MASTER

Tactical strategies for scheduling elective and emergency patients under uncertainty

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Tactical Strategies for Scheduling Elective and Emergency Patients under Uncertainty

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ABSTRACT

This study analyses a tactical planning strategy to plan elective and emergency patients whose arrival is uncertain. For this analysis, four types of resources are considered for the allocation of operations for each patient category. These resources are the operating theatre, beds in the medium and intensive care units and the nursing hours in the intensive care unit. The objective of the tactical planning is to minimize the hospital inefficiency by minimizing the deviations of the resources consumption to the target levels of resources utilization and also consider the patient satisfaction by decreasing average waiting times with additional smoothing constraints. In addition to the tactical planning obtained, some analyses are done at operational level in order to measure the performance of any given tactical plan in terms of patient satisfaction and hospital efficiency. Moreover, in order to see the effect of flexibility about meeting higher demands on the hospital efficiency and patient satisfaction the option of overplanning is also considered. The performance of the proposed solution is tested with some numerical experiments. These numerical results show a trade-off between the hospital efficiency and the patient satisfaction. However, it is also observed that with the additional constraints, both the patient satisfaction and the hospital efficiency performed better.

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SUMMARY

PROBLEM STATEMENT

For the satisfaction of patients and the efficiency of the hospitals, some tactical and operational scheduling should be done for the elective and emergency patients considering the medical people. In order to satisfy the patients in terms of scheduling, the waiting time should be minimized. To achieve this, the scarce resources of the hospitals should be considered as constraints as well. In other words, the efficiency of the hospital should be taken in to account. The utilization of the resources should be as close as possible to the target consumption of them. Since the resources of the hospitals are limited, they face a trade-off between the satisfaction of patients and the efficiency of the resources.

Thus, research question can be defined as "How to find the most appropriate tactical strategy for scheduling elective and emergency patients, that improves hospital resource efficiency with maintaining high patient satisfaction?". Moreover, being able to analyze the performance of the obtained tactical plan at operational level is also crucial for the research.

RESEARCH & DESIGN

Main goal of the research is to find a tactical strategy for the scheduling of the patients that sustain patient satisfaction and hospital efficiency. In tactical level, planning horizon is taken as 4-week period however; this horizon can be adopted according to the characteristics of the departments or hospitals. According to the expected arrival of elective and emergency patients, the required capacity allocation and scheduling of patient categories are done. The utilization of resources and the allocation of them to emergency patients as well as the waiting time of the elective patients are the expected outputs from this analysis.

The mathematical model developed by Dellaert and Jeunet [8] for the tactical planning will be used as the base model for the further analysis. The length of stays in IC and MC units are probabilistic while the operating time is assumed to be deterministic. The number of operations for each patient category that will be planned in each period depends on the average number of arrivals from that patient category, which in our case is assumed to be based on a Poisson distribution. Note that, the number of patients to be planned can be determined considering the trade-off between the flexibility of the system and the idleness of the resources.

The aim of this mathematical model built for the tactical planning is to minimize the sum of the overuse of resources as well as the deviations of utilization levels from target utilization levels of each resource (OT, IC, MC, NH) with a weight assigned to each. The model results in a scheduling of operations for each patient category. For the tactical planning, this model enables all planned elective patients are scheduled while trying to keep the excess usage of resources as limited as possible.

However, since the objective function of this model only takes the hospital efficiency into account, some additional analyses are done in order to take the patient satisfaction into account. The patient satisfaction was related with the average waiting time of the patients until they are operated. In order to decrease the average waiting time of the patients, a heuristic is used for the smoother allocation of the operations.

It was observed that there is a significant trade-off between the smooth allocation of the operations and the utilization levels of the resources. Then, to combine these two objectives, some additional constraints are added to the tactical planning to make the allocation of the operations smoother.

In order to measure the performance of the schedules obtained, the calculations for the average waiting time of the patients are done as well as the average deviation of resource utilizations from their targeted values. In other words, instead of deviations of average utilization of resource from their targeted level, the average deviation of utilization of resources from their targeted level is considered. For this approach, the probability that there may be fewer patients than the planned number is also taken into account. Thus, the performance of the system is measured at an operational level.

Since it is assumed that there is no flexibility between the scheduled operations of patient categories for the tactical plan, the calculations for each patient category can be done independent of the others. By no flexibility, it is meant that, although there are not enough patients from a certain patient category to be operated on that day, it is not possible to use that operating theatre capacity for another patient from another patient category. Thus, considering each patient category independent of each other brings an ease for the calculation.

NUMERICAL RESULTS

The analyses made are measured by some simulation done with the use of sample data that is borrowed from the Thorax Center Rotterdam. For these sample data, the planning period for the tactical planning (T) is taken as 28 days, and again it is assumed that there should not be any operation scheduled on weekends. Moreover, the arrival of the patients were simulated as a Poisson process as mentioned before.

Considering the other relevant data for the tactical planning, first a schedule is obtained with the basic mathematical model. Then, in order to illustrate the effect of smooth allocation heuristic on the utilization levels of the resources, a comparison is made. According to that comparison, it was observed that there is a trade-off between smooth allocation, thus the patient satisfaction and the hospital efficiency. In other words, the schedules obtained with the smooth allocation heuristic have greater hospital inefficiency than the schedule obtained with the basic mathematical model.

Then, to see the effect of additional constraints on the patient satisfaction and the hospital efficiency, the results of the new schedules are obtained and compared with each other. According to these results, it was again observed that with these additional constraints which make the allocation smoother, the efficiency of the hospital gets lower.

Same analyses are done for two overplanning options as well, the intermediate overplanning and large overplanning options. For these options, it was observed that as the amount of overplanning increases, the efficiency of the hospital decreases as expected. Within an overplanning option, the same results hold for the tradeoff between the hospital efficiency and patient satisfaction as well.

In order to illustrate the effect of the smoother allocation on patient satisfaction, the average waiting times of the patients are calculated for all alternative schedules. Again, the trade off between the deviation of utilization levels and the average waiting time of the patients is observed by these results, which can be seen in Figure i.

