairs corresponds to two chairs *close enough* to be assigned to the same nurse. This forbids chairs too far apart or in different rooms. Each pair of chairs includes a primary chair, which is the first chair of the pair. A nurse must be assigned one primary chair per day and this primary chair must be associated with pairs that include the chairs of their patients for the day. Figure 4.6 illustrates an example of pairings between a nurse's primary chair and their patient chairs during an appointment period.

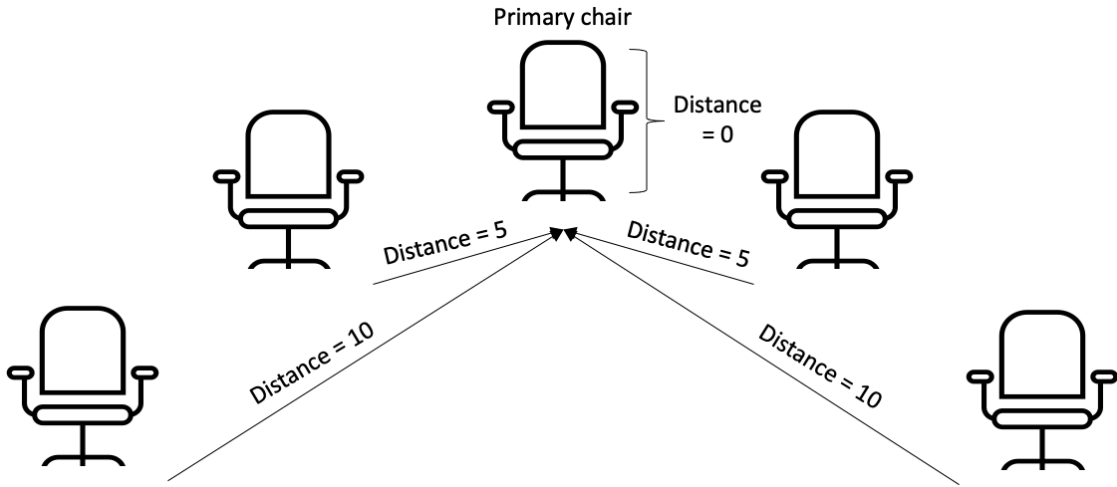


Figure 4.6 Illustration of chair pairings

Each pair of chairs has a score that represents the distance between them. Variable y_{nc} is used to identify the assignment of each nurse to a primary chair per day, while variable u_{nae} calculates the distance between chairs for nurse n . Variables α_a and β are used to compute the acuity part of the workload for each nurse.

We summarize the sets and the parameters used in the mathematical model in table 4.3 and the variables in 4.4.

1. Note that we compared this modeling approach to one where all possible chair assignments are represented, with each assignment referred to as a pattern. Within a pattern, chairs are close to each other and within the same room. We ran both models for 500 seconds on six instances, varying the number of patients and nurses, acuity levels, and working shifts. The mean %GAP with patterns was significantly higher (14.2%) than with the pair of chairs (3.6%). The performance of both models is similar for smaller instances. Given that the aim of the project is to develop a tool for daily use by the hospital, we chose the pair of chairs method since it provides a better solution more quickly in practice.

Table 4.3 Sets and parameters of the NPC model

Sets	Description
C	Set of chairs
E	Set of pairs of chairs
Parameters	Description
b_{na}	Equals 1 if nurse n works during appointment period a
ω_n^j	The maximum number of patients that can be assigned to nurse n during a day depending of their level of experience and the duration of their shift
ϕ_{pn}	Equals 1 if patient can be assigned to nurse n . In order to be assigned to patient p , nurse n needs to be able to complete patient p treatment during their shift depending on the patient's appointment period. Some nurses also can't be assigned to patients because of their experience or the patients' characteristics
Γ_p	Equals 1 if patient p needs to be assigned one for one with a nurse
Φ_{pa}	Equals 1 if patient p has an appointment during appointment period a
l_p	The duration of the hemodialysis appointment of patient p
d^{Max}	The maximum duration of hemodialysis appointments in the same chair during a day
a^{Max}	The maximum duration of hemodialysis appointments in the same chair during two consecutive appointment periods
w_p^n	The average acuity of patient p for nurse n during their shift
h_c^p	The score of patient p for chair c . A chair will have a high score if it is located in a room corresponding to the patient's level of autonomy and if it is the usual treatment chair of the patient
σ_{pc}	Equals 1 if chair c is the usual treatment chair of patient p
λ^c	The number of patients who have to be assigned to their usual treatment chair. This number is calculated based on a specified proportion of patients who must be assigned to their usual chair, provided that a feasible solution exists.
μ_{pnc}	Equals 1 if patient p was previously assigned to nurse n and chair c
λ^{nc}	The maximum number of patients who can be assigned to their previous nurse and chair while obtaining a feasible solution
ψ_{pc}^c	Equals 1 if chair c can be assigned to patient p . A chair can be assigned to a patient if it responds to the patient needs (isolation, bariatric, low chair, etc.) and if it's located in a room that is open during the patient's appointment
γ_{ce}	Equals 1 if chair c is the primary chair of the pair e
r_{ce}	Equals 1 if chair c is assigned to the primary chair in pair e
Ω_e	The distance between the chairs of pair e

Table 4.4 Variables of the NPC model

Variables	Description
x_{pnc}	Equals 1 if nurse n is assigned to patient p in chair c
y_{nc}	Equals 1 if nurse n is assigned to primary chair c during the day
u_{nae}	Equals 1 if the pair of chairs e is assigned to nurse n during period a
α_a	The maximum assigned acuity of a nurse during shift a
β	The maximum average assigned acuity of a nurse during a shift

The objective of the model comprises four components (4.25). The first component evaluates the quality of chair assignments, while the remaining components assess the workload of nurses. For each patient, the score of a chair, which reflects the quality of its assignment to the patient, depends on the patient level of autonomy and, if applicable, its consistency based on previous assignments (i.e. usual treatment chair). The second and third terms measure workload from the perspective of patient acuity levels. They capture the maximum assigned acuity level during each appointment period and throughout a shift. For instance, it is undesirable for the same nurse to handle a high acuity level assignment during both morning and afternoon periods while other nurses manage lower acuity levels. Considering the maximum average acuity assigned during the entire shift addresses this issue. Lastly, the fourth term evaluates the workload from the chair assignment perspective. It computes the total distance between a nurse's primary chair and other assigned chairs.

The objective function is modeled as follows:

$$\text{Minimize } p_1 \sum_{p \in P} \sum_{n \in N} \sum_{c \in C} h_c^p x_{pnc} + p_2 \sum_{a \in A} \alpha_a + p_3 \beta + p_4 \sum_{n \in N} \sum_{a \in A} \sum_{e \in E} \Omega_e u_{nae} \quad (4.25)$$

The constraints in the model can be separated in 4 distinct categories :

1. Nurse-to-patients assignment constraints
2. Patient-to-chair assignment constraints
3. Nurse-to-chairs assignment constraints
4. Acuity constraints

We describe them in the following paragraphs.

Nurse-to-patients assignment constraints The first constraint group is based on the assignment of patients to nurses which depends on the daily capacity and the experience of

the nurses.

$$\sum_{n \in N} \sum_{c \in C} x_{pnc} = 1 \quad \forall p \in P \quad (4.26)$$

$$\sum_{c \in C} x_{pnc} \leq \phi_{pn} \quad \forall p \in P, n \in N \quad (4.27)$$

$$\sum_{p \in P} \sum_{c \in C} \Phi_{pa} x_{pnc} \leq \omega_n^a \quad \forall n \in N, \forall a \in A \quad (4.28)$$

$$\sum_{p \in P} \sum_{c \in C} x_{pnc} \leq \omega_n^j \quad \forall n \in N \quad (4.29)$$

$$\sum_{p \in P} \sum_{c \in C} \Gamma_p \Phi_{pa} x_{pnc} \leq 1 \quad \forall n \in N, \forall a \in A \quad (4.30)$$

$$\sum_{p \in P} \sum_{c \in C} \Phi_{pa} x_{pnc} \geq b_{na} \quad \forall n \in N, \forall a \in A \quad (4.31)$$

Constraints (4.26) assign each patient to a nurse and a chair. Furthermore, constraints (4.27) ensure that nurses can be assigned to patients based on their level of experience and their shifts denoted by ϕ_{pn} . Indeed, depending on the nurse's shift, they can only be assigned to patients scheduled for treatments during specific appointment periods. Constraints (4.28) and (4.29) verify that the maximum number of patients that can be assigned to a nurse during a shift ω_n^a and throughout the day ω_n^j is respected. Constraints (4.30) ensure that a patient requiring one-on-one care, denoted by Γ_p , is assigned a dedicated nurse. Furthermore, constraints (4.31) ensure that if a nurse is working during an appointment period, they are assigned at least one patient.