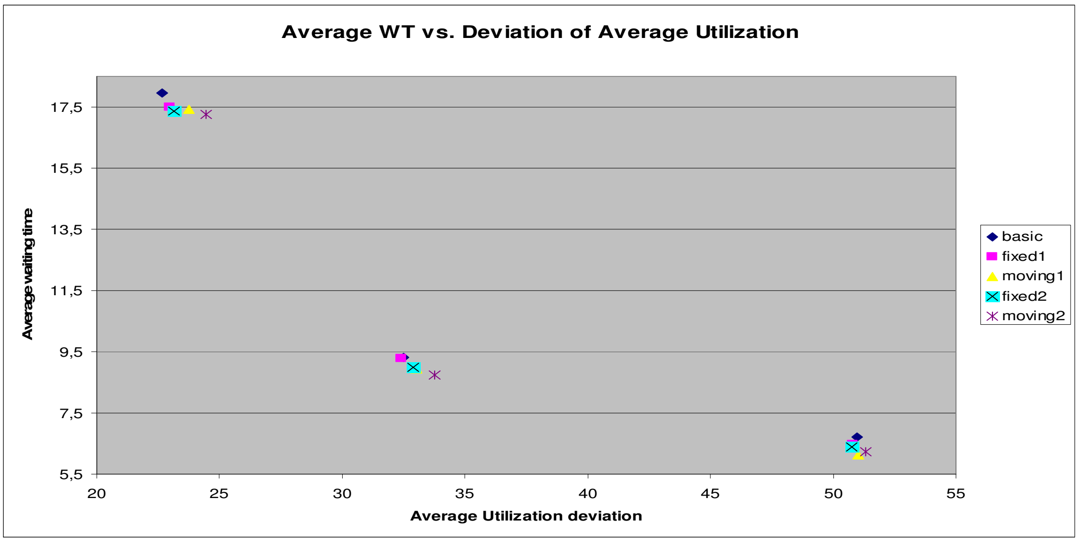

Figure i: The trade-off between the average waiting time and the deviation of average utilization levels from the targeted level plus the overuse of resources

To see the effect of alternative scheduling methods and planning options on the resource efficiency at operational level, instead of comparing the deviation of targeted resource utilization levels from the average utilization levels found by the mathematical model, the average deviation of targeted resource utilization levels from the utilization levels found by the simulation is considered. By this approach, the probability that there will be fewer operations taking place than the planned number is also taken into account. These values are computed for each resource, and it was also assumed that there is no flexibility between the patient categories. According to the assigned weights to overutilization, underutilization and overuse of the resources, it was again observed that the hospital efficiency decreases with the increasing over planning. However, this time, the hospital inefficiency does not increase with increasing patient satisfaction for a given planning option. The comparison of these results for the IC unit can be seen below

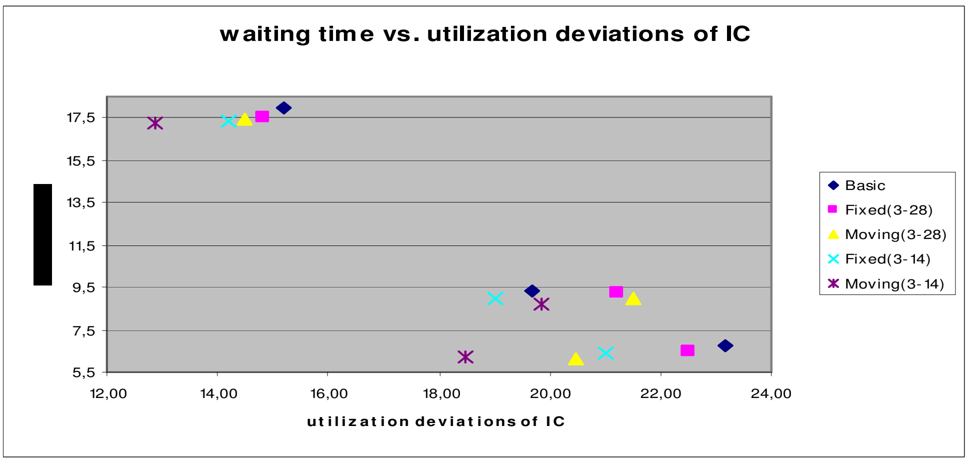

Figure ii: The trade-off between the average waiting time and the weighted sum of average deviation of utilization levels from the targeted level and the overuse of IC

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PART I ORIENTATION

1.1 INTRODUCTION

To make the research more clear, and to identify the main objectives as well as the boundaries of this research, first the orientation part is introduced. In the orientation part, first the literature related with the subject will be reviewed and then, according to the findings of this review the proposal for the research, which will be about the tactical and operational strategies for the scheduling of patients in hospitals, will be explained.

The outline of the orientation part is as follows; first the background of the topic and related literature about the planning and scheduling of operating rooms and patients will be summarized in section 1.2. Next, the definition of the problem will be given. In section 1.4, the research design will be discussed with the scope of the research as well as the proposed project approaches for the both decision levels, tactical and operational. Finally, the planning of the project will be presented.

1.2 BACKGROUND

In this section of the orientation part, a brief summary of the literature survey will be given. According to the literature survey done for the subject of planning and scheduling of the operating rooms, it is found that there are several major criteria for the classification of these studies, such as the patient types, performance measures, decision levels, type of analysis, solution techniques, uncertainty of processes and patient arrivals and applicability of the studies. Thus, in this section, each criterion and studies related with them will be reviewed.

For the planning and scheduling of the operating rooms, there are many studies about the scheduling strategies for hospitals for various types of patients. Some of these studies consider only elective patients, whose operations are planned beforehand, as in the study of Dexter and Traub [9], while the others deal with both emergency and elective patients like Zhang et al. do in their study about operating room capacity allocation [21]. Also, in several studies, only the emergency patients are considered. Moreover, a separate emergency path for all emergency patients of all departments is also considered in the literature.

While scheduling, several performance measures are used. For instance Wullink et al. [20] use the utilization of resources, waiting time of patients and/or surgeons, while Lehtonen et al. [15] consider throughput time for the measure of performance. The leveling of resources such as beds, operating rooms are also considered as performance measures by Belien and Demeulemeester [1], and the financial values obtained from the scheduling by Lamiri et al. [14].

Furthermore, several scheduling strategies developed in the literature are on tactical level while some others are for daily operational decision levels. Some of these higher level planning allocates the capacity to emergency and elective patients, while some others allocate the capacity between departments or patient types.

For the scheduling of the patients in various decision levels, several types of analysis are used. Some of the literature is based on optimization and heuristics [1], and some others use scenario analysis to compare possible scenarios and to decide which one is better [20].

As a solution technique, in various studies, mathematical programming is used such as linear programming, goal programming and mixed integer programming as in the study of Zhang et al. [21]. On the other hand, Dexter and Traub [9] use simulation techniques and heuristics for their research of scheduling of elective patients. Moreover, some analytical procedures are utilized for the solution of the proposed strategies.

In various studies in the literature, the arrival pattern of patients and the length of their stay in the several units of the hospital, like the operating room and the intensive care unit, are taken as deterministic, that is, they are known beforehand with certainty or take the average values for these parameters [2]. However, these deterministic approaches are not very realistic since there is a variability and stochasticity in real world. Thus, to deal with these uncertainties of the real world, some of the literature uses stochastic approaches for the arrival of patients or the duration of processes. For instance, Wullink et al. [20] take duration and the arrival of the surgical cases as stochastic for their discrete operation time event simulation.

Some of the studies about the planning and scheduling of the operating rooms and patients are applicable to the real life situations. In fact, several of them are done according to real life problems, thus they are implemented in practice as in the study of Li et al. [16], which was about an integrated queuing and multiple-objective bed allocation model. On the other hand, some of the researchers do not test their findings with real data, so their applicability is also not tested. Also, since it is easier to find the relevant data from hospitals, a quantity of the studies are tested with real data. However, these tests are not sufficient for the implementation of the findings because of the assumptions made in order to obtain some meaningful results. Lehtonen et al. [15], used discrete event simulation and used real data, however, they made some assumptions because of the high variability in length of surgeries and thus inaccurate surgery times' estimates.