Patient-to-chair assignment constraints The assignment of chairs to patients varies according to various factors such as the opening hours of the hemodialysis center rooms and patient characteristics. The following set of constraints represents these elements.

$$\sum_{p \in P} \sum_{n \in N} \Phi_{pa} x_{pnc} \leq 1 \quad \forall a \in A, \forall c \in C \quad (4.32)$$

$$\sum_{p \in P} \sum_{n \in N} l_p x_{pnc} \leq d^{Max} \quad \forall c \in C \quad (4.33)$$

$$\sum_{a=s}^{s+1} \sum_{p \in P} l_p x_{pnc} \leq a^{Max} \quad \forall s = 1 \dots |A| - 1, \forall c \in C \quad (4.34)$$

$$\sum_{n \in N} x_{pnc} \leq \psi_{pc}^c \quad \forall p \in P, \forall c \in C \quad (4.35)$$

$$\sum_{p \in P} \sum_{n \in N} \sum_{c \in C} \sigma_{pc} x_{pnc} \geq \lambda^c \quad (4.36)$$

$$\sum_{p \in P} \sum_{n \in N} \sum_{c \in C} \mu_{pnc} x_{pnc} \geq \lambda^{nc} \quad (4.37)$$

Constraints (4.32) specify that two patients cannot be seated in the same chair during the same appointment period. Constraints (4.33) and (4.34) verify the combination of patients seated in the same hemodialysis chair. Constraints (4.33) ensure that the total duration of dialysis treatments l_p on a chair does not exceed the operating hours of the hemodialysis center, and constraints (4.34) prevent sequences of dialysis sessions that could cause delays for nurses. For example, two long dialysis sessions cannot be completed consecutively on the same chair. Constraints (4.35) ensure that chairs are suitable for patients' characteristics and are located in rooms open during the patients' appointment periods denoted by ψ_{pc}^c . Furthermore, constraints (4.36) indicate that a minimum number of patients must be assigned to their usual treatment chair σ_{pc} . These constraints are not always used in the resolution of the model. They are incorporated when the usual treatment chairs of patients are known, and there is a need to ensure consistency in chair assignments. Constraints (4.37) are similar by verifying that a minimum number of patients must be assigned to their previous chair and nurse μ_{pnc} . These constraints are applied when it is necessary to adjust patient assignments to nurses and chairs on the day of the appointment due to delays in previous treatments. The methods for integrating constraint (4.36) and (4.37) into different versions of the model, depending on the context of use, are detailed in section 4.6.

Nurse-to-chairs assignment constraints A central element of the nurses' workload is the distance between the patients' chairs assigned to each nurse. To address this, pairs of chairs are assigned to nurses based on the patients' chairs and the nurse's primary chair. The

variable u_{nae} is used to quantify the distance between the chairs assigned to a nurse.

$$\sum_{c \in C} y_{nc} = 1 \quad \forall n \in N \quad (4.38)$$

$$\sum_{e \in E} r_{ce} u_{nae} \geq \sum_{p \in P} \Phi_{pa} x_{pnc} \quad \forall n \in N, \forall a \in A, \forall c \in C \quad (4.39)$$

$$\gamma_{ce} u_{nae} \leq b_{na} y_{nc} \quad \forall n \in N, \forall a \in A, \forall c \in C, \forall e \in E \quad (4.40)$$

Constraints (4.38) assign each nurse a primary chair per day. Indeed, each nurse must be assigned a central chair for the day to ensure that patients' chairs are all in proximity to this point. Constraints (4.39) and (4.40) link patient chairs to nurses' primary chairs, ensuring pairs exist between them. The parameter γ_{ce} is used to represent if a chair is the primary in a pair.

Acuity constraints To calculate the two variables pertaining to nurse assigned acuity in the objective function, the following constraints are included :

$$\sum_{p \in P} \sum_{c \in C} w_p \Phi_{pa} x_{pnc} \leq \alpha_a \quad \forall n \in N, a \in A \quad (4.41)$$

$$\sum_{p \in P} \sum_{c \in C} w_p^n x_{pnc} \leq \beta \quad \forall n \in N \quad (4.42)$$

Constraints (4.41) calculate the maximum assigned acuity for a nurse during each shift α_a , while constraints (4.42) calculate the average acuity assigned per shift for a nurse throughout the day β .

Finally, the last set of constraints is used to define the domain of the variables.

$$x_{pnc} \in \{0, 1\} \quad \forall p \in P, n \in N, c \in C \quad (4.43)$$

$$y_{nc} \in \{0, 1\} \quad \forall n \in N, c \in C \quad (4.44)$$

$$u_{nae} \in \{0, 1\} \quad \forall n \in N, a \in A, e \in E \quad (4.45)$$

$$\alpha_a \geq 0 \quad \forall a \in A \quad (4.46)$$

$$\beta \geq 0 \quad (4.47)$$

4.4.4 Patient appointment time procedure (PAT)

Once patients are assigned to nurses and chairs, one needs to determine their arrival times. The PAT model can be solved independently for each group of patients assigned to a nurse during each shift. This is due to the fact that the NPC model ensures that chair assign-

ments are tailored to the treatment duration of patients, enabling everyone to complete their hemodialysis during the opening hours of the center and without overly extending into the next appointment slot. To achieve this, the operating hours of the hemodialysis center are divided into 15-minute slots. For each group of patient, we define a set of slots during which they need to start their hemodialysis treatment. Notation used in the PAT model is summarized in table 4.5.

Table 4.5 Sets, parameters, and variables of the PAT procedure

Sets	Description
T	Set of slots
T_s	Set of slots during which patients can arrive - $T_s \subseteq T$
Parameters	
ϵ_{pt}	Equals 1 if t is the earliest slot to begin the appointment of patient p
$\theta_{pt_1 t_2}$	Equals 1 if t_2 is the end slot for the treatment of patient p if their appointment starts during slot t_1
Variables	
δ_{pt}	Equals 1 if patient p 's appointment begins during slot t
η	The slot of the latest end for a patient's treatment

In this model, the objective is to minimize patient appointment time and the latest ending time for each group at the hemodialysis center. We aim for each patient to start their appointment as early as possible to allow flexibility in case an appointment runs longer than expected. Additionally, to avoid delays for subsequent appointment periods and to facilitate early closure of the hemodialysis center, we also plan the latest treatment end time to be as early as possible. The objective function (4.48) encapsulates those 2 goals and is modeled as follows:

$$\text{Minimize } p_1 \sum_{p \in P} \sum_{t \in T} \delta_{pt} + p_2 \eta \quad (4.48)$$

We introduce the following key constraints in the PAT model to reflect operational requirements :

$$\sum_{t \in T_s} \delta_{pt} = 1 \quad \forall p \in P \quad (4.49)$$

$$\sum_{p \in P} \delta_{pt} \leq 1 \quad \forall t \in T_s \quad (4.50)$$

$$\sum_{p \in P} \sum_{t_1 \in T_s} \theta_{pt_1 t_2} \delta_{pt_1} \leq 1 \quad \forall t_2 \in T \quad (4.51)$$

$$\sum_{p \in P} \sum_{t_1 \in T_s} t_2 \theta_{pt_1 t_2} \delta_{pt_1} \leq \eta \quad \forall t_2 \in T \quad (4.52)$$

$$\sum_{t \in T_s} t \delta_{pt} \geq \epsilon_p \quad \forall p \in P \quad (4.53)$$

$$\delta_{pt} \in \{0, 1\} \quad \forall p \in P, \forall t \in T \quad (4.54)$$

$$\eta \in T \quad (4.55)$$

Constraints (4.49) stipulate that each patient must be assigned an arrival time that corresponds to the start time of their treatment. Constraint (4.50) and constraints (4.51) ensure that no patients start or finish treatment at the same time (i.e. connected or disconnected simultaneously). Constraints (4.52) identify the end of all treatments, marked by the last disconnection slot for a patient, denoted as η . It is possible that the disinfection of the hemodialysis machine following the treatment of a patient may not be completed before the beginning of the next appointment period. Constraint (4.53) ensures that the following patient's arrival time occurs after the disinfection process is finished. Constraints (4.54) and constraints (4.55) define the domains of the variables.

4.5 Experimentation and results

In this section, we first describe the instances used to run the experiments. Next, to evaluate the performance and the results of the developed models, we conduct three sets of tests. First, we run the PNS model to test how 12-hour shift assignment may impact the quality of schedules and we compare the optimized schedules with those manually developed by the hemodialysis center. In the second set of tests, we present a sensitivity analysis using the NPC model. This addresses directly the problem of assigning the patients to nurses and chairs while considering different prioritization of the components of the objective function. Finally, we collect the optimized scheduling results from the PNS and use them sequentially as parameters in the PNS model. This allows us to compare the initial assignments of the hemodialysis center with the optimized assignments, considering both the initial patient and

staff schedules and those simultaneously optimized with the PNS model. All results presented are obtained using the CPLEX solver. The models were solved on a machine equipped with an Intel Core i5-1035G7 CPU running at 1.20 GHz, with 8 GB of RAM, operating under a 64-bit Windows operating system.

4.5.1 Instance generation

We use three sets of instances, the first one for the PNS model, the second one for the NPC model and the third one to assess the integration between both models. All instances are defined by a number of patients and a number of nurses, and result from a data collection at the hemodialysis center. We refer to each instance as $pr(\#patients, \#nurses)$.

Instance set - PNS The scheduling problem for patients and nurses is addressed over a two-week period. The baseline instance, $pr(198, 24)$ represents the real case from the hemodialysis center. We generate 5 different instances by varying the number of patients and nurses. An analysis of past schedules from the hemodialysis center indicates that the number of patients ranges between 195 and 205. For nurses, we vary the number by two units, covering both tight and softer instances.

Instance set - NPC The NPC model is solved daily, with the number of patients and nurses being roughly half of those in the PNS instances. From a complete week observation (Monday to Saturday), we observe that the number of patients varies between 84 and 107 and the number of working nurses per day ranges from 15 to 22. Typically, fewer patients are seen on the pattern Tuesday/Thursday/Saturday, as one of the three rooms in the hemodialysis center is closed during the evening appointment period. Consequently, the number of available chairs decreases then from 47 to 31. Patients have acuity scores based on the acuity factors described in table 4.1, and nurses are assigned different shifts. Note that the observed week was a representative week, with no holidays or seasonal events, and it accurately captures the usual demand of the center, as hemodialysis treatments schedules are consistent week to week.

Instance set - PNS-NPC As we also aim to evaluate the impact of nurse shifts and patient schedules quality on assignments in section 4.5.4, we employ the optimized baseline instance of the PNS model to develop instances to use in the NPC model. Through the PNS model, an optimized schedule is proposed for patient appointment patterns (f_{pi}) and nurse shifts (m_{nqj}). We then use the patients' appointment patterns (f_{pi}) to determine the associated appointment periods in the NPC model (Φ_{pa}). The results of the PNS model are also used to define which nurses work during which appointment periods (b_{na}) and to adjust the calculation of the average daily acuity according to the type of nurse shifts. Six

new instances representing one week at the hemodialysis center are thus generated with optimized schedules for nurses and patients. Figure 4.7 illustrates the established linkage between the two models.

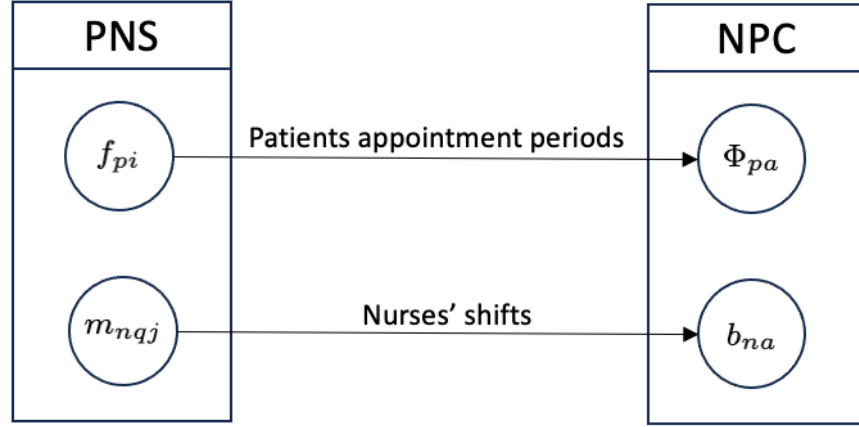


Figure 4.7 Integration of the PNS model results into the NPC model

The proportion of nurses relative to the number of patients can vary compared to the instances of the NPC model, depending on the nurse schedule types defined by the optimization of the PNS model. The number of patients per day varies from 78 to 108, and the number of nurses ranges from 14 to 17.

Table 4.6 summarizes the list and description of instances for the three set of experiments.

Table 4.6 Generated instances

NPC	PNS	PNS-NPC
$pr(198, 24)$	$pr(84, 15)^1$	$pr(78, 14)$
$pr(195, 24)$	$pr(84, 15)^2$	$pr(84, 15)$
$pr(205, 24)$	$pr(85, 17)$	$pr(87, 15)$
$pr(198, 22)$	$pr(103, 20)$	$pr(103, 15)$
$pr(198, 26)$	$pr(104, 22)$	$pr(107, 16)$
	$pr(107, 21)$	$pr(108, 17)$

4.5.2 Analysis of the appointment periods and the nurse schedules : PNS problem

In this first experiment, we test the PNS model across various instances. Notably, this enables us to evaluate the impact of different scheduling types for the nurses. We first optimize the schedules and the appointment periods with the PNS model to determine the optimal value

of the acuity-to-nurse ratio (ω). In a second phase, we minimize the number of patients and nurses who are not assigned to their initial appointment patterns and schedule types. This provides the optimal workload with the optimal number of 12-hour shifts assignment. Table 4.7 presents the results for all five instances, when no constraint on the number of 12-hour shifts is applied and when it is limited. Note that all results are optimal and that the CPU time ranges between 10 seconds and 300 seconds.

Table 4.7 Varying the percentage of nurses completing 12-hour shifts

Instances	Unrestricted % 12h shift nurses		Max 42% 12h shift nurses	
	ω	% of 12h shift nurses	ω	% of 12h shift nurses
pr(198, 24)	11	71	12	42
pr(195, 24)	10	100	12	42
pr(205, 24)	11	75	13	42
pr(198, 22)	11	100	13	41
pr(198, 26)	10	77	11	42

For each instance, we report the maximum average acuity assigned to a nurse during a shift (ω). As expected, the higher the nurse-to-patient ratio, the lower the respective acuity-to-nurse ratio. In some cases, the patient-to-nurse ratio decreases, but the acuity-to-nurse ratio remains unchanged. We also observe an increase in the proportion of nurses completing 12-hour shifts when no limit is applied. Indeed, these nurses can be assigned to patients from two different appointment periods, while nurses on 8-hour shifts can only be assigned to patients from one period. Despite working fewer shifts per week, they are clearly assets for the hemodialysis center since they can be assigned to patients in more appointment periods. However, in reality, only 42% of nurses on average complete 12-hour shifts. Hence, we also tested the model with a maximum of 42% of nurses allowed to complete 12-hour shifts. This increases the average acuity assigned to nurses, particularly for instances with a low nurse-to-patient ratio.

Next, to evaluate the impact of the current operations, i.e. the patient appointment periods and nurse schedules, we conduct several tests with the PNS :

- Fix patient appointment periods, optimize nurse schedules (N^o);
- Fix nurse schedules, optimize patient appointment periods (P^o);
- Optimize both patient appointment periods and nurse schedules (PN^o).

We use the notation PN^f to represent the initial schedules and appointment periods of nurses and patients, which were manually developed by the hemodialysis center without the aid of an optimization model.

For this purpose, we use the instance representing two actual weeks at the dialysis center,

denoted as $\text{pr}(198, 24)$. Table 4.8 presents the results. Note that all are optimal and that the CPU time ranges between 50 seconds and 200 seconds.