In their research, Dellaert and Jeunet [8] study about the efficient way of patient planning for tactical planning while also considering the patient satisfaction for the operational level. Thus, as a starting point of the research, the study of Dellaert and Jeunet about 'Tactical and operational strategies for scheduling elective and emergency patients under uncertainty' will be examined in more detail to combine and test it with other planning methods in order to improve the proposed strategies.

1.2.1 TACTICAL AND OPERATIONAL STRATEGIES FOR SCHEDULING

Dellaert and Jeunet [8], developed a two-stage planning procedure, which is for tactical and operational level, for the planning of elective and emergency patients. For this planning, they take several hospital resources into account so that the best available allocation is done. The resources which were considered were the operating theatre, beds in the medium and intensive care units and the nursing hours in the intensive care unit.

A tactical plan is made with the objective of minimizing the deviations of each resource's expected utilization from the daily target consumption. While making this tactical planning, some capacity is reserved for the emergency patients.

In order to deal with the difference between the actually arriving patients and the average number of patients, on which the tactical planning based, some methods are used such as overplanning and flexibility rules. Moreover, it was assumed that the elective patients can be cancelled and some emergency patients can be sent to other hospitals when there is a lack of capacity.

For the operational planning, to deal with the daily emergency patients, some decision rules and scheduling algorithm is developed for the elective patients and the emergencies, which takes the consumption of the resources into account for the considered patient.

To see the effect of overplanning and flexibility rules on the operational plan of hospital, some performance indicators are used like the patient satisfaction and the hospital efficiency. The performance of these rules and the planning is evaluated by simulation experiments with different levels of demand for emergency. As a result of these simulations, it is observed that there is a trade-off between the patient satisfaction and the hospital efficiency as can be expected. Furthermore, by these simulations, the effect of overplanning, flexibility and cancellation rules are obtained.

On the other hand, there are some issues that were not considered in this study. For instance, there are some emergency and elective patients that might not need an operation but can stay at the hospital for some reason like medical observation. This kind of patients, called conservative patients, does not use the operating theatre but may utilize the other resources like beds and nursing hours. Moreover, the waiting time of the patients is not taken into account for the tactical planning, which is a measure of patient satisfaction. In addition to those, the hospital efficiency is calculated by the deviation of average utilization from the target and capacity levels. However, the deviations of the actual utilization levels of the resources are not considered for this performance measure.

1.3 PROBLEM DEFINITION

For the satisfaction of patients and the efficiency of the hospitals, some tactical and operational scheduling should be done for the elective and emergency patients considering the medical people. The satisfaction of the patients can be determined by the waiting time of the patients, the number of early and late cancellations. Also, it is important for the medical people to know which operations will be done and if they will be available at that time for that operation. Meanwhile, the resources used for these operations and after the operations should be considered as well. In order to schedule a patient, not only medical staff should be available, but also operating theatre and other resources such as beds and nurses in intensive care unit and in medium care should also be available.

In order to satisfy the patients in terms of scheduling, the waiting time and the number of cancellations should be minimized. To achieve this, the scarce resources of the hospitals should be considered as constraints as well. In other words, the efficiency of the hospital should be taken in to account. The utilization of the resources should be as close as possible to the target consumption of them. Since the resources of the hospitals are limited, they face a trade-off between the satisfaction of patients and the efficiency of the resources.

The satisfaction of patients and medical staff is affected by the time of cancellations. For instance, early cancellation of an operation is less irritating for an elective patient than a late cancellation. Similarly, for medical staff, cancellation of operations of whole patient category has more effect on their dissatisfaction than cancellation of an operation of only one patient.

In addition to the situation given above, currently, the existing literature about the tactical and operational strategies for scheduling patients does not take into account the conservative patients, who might not have an operation. These conservative patients also have an effect on the inefficiency of the resources and thus to the satisfaction of the patients.

This situation led us to concentrate on developing tactical and operational strategies for the scheduling of elective and emergency patients considering also the conservative patients. By the proposed tactical planning strategies, the patient satisfaction and also the hospital efficiency can be improved. Thus, research question was defined as "How to find the most appropriate tactical and operational strategies for scheduling elective and emergency patients as well as conservative ones, that improves hospital resource efficiency with maintaining high patient satisfaction?".

However, the research problem was changed into "How to find the most appropriate tactical strategy for scheduling elective and emergency patients that improves hospital efficiency and patient satisfaction?' by leaving the conservative patients and the operational strategies out, in order to concentrate on the tactical planning and analyze it deeper. One of the main reasons to leave the conservative patients is that they can still be considered as a normal patient type with operation duration of zero hours. Also, finding an appropriate way to measure the performance of the system can be stated as another research problem. Thus, these can be achieved by improving the existing literature with alternative planning methods and testing them with proposed measurements for the hospital efficiency and patient satisfaction.

1.4 RESEARCH DESIGN

In order to answer the central research question a good approach to the research is essential. This section defines the project scope, the project approach and the deliverables.

1.4.1 SCOPE

Due to time and complexity constraints, the research scope should narrow down. Operations in hospitals and health care include a lot of sub-problems, such as the duration of the operations or the availability of the medical staff, which make the whole problem very complicated.

In order to handle the complexity, our main focus will be the sub-problem of scheduling and planning of patients by taking the patient satisfaction and the utilization of resources of the hospital into account. Planning of patients can be done for tactical and operational level. Tactical planning of patients can be defined as deciding which patient category to be operated at what time taking the preceding and consequent unit capacities into account. This allocation is based on the demand levels of patient types which require different usage of different resources. Other sub-problems such as allocation of resources to departments will be out of scope.

1.4.1.1 System Boundaries

In this part, system boundaries are defined. While the narrow system of interest defines the system that will be dealt, the wide system of interest includes narrow system of interest in addition to the other facts that can not be interfered.

Narrow System of Interest:

Narrow system of interest is the initial system that will be focused on.

- Usage of resources by patients from each category
- Working hours of medical people
- Operating Theatre working time
- Sequence of patient categories
- Utilization of resources
- Allocation of resources

Wide System of Interest:

Wide system of interest is the outer environment affecting our narrow system of interest that cannot be interfered.

- Capacity of resources
- Paths followed by patients from each category
- Medical procedures
- Income from operated patients
- Other financial issues

1.4.1.2 Objective

The objective of the research is to find a scheduling strategy at a tactical level, so that the satisfaction of the patients can be met while having the utilization of the resources as close to as targeted utilization levels.

1.4.1.3 Decision Variables

Decision variables are inputs that are planned to be reorganized for the tactical scheduling strategy:

- Number of operations per type per day on a given day.
- Allocation of resources for the emergency patients.
- Over and under utilization of resources for each type.