Table 4.8 Comparison of the initial and optimized solutions for the PNS model

Solution type	ω
Hemodialysis center nurse and patient schedule (PN^f)	13
Hemodialysis center nurse schedule and optimized patient schedule (P^o)	12
Hemodialysis center patient schedule and optimized nurse schedule (N^o)	12
Optimized patient and nurse schedules (PN^o)	11

The simultaneous optimization of schedules reduces the acuity-to-nurse ratio by 2 points compared to the manually created schedules by the hemodialysis center. Since the model's objective is to minimize the maximum acuity-to-nurse ratio (ω), it should strive to distribute the acuity evenly among nurses across appointment periods to avoid any period having an excessively high ratio. Given that the minimum acuity of a patient is 1, this implies that for many appointment periods, nurses will be assigned the equivalent of 2 fewer patients. Although this reduction does not cause a significant impact during a single workday, over the long term, this decrease in workload could represent substantial time savings. Moreover, given the assignment constraints, the maximum acuity assigned to a nurse during a shift is often higher than the acuity-to-nurse ratio (ω). Thus, it is essential in scheduling to strive to reduce this ratio.

However, schedule optimization requires adjustments to the current schedules of the hemodialysis center. To shift the acuity-to-nurse ratio (ω) from 13 to 12 while maintaining the existing nurse schedules, only 2 patients would need to change their appointment patterns. This solution could be beneficial for the hemodialysis center as it would reduce the average nurse assigned acuity while only altering the appointment patterns of 1% of the patients. If the appointment patterns for the patients remain the same as those of the hemodialysis center but the type of nurse schedule becomes a variable, the maximum acuity-to-nurse ratio (ω) also decreases by 1. To achieve this, 12.5% of the nurses would need to switch from 8-hour shifts schedules to 12-hour shifts schedules. Finally, to reach a ratio of 11 with the simultaneous optimization of patient and nurse schedules, 2% of patients would need to change their appointment patterns, and 33.3% of nurses their schedule types. Figure 4.8 illustrates the difference in the average number of nurses completing each shift duration during the appointment periods for the initial hemodialysis center schedule (PN^f) and the optimized schedule (PN^o).

Furthermore, by optimizing the schedules using the PNS model, the standard variation of the number of nurses working each day decreases from 3.1 to 0.8.

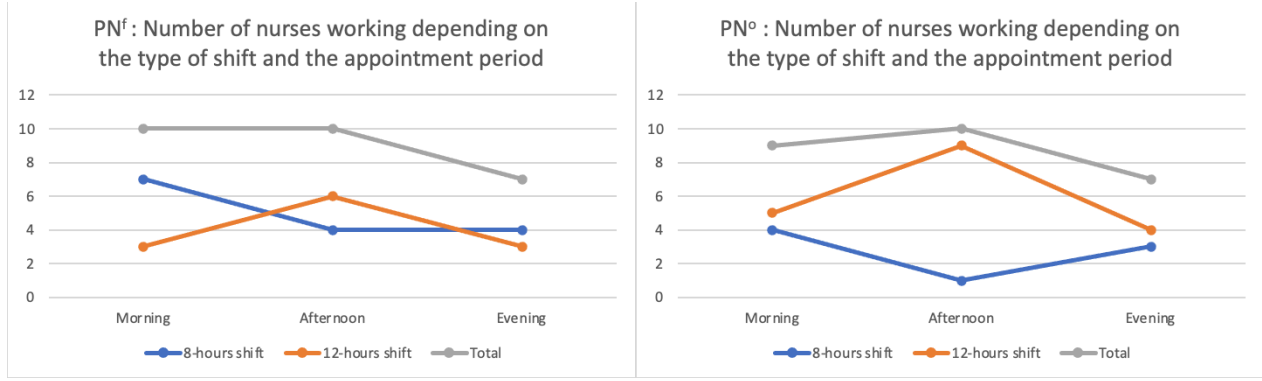


Figure 4.8 Distribution of the number of nurses working during appointment periods according to solution types

4.5.3 The NPC problem

To assess the performance of the NPC problem, we identify five key indicators. The first indicator k_1 serves to represent the percentage of patients that are not assigned to chairs in rooms corresponding to their level of autonomy. k_1 is related to the chair score (h_c^p) evaluated for each patient (x_{pnc}). The second indicator k_2 corresponds to the maximum total acuity assigned to a nurse during an appointment period. We can establish a relationship between the sum of the nurses' maximum assigned acuities for each appointment period (α_a) in the objective function, and the performance indicator k_2 . Next, the indicator k_3 represents the maximum standard deviation between nurses' assigned acuity during an appointment period. The fourth performance indicator k_4 corresponds to variable β , which is the maximum average acuity assigned to a nurse during a day. The last indicator k_5 represents the number of occurrences where nurses are assigned to a series of non-continuous chairs. For instance, a nurse assigned to non-continuous chairs might have, between two of her patients' chairs, an unoccupied chair or a patient belonging to another nurse. This indicator is related to the variable u_{nae} representing the distance between a nurse's chairs during each shift.

We first conduct a sensitivity analysis to determine the appropriate weights for the components in the objective function of the NPC model. We then follow with an analysis of different levels of optimization.

4.5.4 Setting the appropriate weights : Nurse-to-patient-to-chair assignment problem

The first experiment aims to conduct a sensitivity analysis to determine the appropriate weights for the components in the objective function of the NPC model. The discussions with

the hemodialysis center show that assigning patients to chairs located in rooms corresponding to their level of autonomy, expressed by the indicator k_1 , is considered a priority. For the management of the hemodialysis center, it is easier to group similar patients in the same rooms. Subsequently, the hemodialysis center prioritizes indicators related to equity, such as k_2 , k_3 and k_4 . This analysis is completed using the data of a typical day at the hemodialysis center. Regular patient treatment chairs are not considered to avoid limiting the quality of the results, particularly when calculating workloads.

Table 4.9 presents the results when varying the weights of the components of the objective function : (p_1, p_2, p_3, p_4) . Values of the weights vary from 1 to 2. Each line of the table shows the average results over the 6 instances for the NPC model. The CPU time required to run the model varies between 50 seconds and 13,000 seconds with GAPs ranging between 2.5% and 6.4% depending on the combinations of weights and the instances. The procedure for calculating the GAP for each instance is detailed in appendix 4.9.1. It is also noted that, as the components of the objective function vary in scale, they are standardized by dividing each by its anticipated optimal value. The calculation of these optimal values is also addressed in appendix 4.9.1.

Table 4.9 Sensitivity Analysis for the NPC model

Weights	k_1	k_2	k_3	k_4	k_5
(1, 1, 1, 1)	6	13.8	1.1	12.5	1.5
(2, 1, 1, 1)	3.3	13.4	1.4	12.7	1.3
(1, 2, 1, 1)	8	13.4	1.1	12.7	1
(1, 1, 2, 1)	8.5	14.4	1.4	12	1.3
(1, 1, 1, 2)	6.7	13.6	1.2	12.5	0.3
(2, 2, 1, 1)	5.3	13.6	1.3	12.7	1.3
(2, 1, 2, 1)	4.8	13.6	1.5	12.3	1.7
(2, 1, 1, 2)	3.2	13.6	1.8	12.7	0.5
(1, 2, 2, 1)	8.7	13.6	1.2	12.7	2.5
(1, 2, 1, 2)	8.5	13.4	1	12.7	1.5
(1, 1, 2, 2)	5.9	13.6	1.6	12.5	0.5
(2, 2, 2, 1)	5.7	13.6	1.4	12.7	1.7
(2, 2, 1, 2)	5.9	13.4	1.1	12.7	0.7
(2, 1, 2, 2)	6	13.8	1.4	12	1.8
(1, 2, 2, 2)	8.1	13.8	1.1	12.7	1.8
Average	6.3	13.6	1.3	12.5	1.3
Δ^k (%)	28	3	17	2	47

To quantify the sensitivity, we calculate the coefficient of variation Δ^k (defined as the ratio of the standard deviation to the mean) for each performance indicator across all scenar-

ios. Performance indicators with high coefficients of variation indicate greater sensitivity to weight changes, whereas those with low coefficients of variation suggest more consistent performance. The coefficients of variation for indicators k_1 to k_5 are 28%, 3%, 17%, 2%, and 47%, respectively. The analysis shows that k_5 presents the highest coefficient of variation, underscoring its significant sensitivity to weight adjustments. The values of k_5 range from 0.3 to 2.5, averaging at 1.3. In a parallel experiment, we confirm the importance of the distance between chairs. When setting the weight associated with the distance between a nurse's assigned chairs (p_4) in the objective function to 0 (i.e., distance is not considered), 100% of the nurses during each appointment period could be assigned to non-consecutive chair series, resulting in an average value for the k_5 indicator of 25.7.