1.4.1.4 Parameters

Parameters are uncontrollable inputs that cannot be interfered.

- Path followed by patient categories
- Consumption of resources by each patient category
- Capacity of the resources
- Target utilization of the resources
- Arrival rate of the elective and emergency patients

1.4.1.5 Performance Measures

Performance measures are the outputs that will show the performance of the system obtained with the tactical planning.

- Over and under utilization of resources
- Exceeding capacities
- Average waiting time of the patients

1.4.2 APPROACH

Proposed project approach is adapting and testing the models in literature for the scheduling and planning of the patients. Main goal of the research is to find a tactical strategy for the scheduling of the patients that sustain patient satisfaction and hospital efficiency.

The planning strategies can be studied in two hierarchical levels, tactical planning and operational planning. In tactical level planning, allocation of operations of patient groups to operating days is done considering the preceding and the following units' resource availability as well so that the demand can be met. The objective of the tactical planning is to obtain a schedule for patient types that minimize the variations from targeted utilization levels of resources and thus the working time of the relevant surgeons as well and also to obtain a higher patient satisfaction with lower average waiting times before the operation. In operational planning, the result of the tactical planning is updated according to the real demand occurred until that time. Taking into account these, a decision of cancelling or operating can be given for patients.

1.4.2.1 Tactical Level

In tactical level, planning horizon is taken as a 4-week period, however, this horizon can be adopted according to the characteristics of the departments or hospitals. According to the expected arrival of elective and emergency patients, the required capacity allocation and scheduling of patient categories are done. For this level of planning, the operating room capacity can be taken as blocks in order to prevent the idleness of the operating room. Moreover, some type of heuristics can be utilized in order to reduce the waiting time of a patient type, for instance a limitation can be put on the amount of patient per type per day or per *n* days in order to obtain a smoother allocation of the operations over the planning horizon.

The utilization of resources and the allocation of them to emergency patients as well as the waiting time of the elective patients are the expected outputs from this analysis. Moreover, the scheduling of the elective patient types is also obtained to meet the total demand of patients.

In order to obtain the tactical level strategies, modeling tools will be used as well as simulations to test the developed model. Also, some alternative planning methods and heuristics will be tested as well as some different scenarios about overplanning to find a better planning strategy.

1.4.2.2 Operational Level

In operational level, the detailed scheduling of the patients is done on a daily basis. Taking into account the real arrival of the patients, some updates are done to the schedule prepared for the tactical level. To do so, some elective patients or even categories can be cancelled because of lack of patients from that category.

Expected outputs from this analysis are schedules for patient categories on a daily basis. Also the number of cancellations, average waiting time of the patients, the utilization levels of the resources and exceeding capacities can be delivered as a result of operational level planning to see the patient satisfaction and also the hospital efficiency. Moreover, since the variation of the hospital efficiency is a better measure of performance than the deviation of average utilization from target and capacity, the distribution of resource usage levels will be considered for the hospital efficiency.

Again some simulation tools will be utilized to test the performance of the system at operational level. Modeling and heuristics will be used to determine the planning strategies. Moreover, the complexity of the planning strategy is more crucial for operational level since it should be easier to carry out at an operational level.

1.5 PROJECT PLANNING

In this part a global planning of this master-thesis project will be presented. The milestones of the project are the processes below, also given in Figure 1.

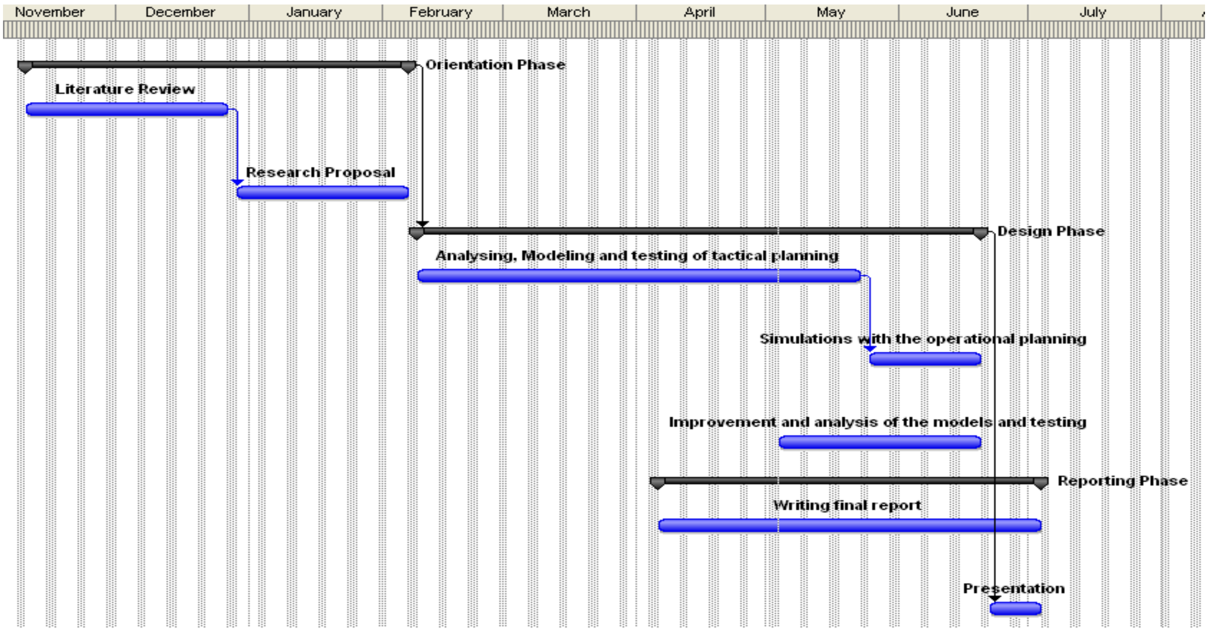


Figure 1: The planning of the project

For the orientation phase, a literature review was conducted in order to get familiar with the researches and studies in this area and also to find a suitable research subject for further improvement and studies. Moreover, depending on this literature survey, a research proposal is carried out in the orientation phase. Within the proposal, the definition of the problem is given. Also the scope of the research is defined as well the approaches for the design of the research.

For the design phase, the model and heuristic approaches for the tactical and operational planning will be done according to the analysis made. First some analysis will be done for the tactical model for elective patients. Then, some heuristics approaches and mathematical modeling will be considered to improve the current system and to find an appropriate scheduling that considers the efficiency of resources as well as the patient satisfaction. These proposed models and heuristics will be tested by simulation models in order to see the performance of the system at an operational level.

When some findings and results are obtained at the design phase, the reporting phase starts parallel to the design phase. In this phase, the preparation of the final report and the presentation of the final outcomes of the research will be done.