The first performance indicator (k_1) also shows considerable variability with a coefficient of variation of 28%, a maximum of 8.7 and a minimum of 3.2. In contrast, k_2 and k_4 have relatively low coefficients of variation of 3% and 2%, indicating more stable performance despite changes in the weights. The values of k_2 range from 13.4 to 13.8, while values of k_4 range from 12.0 to 12.7. k_3 shows moderate variability with a coefficient of variation of 17%. The average value of k_3 is 1.3 with a maximum of 1.8 and a minimum of 1.

We then analyze the variations in weights and the corresponding changes in the values of the indicators. First, when p_1 increases, there is also an increase in the maximum standard deviation of the nurses' assigned acuity (k_3). To satisfy the patients' autonomy levels, some chair arrangements could thus hinder the equitable distribution of acuity among the nurses.

Furthermore, for most instances in which the value of p_2 is increased, k_3 take relatively low values. This confirms that minimizing the maximum acuity assigned to a nurse for each appointment period should also contribute to the equitable distribution of workload among nurses. However, when p_2 increases simultaneously with p_3 , this negatively impacts k_4 by increasing its value. Since p_2 and p_3 are associated with indicators k_2 and k_4 respectively, this suggests that when both weights are increased equally, improvements are more favorable for indicator k_2 .

To determine the weights to use in the tool developed for the hemodialysis center, we base our analysis on their prioritization of indicators. Given that respecting the autonomy level of patients during chair assignments is considered paramount, we prioritized weight combinations (2, 1, 1, 1) and (2, 1, 1, 2) that yielded the lowest values for the performance indicator k_1 . When comparing the combinations (2, 1, 1, 1) and (2, 1, 1, 2), very small differences are observed, with the first combination offering slightly better equity. Therefore, the weights (2, 1, 1, 1) are selected for the model developed for the hemodialysis center.

Comparison of the initial and the optimized solutions : Nurse-to-patient to chair assignment problem

Lastly, we compare the nurse-to-patient-to-chair assignments over six days of the week by analyzing key performance indicator values for different assignment methods. We compare the assignments initially planned by the hemodialysis center (H) to those from the nurse-to-patient-to-chair assignment model (M). For the optimized assignments using the model, we use the initial schedules of patients and nurses defined by the hemodialysis center as inputs (PN^f), as well as schedules optimized using the PNS model (PN^o). The goal of the experiment with PN^o is to evaluate the impact of nurse shifts and patient appointment periods on the quality of assignments. This results in three distinct levels of optimization : $H - PN^f$, $M - PN^f$, and $M - PN^o$. To complete the experiment $M - PN^o$, we use the instance set PNS-NPC. As there is no imposed maximum on the number of nurses who can complete 12-hour shifts in the solved PNS model, the proportion of nurses working 12-hour shifts increases from 42% in the instance set NPC to 75% in the instance set PNS-NPC. Additionally, 3 patients would need to change their appointment patterns in the instances PNS-NPC.

The model runs until a minimum GAP is reached. We detail the method to calculate this GAP and the measured performance indicators in 4.9.1 and the results from the experimentation in Table 4.10.

With no surprise, optimized solutions are better than the current ones used at the hospital. The initial solution $H - PN^f$ (current solution used at the hospital, both in terms of staffing, scheduling of nurses and patients) is the least performing for the k_1 indicator, which measures the percentage of patients assigned to rooms corresponding to their level of autonomy, with an average of 6.05% and a standard deviation of 4.33%. This standard deviation is the highest measured across all solutions and indicators. Solution $M - PN^f$ (optimized nurse-to-patient-to-chair assignments with current staffing and scheduling of nurses) stands out with an average value of 3.15%, while $M - PN^o$ (all decisions are optimized) presents a slightly higher value of 4.83%.

For k_2 , the maximum acuity assigned to a nurse during an appointment period, the optimized solution $M - PN^f$ shows significant improvements compared to the manual solution. The k_2 indicator decreases from an average value of 18.67 in the initial solution $H - PN^f$ to an average of 13 in the optimized solution $M - PN^f$. The benefit of simultaneous optimization of schedules is also demonstrated as solution $M - PN^o$ shows an average of 11.33. This represents an improvement of approximatively 13%. Note that for k_4 , the average acuity assigned to a nurse during a day, results are almost identical to k_2 .

Table 4.10 Comparison of the initial and optimized solutions for the NPC model

Days	Instances	Solution type	k1	k2	k3	k4	k5
Monday	pr(107, 21)	$H - PN^f$	12.1	18	4.3	18	7
Monday	pr(107, 21)	$M - PN^f$	2.8	11	1.9	11	0
Monday	pr(107, 16)	$M - PN^o$	6.5	11	0.7	11	3
Tuesday	pr(85, 17)	$H - PN^f$	2.4	18	3.6	18	6
Tuesday	pr(85, 17)	$M - PN^f$	2.4	14	1	14	0
Tuesday	pr(87, 15)	$M - PN^o$	2.4	11	0.7	11	1
Wednesday	pr(104, 22)	$H - PN^f$	10.6	17	4	17	6
Wednesday	pr(104, 22)	$M - PN^f$	3.8	12	2.5	11	2
Wednesday	pr(108, 17)	$M - PN^o$	6.5	11	0.5	11	3
Thursday	pr(84, 15)	$H - PN^f$	2.4	21	3.2	21	8
Thursday	pr(84, 15)	$M - PN^f$	3.6	14	1.1	14	0
Thursday	pr(84, 15)	$M - PN^o$	3.6	11	1	11	1
Friday	pr(103, 20)	$H - PN^f$	2.9	18	4.1	17.5	5
Friday	pr(103, 20)	$M - PN^f$	3.9	12	2	12	0
Friday	pr(103, 15)	$M - PN^o$	6.8	11	0.8	11	3
Saturday	pr(84, 15)	$H - PN^f$	5.9	20	3.4	20	9
Saturday	pr(84, 15)	$M - PN^f$	2.4	15	1.6	14	1
Saturday	pr(78, 14)	$M - PN^o$	3.8	13	1.4	12	0

Regarding the maximum standard deviation between nurses' assigned acuities (k_3), solution $H - PN^f$ has an average value of 3.77. The value of $M - PN^f$ is 1.68, and the value for $M - PN^o$ of 0.85 is the lowest. Thus, with $M - PN^o$, total assigned acuities are lower for nurses and vary less among them, resulting in a more equitable distribution.

For the performance indicator k_5 , which represents the number of nurses assigned to a series of non-consecutive chairs, the optimized solution $M - PN^f$ achieves a 93% reduction compared to the initial solution, with an average of 0.5 compared to an average of 6.83 for $H - PN^f$. Solution $M - PN^o$ is less effective for this distance-related indicator, with an average of 1.83.

Assessing consistency of treatment chairs in PNC

This last experiment aims to evaluate the impact of consistency of treatment chairs. To perform this test, we use the level of optimization $H - PN^o$ and solve the assignments for Monday and Tuesday. The chairs obtained for each patient become the regular chair and should be used for the following appointments (from Wednesday to Saturday).

When solving the PNC with consistency of chairs, the average value k_2 for these days increased by 4% compared to when regular treatment chairs were not considered. Meanwhile, the k_4 and k_5 indicators remained approximately the same. This suggests that con-

sidering chair consistency does not significantly impact the quality of the results. Additionally, since the same patients typically return on Monday/Wednesday/Friday or Tuesday/Thursday/Saturday, enforcing consistency of chairs does not reduce the quality of the solutions in terms of nurse acuity and workload. This patient preference is achieved at no additional cost to the center.

4.6 The decision support tool

One of the objectives of our project, conducted in collaboration with a hospital partner, was to develop a transferable tool for optimizing the assignment of patients to nurses and chairs. This problem was identified as having the most significant impact on the hemodialysis center’s operations. We will discuss in the following three specific points : how to use the tool, when to use the tool, and the tool transfer steps.

4.6.1 How to use the tool?

To ensure the long-term usability of our tool, we used Excel. Excel is a user-friendly software that is well-known to the hemodialysis center. This facilitates adoption and reduces the learning curve. The tool allows the user to optimize assignments through the four distinct versions of the model. The user can specify the desired days for optimization for the latter two phases and only has to press on a button corresponding to the desired version to start the optimization. A Visual Basic for Applications (VBA) script triggers the model coded in Julia [23]. We use the open source solver HiGHS [24]. Once the model reaches the desired GAP, the results are automatically printed in a CSV file. When VBA detects that the optimization is completed, the CSV results are displayed in the Excel file. The process for completing the optimization and displaying the results is illustrated in figure 4.9.

In collaboration with the hemodialysis center, we designed a detailed data file displaying a wide array of adjustable parameters to ensure long-term usability despite changes within the center. The following parameters can be specified:

Patients Users can specify patients’ acuity factors, levels of autonomy, hemodialysis durations, appointment schedules, treatment notes, and chair characteristics required for their needs. Chairs assigned to patients must possess these characteristics and multiple characteristics can be specified. For example, a patient may require a low chair in isolation. Additionally, users can specify if a patient should not be assigned to a particular chair or nurse, if they are a regular patient, and if they require one-on-one care.

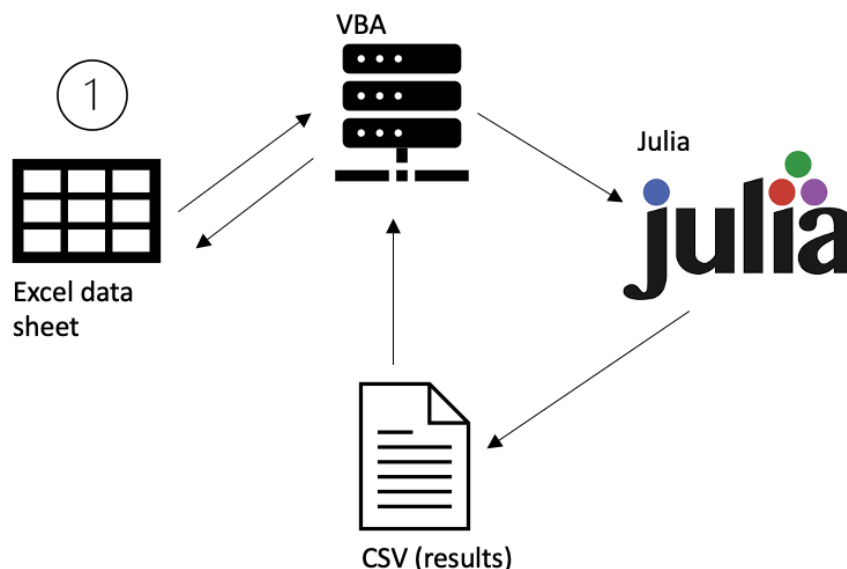


Figure 4.9 Results Display Process

Nurses Users can define nurses' work schedules and the maximum number of patients they can be assigned to during an appointment period and a day, based on their experience level and their shift. Users can also add or remove shifts and specify the appointment periods for each shift during which nurses can be assigned to patients. For the first phase of the model, users can also specify the typical number of nurses per shift per day.

Chairs Users can specify each chair's characteristics and room location. A chair must meet at least the required characteristics of a patient's needs to be assigned to them. Users can also automatically generate the distances between chairs. If the layout of the hemodialysis center changes, users can manually update the distances between chairs.

Finally, users have the option to modify the opening periods of rooms and the scores for acuity factors. To enhance usability, we added features that allow users to automatically add patients, nurses, chairs, and acuity factors into the tables.

For result visualization, the tool offers a table which shows the regular chair assignments for patients, while daily sheet for each analyzed day indicates the patient assignments to chairs and nurses. We maintained the same display format used by the hemodialysis center to facilitate understanding and change management. Figure 4.10 illustrates an example of the resulting assignment of the model.

maximum number of patients that can be assigned to their usual treatment chair, while having a feasible solution.

This version of the model is solved each time a new regular patient is admitted to the hemodialysis center.

Weekly assignments This version is resolved weekly to complete the assignments for the following week. In this version, the appointment periods of the patients and the staff schedules for the targeted week are fixed. Constraints (4.36) are added to ensure that a certain proportion of patients are assigned to their usual chairs. Indeed, it is important for the hemodialysis center to assign many patients to their regular treatment chairs. However, we do not wish to enforce the assignment of all patients to their usual chairs in order to allow flexibility in adjusting some chair assignments. This aims to improve the distribution of acuity or to increase the distance between nurses' chairs. Also, since the hemodialysis center frequently admits new patients for short period, these patients are not always assigned to a regular treatment chair.

Weekly assignment updates Occasionally, hemodialysis treatments last longer than expected during a day. Since chairs remain occupied, this can cause delays for patients waiting for those chairs. We implemented the fourth version of the model to allow the hemodialysis center to reorganize assignments as needed. During this phase, we introduce the additional constraints (4.37) to ensure a feasible reorganization while limiting the assignment modifications.

We employ a similar approach to the one presented for the weekly assignments version of the model. Constraints (4.37) specifies that a certain number of patients must keep their initial chair and nurse. We adjust the parameters in the model so that occupied chairs cannot be assigned to other patients, and we calculate the maximum number of patients that can keep their initial assignment while obtaining a feasible solution.

4.6.3 Tool transfer

To assist us in the development of the model and the tool, we established a working group including assistants, nurses, and the head nurse. This group allowed us to make targeted improvements, and to modify the interface to ensure user-friendliness. For instance, we identified the parameters most frequently adjusted during the assignment planning process and highlighted them in the interface. Additionally, we developed a user guide and scheduled guided usage sessions to ensure a thorough understanding of the tool's functionality.

Through this working group, the hemodialysis center team was actively involved in the tool's development, ensuring that it meets their daily needs. This involvement facilitated the tool's adoption by the hemodialysis center.

4.7 Managerial insights

Through our discussions with the hemodialysis center's managers and nurses, we were able to enrich the modeling process. These insights allowed us to prioritize the quality criteria for assignments, obtain feedback on the completed case study, and formulate recommendations based on the perceived challenges in the current assignment process.

Prioritization of quality criteria First, managerial insights allowed us to determine that prioritizing the patient's autonomy level is essential when assigning them to regular treatment chairs. Patients should therefore, if possible, be assigned to regular chairs in rooms that correspond to their level of autonomy. However, in order to reduce the total acuity for a significant number of nurses, it is acceptable for a patient to not be placed in a room matching their autonomy level. Thus, we defined equity as the second priority, followed by the distance between the nurse's chairs. This prioritization was incorporated into the determination of the weights for the objective function.

Feedback By completing the case study, we were able to gather insights from the head nurse and her assistants on the impact of our approach. First, this process allowed them to formally define acuity criteria. Previously, acuity was estimated by the assistant head nurses based on their knowledge of the patients, without a precise system to calculate this metric. With the new acuity measurement system, it is now easier to compare nurses' workloads and schedule patients according to the total acuity of patients in each appointment period. The development of the tool also facilitated the reflection and formalization of quality criteria for the assignments. Moreover, to obtain the necessary data for solving the model, a detailed inventory of the hemodialysis center's chairs and their specific characteristics, as well as patient attributes, was conducted. These data were dispersed across multiple documents, lacking a centralized and accessible format, and they were not updated often. By gaining better knowledge of the chairs and patients, the center has now additional management tools at its disposal. Finally, and most importantly, the developed tool enhances equity and saves valuable time for assistant head nurses when planning assignments.

Recommendations During the case study, the insights gained from understanding the center’s organization allowed us to make informed recommendations. For example, we learned that patients were often dissatisfied with the waiting times at the hemodialysis center. Since all patients arrive simultaneously to adhere to the start times of appointment periods, and often with the aim of beginning their treatment first, it can sometimes take a considerable amount of time for a patient to actually begin their treatment. Without eliminating the concept of appointment periods at the hemodialysis center, we recommended suggesting arrival times within the appointment period based on the patients’ dialysis treatment durations. This recommendation was accepted, and we subsequently incorporated this feature into the developed tool.