PART II RESEARCH & DESIGN

2.1 INTRODUCTION

In the previous part, the literature about the planning and scheduling of the operating rooms was reviewed and the proposal for the research was given by the definition of the problem, design of the research and the planning of the project. In this part, first a description of the general situation for the problem of operating room planning will be given. Moreover, the tactical and operational strategies developed by Dellaert and Jeunet [8] were mentioned in the orientation part. In this section, the mathematical model developed by them for the tactical planning will be used as the base model for the further analysis. Thus, first an explanation of that mathematical model will be given. However, as that model does not take the waiting times of the patients into account for the tactical planning, some analysis and improvements will be done about the waiting time of the patients such as smooth allocation of the operations. After the explanation of the mathematical model, a heuristic model will be developed to see the effect of smooth allocation on resource utilization levels. Then, to combine these two objectives, some constraints will be explained and added to the basic mathematical model to obtain a smoother allocation while taking the utilization levels into account. Next, in order to see the performance of any given tactical plan in reality, some analyses are made for the patient satisfaction and hospital efficiency. To do so, the tactical plan was used for the operational level without any flexibility. The functions to find the average waiting time of the patients are described to measure the patient satisfaction. Furthermore, for the hospital efficiency analysis, the distribution of the resource usage levels are taken into account at an operational level instead of average utilization of the resources, in order to see the variation of their utilization. Thus, in the last parts of this section, some analyses are done to be able to measure the performance of any given tactical plan in terms of patient satisfaction and hospital efficiency.

2.1.1 GENERAL DESCRIPTION OF THE SYSTEM

For the analysis and improvements for the operating room planning and scheduling, first the system should be understood extensively. Thus, in this part a general description of the procedures and the paths followed in the system will be given as some characteristics of the system.

As mentioned before in the orientation part, the patients can be divided into two categories like elective patients, whose operations are planned beforehand, and emergency patients, who require immediate operations. The planning of elective patients is done for a longer term for the tactical level in order to allocate the operations so that the resource usage levels become as efficient as possible. On the other hand, the operational planning is done for a shorter period such as daily or weekly. For the operational level, the tactical plan is used as a basis with more flexibility for the scheduling of elective and emergency patients, after their actual arrivals.

In order to make the planning of these patients, some categories are formed according to the paths they follow after they enter the system and also their resource usage levels. In the Figure 2 below all possible paths that can be followed by patients are illustrated. After the arrival of the patients from each category, they follow the corresponding paths according to their category type. Some of them can go directly to operating theatre while some others need to spend some days at the medium care before the operation depending on the patient categories. After the operation, patients stay at the intensive care unit and the medium care unit for several days with some probabilities which also depends on the patient category types.

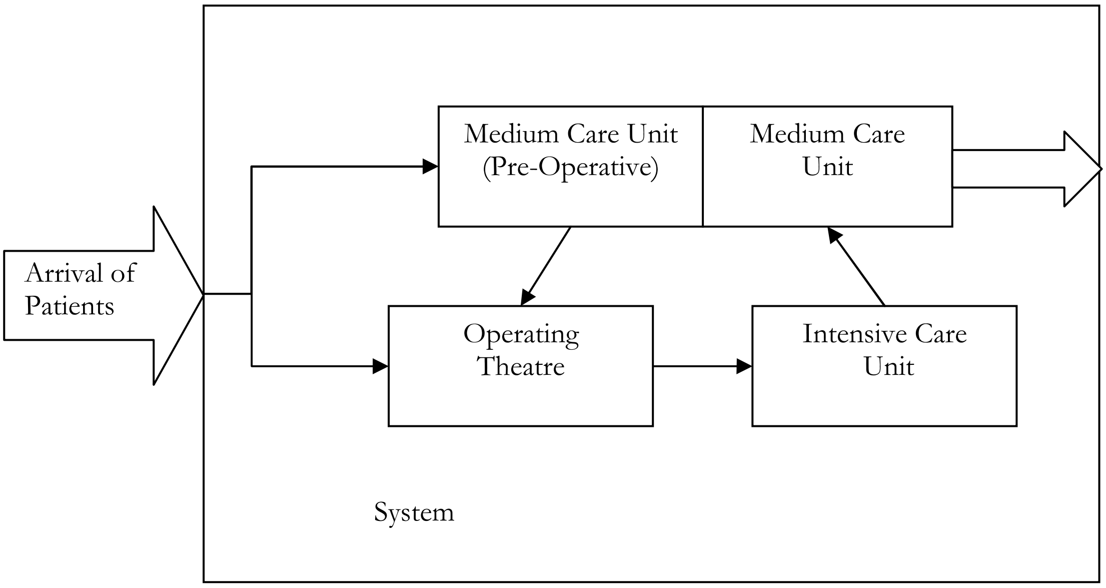


Figure 2: Paths followed by patients after they entered the system

As can be seen from the Figure 2, there are 3 major units related with the planning of the operating room; the operating theatre (OT) , medium care unit (MC) and the intensive care unit (IC). Moreover, the nursing hours for the intensive care unit (NH) are also considered as one of the major resources since it is also a scarce resource for the system. The capacity of these resources may differ from day to day as well as their targeted utilization levels.

The arrival of the patients are probabilistic as well as the length of stay in intensive care and medium care units. On the other hand, although the duration of the operations may differ, these durations are considered as deterministic using the average values for them. Also, the number of pre-operative days in medium care unit is assumed to be deterministic. The nursing hours required for each patient category on a certain day is also definite. These probabilities and values are based on the observations and data collected. Moreover, the numbers of operations to be planned for each patient category in a planning horizon are taken according to the average number of patients arriving in a planning period. These numbers are chosen considering the flexibility of the system to meet the real demand. For instance, the number of operations to be scheduled in one period differs for overplanning options, in which there are more operations scheduled than the average demand for a patient category.

To find an efficient planning for the usage levels of resources in the medium-run, a tactical planning is determined that schedules operations of each patient category for each day. In addition to the tactical planning, operational strategies are developed to handle the differences between the actual arrival of elective and emergency patients and the projected ones. These operational strategies are based on a shorter-term such as daily or weekly.

2.2 BASIC MATHEMATICAL MODEL

In this section, an explanation of the mathematical model developed by Dellaert and Jeunet [8] will be given. Note that this mathematical model is also based on the system described in section 2.1.1 and it will be a base model for further analyses and improvements. As mentioned before, the length of stays in IC and MC units are probabilistic while the operating time is assumed to be deterministic. The number of operations for each patient category that will be planned in each period depends on the average number of arrivals from that patient category, which in our case is assumed to be based on a Poisson distribution. Note that, the number of patients to be planned can be determined considering the trade-off between the flexibility of the system and the idleness of the resources. For instance, it is possible to make an overplanning of the patients to be operated, which brings the system more flexibility, however, in case of a smaller number of actual arrivals the system and the resources may become idle.

The aim of this mathematical model built for the tactical planning is to minimize the sum of the overuse of resources as well as the deviations of utilization levels from target utilization levels of each resource (OT, IC, MC, NH) with a weight assigned to each. The model results in a scheduling of operations for each patient category. For the tactical planning, this model enables all planned elective patients are scheduled while trying to keep the excess usage of resources as limited as possible.