Except for suggesting arrival times, we did not alter the center’s current organization and processes. However, we provided recommendations on how to improve the operations of the center in the future. Our main recommendation is to organize assignments by task rather than by patient. As certain tasks are already distributed among the nurses (specifically to support nurses completing 12 hour shifts during the afternoon appointment period), this would allow for the advanced planning of task distribution. Currently, these additional tasks to assist other nurses are not always planned, so this approach would help in balancing the workload. It would also enable the testing of different task distribution models among the nurses. The developed assignment model could be adapted to allocate tasks rather than patients, allowing the evaluation of various task distribution.

4.8 Conclusion

In conclusion, our paper aimed to develop mathematical models to optimize the staffing and scheduling of a hemodialysis center, and to manage the daily assignment of patients to nurses and chairs. Using the staffing and scheduling model, we assessed the impact of different configurations of nurse shifts and patient appointment periods. The assignment optimization, using a multi-objective model, involved minimizing the distance between assigned chairs, ensuring equity among nurses, matching patients to chairs based on their autonomy levels, and maintaining consistent chair assignments for patients. To address operational needs, we created a four-version resolution process for generating regular, weekly, and daily treatment chair assignments.

Our assignment model significantly reduces nurses’ average workload compared to manual assignments, with a 30% decrease in maximum daily workload per nurse. We also found that increasing the proportion of nurses on 12-hour schedule types reduces their overall workload. Additionally, we developed a tool for the hemodialysis center to streamline daily operations,

reduce assignment time, and allowing staff to spend more time providing patient care, thereby improving efficiency and reducing patient waiting times.

While our tool is designed for quick results, further integration with nurse and patient scheduling problems could be explored in contexts where resolution time is not a constraint. Additionally, studying the impact of assigning nurses to tasks instead of patients could be beneficial.

4.9 Appendices

4.9.1 Lower bounds and indicators for the NPC problem

The NPC model converges slowly towards optimality. Due to the high resolution time required to obtain an optimal solution, we stop the resolution when a minimum GAP is reached. To determine this GAP, we established that the maximum total acuity assigned to a nurse during an appointment period (α_a) could have a deviation of 1 from its optimal value. We also allow a deviation of 1 from the optimal value of the average acuity assigned to a nurse per appointment period (β). In the definition of acuity, the smallest possible acuity is 1. This deviation thus implies that one or more nurses are assigned an additional patient with the minimum possible acuity, which we consider acceptable.

To calculate the minimum permitted GAP with these deviations, we first estimate the optimal value of the objective function for each instance. In order to achieve this, we calculate the optimal value of each component of the objective function and then multiply it by the associated weight. To estimate the optimal value of the distance variable, we calculate the average number of patients assigned to each nurse and assume that all patient chairs are adjacent in the rooms. Then, we calculate the distance between these chairs, assuming the nurse's primary chair is located at the center of the group of chairs. We also hypothesize that all patients are assigned to chairs in rooms corresponding to their level of autonomy, which allows us to calculate the chair scores for the patients.

Finally, for acuity, we divide the total acuity of the patients during each appointment period by the number of nurses working during that period. We round this average acuity up to the nearest whole number to estimate the maximum acuity during each appointment period (α_a). We then assume that the shift with the highest maximum acuity corresponds to the maximum average acuity assigned to a nurse (β). Equations (4.56) and (4.57) detail the approximation formulas for α_a and β .

$$\left\lceil \frac{\sum_{p \in P} w_p \Phi_{pa} x_{pnc}}{\sum_{n \in N} b_{na}} \right\rceil \approx \alpha_a \quad \forall a \in A \quad (4.56)$$

$$\max_{a \in A} (\alpha_a) \approx \beta \quad (4.57)$$

By estimating the optimal value of the objective function and the permissible deviation for the acuity variables, the minimum GAP is calculated for each instance and for each combination of weights.

CHAPITRE 5 DISCUSSION GÉNÉRALE

Cette discussion générale a pour objectif d’approfondir la méthodologie utilisée pour développer le modèle d’affectation, de présenter une analyse complémentaire des résultats obtenus, ainsi que de décrire les fonctionnalités additionnelles intégrées à l’outil développé.

5.1 Modélisation des chaises affectées à une infirmière

Dans l’article, nous abordons brièvement les méthodes de modélisation considérées afin de représenter les chaises affectées à une infirmière dans le modèle d’assignation. La comparaison des deux modèles proposés et leur optimisation afin de diminuer leur temps de résolution a constitué une part importante du projet. En effet, il était essentiel que le temps de résolution du modèle sélectionné soit raisonnable afin qu’il puisse être résolu quotidiennement par le centre d’hémodialyse. Comme les chaises d’une infirmière doivent toutes être à proximité, la première méthode consistait à affecter une infirmière à une chaise centrale durant la journée et à minimiser la distance des chaises de ses patients par rapport à cette chaise. La deuxième méthode était axée sur le développement de patrons de chaises situées à proximité dans les salles. Chaque patron avait un score selon l’espacement de ses chaises et une infirmière était associée à un patron selon le nombre de patients qui lui étaient affectés. Une des composantes de la fonction objectif était de minimiser le score du patron affecté à chaque infirmière.

Afin de comparer les performances des deux modélisations, nous avons généré 6 instances représentant des journées typiques au centre d’hémodialyse. Ces dernières sont définies comme ceci : $pr(\#patients, \#infirmières)$. Pour ce faire, les modèles ont été résolus durant une période de 500 secondes, un temps considéré comme acceptable pour obtenir une solution pour le centre d’hémodialyse, et le plus petit gap d’optimalité atteint a été enregistré. Le tableau 5.1 présente les différences entre les performances des modélisations.

TABLE 5.1 Comparaisons des performances des modélisations

Instances	% GAP modèle distance	% GAP modèle patron
pr(84, 15)	2.83	4.56
pr(84, 15)	2.85	2.82
pr(85, 17)	2.35	2.02
pr-(103, 20)	4.15	31.22
pr-(104, 22)	5.63	9.40
pr-(107, 21)	3.84	34.87

L'analyse des résultats permet de constater que les modèles ont des performances similaires pour les instances comportant moins de patients et d'infirmières. Le modèle utilisant le concept des patrons est même légèrement meilleur pour deux instances. Toutefois, lorsque la taille des instances s'accroît, l'écart de performance entre les 2 modèles devient plus apparent. Le modèle basé sur les distances présente des gaps d'optimalité nettement inférieurs au modèle des patrons. Nous avons donc choisi le concept des distances dans la modélisation du problème comme ce modèle convergeait plus rapidement vers des valeurs basses de gaps que l'autre modèle développé.

5.2 Performance des quarts de 12 heures

En analysant les résultats du modèle d'optimisation des horaires des patients et des infirmières, ainsi que le modèle d'affectation, nous concluons que les quarts de 12 heures sont à privilégier pour obtenir une répartition plus équitable des patients entre les infirmières. Nous nous sommes interrogés sur les facteurs expliquant le lien entre ce type de quart et un meilleur équilibrage de la charge de travail.

Les infirmières effectuant des quarts de 8 heures ne peuvent être assignées qu'aux patients d'une seule période de rendez-vous, alors que les infirmières effectuant des quarts de 12 heures ont l'avantage de pouvoir compléter les traitements des patients durant deux périodes de rendez-vous consécutives. Elles contribuent ainsi à une répartition plus équitable de la charge de travail durant ces deux périodes. Une infirmière ayant un horaire composé de quarts de 8 heures travaillera durant 10 périodes de rendez-vous sur une période de deux semaines, tandis qu'un horaire de quarts de 12 heures mènera à travailler durant 13 périodes distinctes. De plus, durant une journée, les infirmières complétant des quarts de 12 heures peuvent avoir une charge de travail plus élevée durant la première période de rendez-vous et une charge plus légère durant la seconde, offrant ainsi une plus grande flexibilité dans la répartition de la charge de travail.

Lors de nos premières rencontres avec le centre d'hémodialyse, une infirmière effectuant un quart de 12 heures de jour devait être associée à une infirmière effectuant un quart de 12 heures d'après-midi. Les deux infirmières étaient affectées ensemble à la même section de patients durant l'après-midi. Cela évitait que l'infirmière du quart de jour ne manque de temps pour débrancher les patients ou que l'infirmière du quart d'après-midi n'ait besoin d'aide pour les brancher. Toutefois, en raison des pénuries de personnel, cette organisation a dû être abandonnée par le centre. Les infirmières effectuant des quarts de 12 heures sont maintenant assignées à des patients sur deux périodes de rendez-vous, sans avoir une deuxième infirmière désignée pour les aider durant l'après-midi. Si une infirmière effectuant un quart

de 12 heures de jour manque de temps pour débrancher ses patients, elle est aidée par les infirmières des quarts de 8 heures de soir, qui commencent leur quart avant l'arrivée de leurs patients. Elles peuvent également être épaulées par les infirmières des quarts de 8 heures et de 12 heures de l'après-midi, si celles-ci ne sont pas trop débordées.