In order to find the schedule according to the objective, the following parameters are defined as well as the variables and the corresponding mathematical model is built. The explanation of each constraint is given in parentheses next to these constraints.

Parameters:

N	Number of patient's categories
c	Category index, c=1..N
T	Length of the cyclic planning horizon in days
t	Day index, t=1..T
P_c	Target number of elective patients of category c to be operated during the horizon
S_c	Operation duration in hours for a patient of category c
l_c	Number of pre-operative day in MC unit for one patient of category c
r	Resource index, r={OT, IC, NH, MC}
$p_{IC,c,t}$	Probability that a patient from category c is (still) at the IC unit t days after operation, $t = 0, 1, 2, \ldots, L_{IC}^{max}$
L_{IC}^{max}	Maximum length of stay recorded in IC over all categories
L_{MC}^{max}	Maximum length of stay recorded in MC over all categories
$p_{MC,c,t}$	Probability that a patient from category c is at the MC unit t days after operation, $t = 0, 1, 2, \ldots, L_{MC}^{max}$
$w_{c,t}$	IC nursing workload (in hours) required for a patient of category c, t days after operation
$C_{r,t}$	Maximum capacity for resource r on day t (expressed in number of hours for OT and NH and in number of beds for IC and MC)

$R_{r,t}$	Target utilization of resource r on day t
$\beta_{c,t}$	Arrival rate for emergency patient of category c on day t
$q_{c,t}$	Probability that an emergency patient of group c arrives during the day t and not during the night
α_r	Relative importance of resource r as assessed by the stakeholders in the hospital
b	penalty for the overuse of the resources

Variables:

$X_{c,t}$	Number of patients from category c operated on day t, with c=1..N and t=1..T
$O_{r,t}$	Over utilization of resources relative to the target use for resource r on day t, r={OT, IC, NH, MC} and t=1..T
$U_{r,t}$	Under utilization of resources relative to the target use for resource r on day t, r={OT, IC, NH, MC} and t=1..T
$E_{r,t}$	Overuse of resource r on day t compared to the maximum capacity

Objective function:

$$\sum_{r=\{OT,IC,NH,MC\}} \alpha_r \sum_{t=1}^{T} \left(O_{r,t} + U_{r,t} + b \cdot E_{r,t}\right)$$

Constraints :

$$\sum_{t=1}^{T} X_{c,t} = P_c \qquad c= 1..N \qquad \text{(target patient throughput)}$$

$$\sum_{c=1}^{N} s_c X_{c,t} + \sum_{c=1}^{N} s_c q_{c,t} \beta_{c,t} \leq C_{OT,t} + E_{OT,t} \qquad t= 1..T \qquad \text{(overuse of OT)}$$

$$\sum_{c=1}^{N} s_c X_{c,t} + \sum_{c=1}^{N} s_c q_{c,t} \beta_{c,t} \leq R_{OT,t} + O_{OT,t} \qquad t= 1..T \qquad \text{(overutilization of OT)}$$

$$\sum_{c=1}^{N} s_c X_{c,t} + \sum_{c=1}^{N} s_c q_{c,t} \beta_{c,t} \leq R_{OT,t} - U_{OT,t} \qquad t= 1..T \qquad \text{(underutilization of OT)}$$

$$\sum_{c=1}^{N} \sum_{j=0}^{L_{IC}^{\max}} p_{IC,c,j} X_{c,t-j} + \sum_{c=1}^{N} \sum_{j=0}^{L_{IC}^{\max}} p_{IC,c,j} \beta_{c,t-j} \leq C_{IC,t} + E_{IC,t} \qquad t= 1..T$$

(overuse of IC)

$$\sum_{c=1}^{N} \sum_{j=0}^{L_{IC}^{\max}} p_{IC,c,j} X_{c,t-j} + \sum_{c=1}^{N} \sum_{j=0}^{L_{IC}^{\max}} p_{IC,c,j} \beta_{c,t-j} \leq R_{IC,t} + O_{IC,t} \qquad t= 1..T$$

(overutilization of IC)

$$\sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} p_{IC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} p_{IC,c,j} \beta_{c,t-j} \le R_{IC,t} - U_{IC,t} \quad \text{t= 1..T}$$

(underutilization of IC)

$$\sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} w_{c,j} p_{IC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} w_{c,j} p_{IC,c,j} \beta_{c,t-j} \le C_{NH,t} + E_{NH,t} \quad \text{t= 1..T}$$

(overuse of NH)

$$\sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} w_{c,j} p_{IC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} w_{c,j} p_{IC,c,j} \beta_{c,t-j} \le R_{NH,t} + O_{NH,t} \quad \text{t= 1..T}$$

(overutilization of NH)

$$\sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} w_{c,j} p_{IC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{IC}^{\max}} w_{c,j} p_{IC,c,j} \beta_{c,t-j} \le R_{NH,t} - U_{NH,t} \quad \text{t= 1..T}$$

(underutilization of NH)

$$\sum_{c=1}^{N}\sum_{j=1}^{l_c} X_{c,t+j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{MC}^{\max}} p_{MC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{MC}^{\max}} p_{MC,c,j} \beta_{c,t-j} \le C_{MC,t} + E_{MC,t} \quad \text{t= 1..T}$$

(overuse of MC)

$$\sum_{c=1}^{N}\sum_{j=1}^{l_c} X_{c,t+j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{MC}^{\max}} p_{MC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{MC}^{\max}} p_{MC,c,j} \beta_{c,t-j} \le R_{MC,t} + O_{MC,t} \quad \text{t= 1..T}$$

(overutilization of MC)

$$\sum_{c=1}^{N}\sum_{j=1}^{l_c} X_{c,t+j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{MC}^{\max}} p_{MC,c,j} X_{c,t-j} + \sum_{c=1}^{N}\sum_{j=0}^{L_{MC}^{\max}} p_{MC,c,j} \beta_{c,t-j} \le R_{MC,t} - U_{MC,t} \quad \text{t= 1..T}$$

(underutilization of MC)

$X_{c,t} = 0$ *and* $X_{c,t+1} = 0$ t=6+7(j-1), j=1,…,(T/7), c=1,…,N (weekends)

$X_{c,t} \in \{0,1,2,...\}$ c=1,…,N , t=1,…,T (integrality)

With the mathematical model given above, the tactical plan for the elective patients is then obtained. However, it is observed that for some patient types it is possible that all the required operations take place on the same day or at least not so equally allocated, which may lead to an increase for the waiting times of the patients. Although, the waiting times of the patients are not considered in the objective function, it has also an importance for the performance of the system in the operational level. Thus, in order to minimize the waiting time of the patients, a smooth allocation is considered so that the variation of the time between operations become as small as possible and the waiting time of the patients decrease. To see the effect of smooth allocation of operations on the utilization levels, a heuristic is constructed, which is explained in the next section.

2.3 SMOOTH ALLOCATION

For the waiting time of the patients, it is thought that if the variation of the time between operations decreases, the waiting time of the patients decreases as well. Thus, equal allocation of the operations is considered. With the aim of smoother operation allocation, the concept of small cycles is introduced. Then, the effect of this smooth allocation on the utilization levels of the resources is tested by a heuristic.

2.3.1 SMALL CYCLES

To obtain less variation of the times between the operations, the planning period is divided into small cycles. For instance, instead of allocation n operations of a patient category in a period of T days, allocation of n/2 operations in T/2 days is considered. Thus, the new length of that cycle becomes T/2. By obtaining these small cycles, scheduling all of the operations of a patient category on a single day or at least clustering of operations around a single point will be prevented. Moreover, instead of using a cycle length of T/2, using the cycle length of T/4 prevents the allocation from clustering in a stronger way. In other words, while the cycle length of T/2 allows at least two clustering of operations, the cycle length of T/4 would allow at least four clusters of operations for that patient category. Thus, the smaller cycles used, the smoother the allocation gets. To illustrate the concept of small cycles, assume there are 10 operations to be scheduled in 5 days. In the worst case in terms of waiting time, all of them are scheduled at the same day as given in Figure 3 (a). However, on the other hand, if small cycle length of 1 day is considered, there will be 2 operations scheduled on each day as shown in Figure 3 (b) which makes the allocation of the operations smoother.

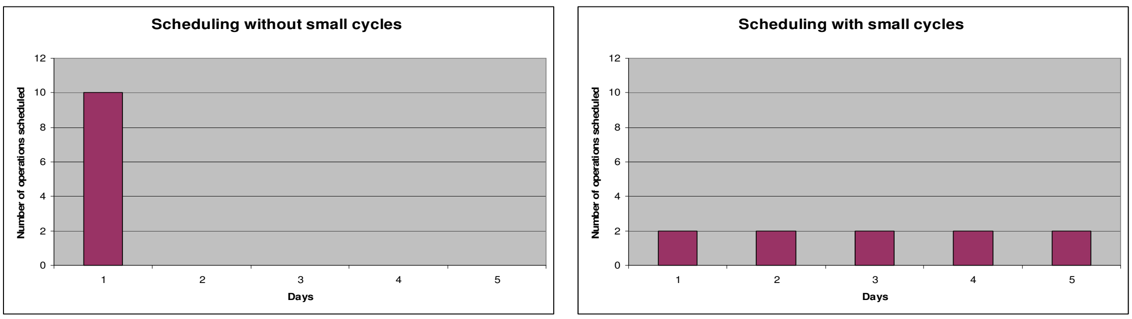


Figure 3: The scheduling of 10 operations (a) without (b) with small cycles

Moreover, when the average number of operations to be scheduled in each small cycle, x, is not an integer but a fractional number, then there will be $\lceil x \rceil$ operations scheduled in small cycles with a probability of $p = x - \lfloor x \rfloor$, and $\lfloor x \rfloor$ operations scheduled with a probability 1-p.

Note that, since the number of patients to be planned in the planning period differs for each patient category, it is possible to have different small cycle lengths for each patient category as well depending on the total number of patients to be scheduled for the whole period. For instance, a patient category that has 4 operations to be scheduled in the whole period can have a small cycle of T/4 so as to have a smoother allocation. On the other hand, for another patient category with the planned operation number of 2, having a small cycle length of T/2 would be enough to obtain the smooth allocation.

As the concept of these small cycles is now introduced, the effect of them on the utilization levels of the resources can be tested. In section 2.2.3, more explanation will be given about scheduling of operations with these small cycles.

2.3.2 THE EFFECT OF SMOOTH ALLOCATION

To see whether the equally allocated operations has an effect on the utilization and overuse levels of the resources, a heuristic model is constructed to allocate the operations as smooth as possible with the given small cycle lengths. To allocate the operations smoothly to days, the heuristic first orders the patient types. In order to see which one is a better option, the heuristic is followed for both in a descending and in an ascending order; so that the most or the least frequent patient type is scheduled first taking into account the operating room availability and the required hours for each operation. After scheduling the most or the least frequent patient type, the model continues with the following patient category again taking the remaining operating room capacities into account.

To make this scheduling equally allocated, the small cycle lengths are considered, which can be different for each patient category depending on their total number of operations to be planned for the whole period. These small cycle lengths are defined as small as possible for each patient category, so that the time between each two operations is as small as possible as well as the variation of the time between the operations. The details of the smooth allocation heuristics are given in the steps below.

Step 1.

Order the patient types in a descending / ascending order according to the total number of operations planned and the total hours required for these operations in a period. (ord=1,..,C) (For the first patient category on the row, ord=1) Go to Step 2 for ord=1.

Step 2.

For a given patient category ord, determine

→ the number of small cycles (nc_{ord})

→ the length of small cycles ($len_{ord} = \frac{T}{nc_{ord}}$)

→ the number of operations planned per small cycle depending on the average number of operations per small cycle (nso_{ord}).

$$nso_{ord} = \frac{P_{ord}}{nc_{ord}}$$

$$p = nso_{ord} - \lfloor nso_{ord} \rfloor$$

If p>0 → $nso_{ord} = \lceil nso_{ord} \rceil$ with a probability of p, and $nso_{ord} = \lfloor nso_{ord} \rfloor$ with a probability of 1-p.

Set $aop_t = 0$ ∀t=1,2,..,T (number of operations assigned on day t) and $bt = round\left(\frac{len_{ord}}{nso_{ord}}\right)$.

Set t=1, and go to Step 3.

If the required number of operations per day is greater than 1, then the scheduling of the operations should take the average number of operations per day.

Step 3.

Let $rcap_t$ be the remaining capacity of operating theatre on day t.

If $rcap_t \geq S_{ord}$ → Set $aop_t = aop_t + 1$ and go to Step 4

Else → Set t=t+1 and go to Step 3.

Step 4.

Set t=t+bt.

If $\sum_{t=1}^{len_{ord}} aop_t = nso_{ord}$ → Go to Step 7.

Step 5.

Check if $rcap_t \geq S_{ord}$ and $\sum_{t=1}^{t-1} aop_t \geq nso_{ord} \times \frac{t-1}{len_{ord}}$ while $\sum_{t=1}^{t-1} aop_t \leq nso_{ord}$

If TRUE → Set $aop_t = aop_t + 1$ and $rcap_t = rcap_t - S_{ord}$, and go to Step 4.

Else if t=1 → Set t=t+1 and go to Step 5.

Else → Go to Step 6.

Step 6.

$$If \sum_{t=1}^{t-1} aop_t \geq nso_{ord} \times \frac{t-1}{len_{ord}} = \text{FALSE} \ \text{ and } \ rcap_t \geq S_{ord} = \text{TRUE}$$

Then If $rcap_{t-1} < S_{ord}$ ➔ Set $aop_t = aop_t + 1$ and $rcap_t = rcap_t - S_{ord}$, and go to Step 4.