Ces besoins de collaboration entre les infirmières dus à l'organisation de leurs quarts nous poussent à suggérer des affectations basées sur les tâches plutôt que sur les patients. Cela permettrait de mieux organiser la collaboration entre les infirmières et d'améliorer la répartition de la charge de travail. En effet, si une infirmière aide une collègue, cela ajoute une charge de travail qui n'était initialement pas prévue lors des affectations.

5.3 Développement de l'outil

Après les premières démonstrations de l'outil d'optimisation à la clinique d'hémodialyse, certains ajustements ont dû être intégrés afin d'assurer un fonctionnement optimal. Tout d'abord, selon la nature des données entrées, il est possible qu'aucune solution réalisable ne soit trouvée par le modèle. Par exemple, le nombre d'infirmières pourrait être insuffisant pour le volume de patients ou le nombre de chaises en isolation pourrait être trop bas pour répondre aux demandes des patients. Comme une grande variété de paramètres peut être spécifiée par l'utilisateur, nous avons intégré un code simple en VBA permettant de conseiller à l'utilisateur des manières d'adapter les données pour obtenir une solution réalisable.

De plus, puisque le nombre d'infirmières prévu à l'horaire est souvent insuffisant pour traiter tous les patients, l'interface a spécifiquement été adaptée pour traiter ce problème. Ainsi, si le problème n'est pas réalisable en raison d'un manque d'infirmières, l'interface proposera à l'utilisateur d'ajouter le nombre minimal d'infirmières nécessaire pour obtenir une solution réalisable. Des infirmières supplémentaires seront intégrées dans la liste des infirmières travaillant durant la journée ciblée. Le centre d'hémodialyse n'aura alors qu'à trouver le personnel nécessaire pour répondre aux besoins identifiés.

Ensuite, en consultant les infirmières de la clinique d'hémodialyse, nous avons pu identifier les paramètres les plus susceptibles de changer fréquemment. Grâce à ces informations, nous avons réorganisé les pages du fichier Excel et les colonnes des tableaux pour mettre ces paramètres en évidence. Par exemple, les horaires des infirmières sont générés toutes les deux semaines, et les périodes de rendez-vous des patients sont souvent modifiées, alors nous avons placé les feuilles recueillant ces données au début du document. De plus, si un patient n'est pas autonome, nous pouvons le considérer comme semi-autonome. Nous avons donc retiré la colonne indiquant qu'un patient était semi-autonome de la table des caractéristiques des

patients, car cette information peut être déduite d'une autre colonne. Cela réduit le nombre de champs disponibles dans le fichier Excel et facilite son utilisation. La figure 5.1 présente la table utilisée pour spécifier les caractéristiques des patients dans l'interface sur Excel.

Patient	Non autonome	1 pour 1	Besoin chaise	Durée	Salle habituelle	Chaise habituelle	Cathéter	Confusion	Canne ou marchette	Fauteuil roulant	Isolém	Injection SC	IV rég	IV anti
Patient 1			ISO, F.bas	4	5000	20					x			
Patient 2	x			4	3000	22				x				
Patient 3				4	5000	16						x		
Patient 4	x			4										
Patient 5				4	4000	4	x							
Patient 6	x			4	3000	7								
Patient 7	x			4	3000	15	x		x					
Patient 8	x			4	4000	24	x		x					
Patient 9	x			4			x			x				
Patient 10	x		ISO	3,5			x				x			
Patient 11	x		F.obese	4	3000	6	x							
Patient 12	x			4	3000	10			x			x		
Patient 13	x			4	4000	20	x							
Patient 14				5	5000	8								
Patient 15	x		ISO	3,5	3000	20	x				x			
Patient 16	x			4	4000	20	x							
Patient 17	x			4	4000	18			x					
Patient 18				4	5000	15								
Patient 19	x			4	3000	5								
Patient 20	x			4	4000	16	x							
Patient 21	x			3,5	4000	14	x			x				
Patient 22				3,5	3000	8	x					x		
Patient 23	x			3,5	4000	8	x			x				
Patient 24				4	3000	3								
Patient 25	x			4			x			x				

FIGURE 5.1 Table d'entrées des données sur les caractéristiques des patients

Également, certains champs, tels que la distance entre les chaises, ont été cachés aux utilisateurs. En effet, bien que le guide d'utilisation fournisse des instructions sur la manière d'accéder au tableau des distances si nécessaire, ce paramètre ne devrait pas être modifié fréquemment. Nous avons souhaité éviter que les utilisateurs aient à consulter un tableau volumineux sur les distances, potentiellement difficile à interpréter, ou à estimer eux-mêmes les distances entre les chaises. Par conséquent, nous avons développé un code en VBA pour calculer automatiquement les distances entre les chaises. Étant donné que les chaises sont disposées en cercle, il suffit de connaître les chaises adjacentes à gauche et à droite pour déterminer ces distances.

CHAPITRE 6 CONCLUSION

L'assignation des patients aux infirmières et aux chaises lors de leur rendez-vous est une tâche quotidienne pour un centre d'hémodialyse. Afin de libérer les infirmières de ce fardeau administratif, ce mémoire présente un modèle d'optimisation multi-objectifs des affectations en hémodialyse. Ce modèle est basé sur le fonctionnement du centre externe d'hémodialyse du CHUM.

Deux objectifs principaux ont été définis pour le modèle : la minimisation de la charge de travail affectée aux infirmières, ainsi que la constance et le respect du niveau d'autonomie lors de l'affectation des chaises aux patients. Pour une infirmière, la charge de travail est représentée par la distance à parcourir entre les chaises de traitement, l'acuité des patients affectés durant chacune des périodes de rendez-vous et, pour les infirmières travaillant durant plusieurs périodes de rendez-vous consécutives, l'acuité moyenne par période. Pour ce faire, nous avons identifié et quantifié des facteurs influençant le niveau d'acuité d'un patient.

Afin de réduire le temps d'attente des patients, nous avons également élaboré une procédure pour générer des heures d'arrivée pour les patients selon les affectations de la période de rendez-vous. De plus, un modèle d'optimisation des périodes de rendez-vous des patients et des horaires de travail des infirmières a été développé. Grâce à ce modèle, nous avons évalué l'effet d'horaires optimisés sur les affectations.

L'analyse des résultats nous a permis de constater que le modèle d'affectation améliore grandement la charge de travail des infirmières durant leur quart. En moyenne, la charge de travail maximale d'une infirmière diminue de 30% comparativement aux assignations manuelles. Nous avons également établi un lien entre la diminution de la charge de travail des infirmières et l'augmentation de la quantité d'infirmières complétant des quarts de travail de 12 heures.

Afin de pérenniser l'utilisation du modèle développé, nous avons bâti une interface sur Excel intuitive et simple à utiliser pour le personnel du centre.

Les modèles développés prennent en compte un nombre important de facteurs influençant le quotidien du centre d'hémodialyse. Cependant, bien que le modèle d'optimisation des horaires soit conçu pour considérer les préférences des patients et des infirmières, celles-ci n'ont pas été intégrées dans les instances de test. En l'absence de données sur les préférences, cet aspect a dû être exclu des analyses de résultats. Les préférences des patients auraient également pu être intégrées dans la procédure de détermination des heures de rendez-vous.

Plusieurs pistes d'amélioration pourraient être intégrées au modèle. Il serait avantageux de modéliser les affectations des infirmières à des tâches plutôt qu'à des patients afin de laisser davantage de flexibilité dans l'organisation du travail. Également, le problème d'affectation pourrait être intégré au modèle d'optimisation des horaires. Nous avons testé la résolution séquentielle dans le cadre de l'étude de cas, mais la combinaison des deux problèmes aurait certainement des bénéfices.

Enfin, étant donné les similarités entre les cliniques d'hémodialyse et de chimiothérapie, il serait pertinent d'adapter le modèle d'affectation développé pour l'hémodialyse et de l'évaluer dans le contexte des cliniques de chimiothérapie.

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