Else ➔ Set t=t-1 and go to Step 5.

Else ➔ Set t=t+1 and go to Step 5.

Step 7.

After scheduling all operations for that small cycle, continue with the new small cycle with the same steps starting from Step 3. Before starting to the next small cycle check whether the current small cycle is the last one before the one with an extra operation or the one with an extra operation to be planned. If it is one of them, then make the required adjustments for the total number of operations to be planned and then go to Step 3. If not, then directly continue with Step 3.

Step 8.

After scheduling all operations for that patient type, continue with the next patient type on the row from Step 2 until all the patient categories are scheduled.

After obtaining the schedule of each patient type, the utilizations and overuse of each resource type is calculated according to the model given above. The schedules are obtained both for the ascending and the descending order. It is seen that, there is a significant difference in terms of utilization and overuse levels of resources of the planning obtained by the mathematical model explained in section 2.2.1 and the planning that considers smooth allocation of operations. Thus, it can be mentioned that there may be some trade-offs between the smooth allocation, so the waiting time of the patients and the utilization and the overuse levels of the resources.

To see the significance of this trade-off, it is decided to make some improvements to the mathematical model and add some constraints to it, which will be introduced in the following section, so that the average waiting time of the patient type will decrease while still considering the utilization and usage levels of the resources.

2.4 ADDITIONAL CONSTRAINTS

With the heuristic constructed in the previous section, it was observed that there is a significant trade-off between the smooth allocation of the operations and the utilization levels of the resources. In other words, the trade-off is between the patient satisfaction and the efficient use of the resources.

To obtain a tactical planning that considers the efficient use of resources while taking the patient satisfaction into account, some adjustments are done to the basic mathematical model mentioned in the section 2.2.1. Constraints are added to that mathematical model which makes the model to allocate the operations of each patient category according to their predefined small cycle length.

To make the mathematical model consider these predefined small cycles, two types of constraints are created; one limits the number of patients only for the fixed small cycles while the other one deals with the moving small cycles.

2.4.1 FIXED SMALL CYCLES

In order to find a planning that schedules operations more equally and smoother, it is decided to divide the period into some small cycles and add a constraint to the model so that there should be at most the required amount of operations scheduled for that cycle, which may lead to prevent the operations to cluster around some days of the whole period. To satisfy these conditions, following parameters and constraints are added to the previously given mathematical model above.

Parameters and index:

len_c the length of the small cycles of each patient category c.

n_c small cycle index for each patient category. $n_c = 1,2,..,(T/len_c)$.

Additional constraints:

To have at most the required amount of operations for each small cycle. The integer part of the average number of operations per small cycle is considered for the right hand side of the constraint to make each cycle has at least that amount of operations scheduled, and the additional ones can be considered in the next constraint.

$$\sum_{t=(n_c-1)len_c+1}^{n_c len_c} X_{c,t} \geq \left\lfloor P_c \frac{len_c}{T} \right\rfloor \qquad \forall c, n_c$$

While considering the lower limit for each small cycle, the cumulative number of operations scheduled for small cycles for each patient category is also taken into account with an additional constraint. By this one, the number of operations required until the next small cycle is satisfied.

$$\sum_{t=1}^{n_c len_c} X_{c,t} \geq \left\lfloor n_c P_c \frac{len_c}{T} \right\rfloor \qquad \forall c, n_c$$

With the help of additional constraints, it is now possible to allocate the operations more equally across the small cycles. However, it is also observed that the operations may form some clusters again at the end of a small cycle and at the beginning of the next small cycle or vice versa, which leads to still high variation of the time between two operations. Thus some adjustments need to be done to these constraints, and instead of these fixed small cycle constraints, a moving constraint can be considered to prevent this issue.

2.4.2 SMALL MOVING CYCLES

With the tactical plan obtained by the fixed small cycles, it was observed that the distance between two operations may deviate too much. Thus, to prevent the scheduling from this, and to obtain a smoother plan with low variation of the time between two operations, a new constraint is decided to be added to the original mathematical model. Hence, instead of limiting the number of operations to be scheduled in one small cycle for each patient category, the moving cycles are now considered with the additional parameters and constraint given below.

For instance let the small cycle length of a patient category be *l* and the number of operations to be scheduled be *n*. By this constraint, for that patient category, the number of operations scheduled in each *l* days now becomes at least *n*.

Parameters and index:

len_c	the length of the small cycles of each patient category c.
n_c	small cycle index for each patient category. $n_c = 1,2,..,(T/len_c)$.
m_c	moving cycle index for each patient category. $m_c = 1,2,..,(T-len_c+1)$.

Additional constraint:

By this constraint, it is aimed to have at least the average number of required of operations for each small moving cycle. Since it is possible to have the average number as a fractional number, the lower integer value is considered. Thus, the lower integer value of average number of required operations will be satisfied for each cycle, and the rest will be considered with the other constraint that deals with cumulative requirements.

$$\sum_{t=m}^{(m-1)+len_c} X_{c,t} \geq \left\lfloor P_c \frac{len_c}{T} \right\rfloor \qquad \forall c, m_c$$

As only the lower integer value of the average number of operations is considered in the previous constraint, another constraint is introduced to handle the cumulative number of required operations for small cycles. By this one, the number of operations required until the next small cycle is satisfied.

$$\sum_{t=1}^{n_c len_c} X_{c,t} \geq \left\lfloor n_c P_c \frac{len_c}{T} \right\rfloor \qquad \forall c, n_c$$

With this constraint, the smooth allocation of operations to the small cycles can now be achieved. As the small cycles are now moving, the variation of the distance between two operations is thus lowered and become more equal. In other words, since this constraint is valid for every *l* days in the planning period, it enables the mathematical model to assign the operations of each patient category smoother, with lower variation of the time between the operations.

After the addition of these new constraints, the waiting time calculations will be done in the next section with the aim of observing the effect of schedule changes on patient satisfaction.

2.5 WAITING TIME CALCULATIONS

To see the effect of or the smoothing of the operation schedules or at least the changes in the scheduling to the patient satisfaction at an operational level, some calculations are needed to be done to find the average waiting time in terms of small cycles as well as the average number of days that patients should wait until they get operated. Note that, for the operational planning, the tactical planning is used without any flexibility at an operational level.

The average waiting time of each patient category is calculated separately since they may have different lengths of small cycles. Moreover, since it is assumed that there is no flexibility between the scheduled operations of patient categories for the tactical plan, the calculations for each patient category can be done independent of the others. By no flexibility, it is meant that, although there are not enough patients from a certain patient category to be operated on that day, it is not possible to use that operating theatre capacity for another patient from another patient category. Thus, considering each patient category independent of each other brings an ease for the calculation of waiting times.

2.5.1 AVERAGE WAITING TIME: AVERAGE NUMBER OF SMALL CYCLES

As to observe the effect of scheduling on the average number of small cycles that a patient should wait until the small cycle, in which its operation takes place, first the arrival rates of each patient category for each small cycle is considered.

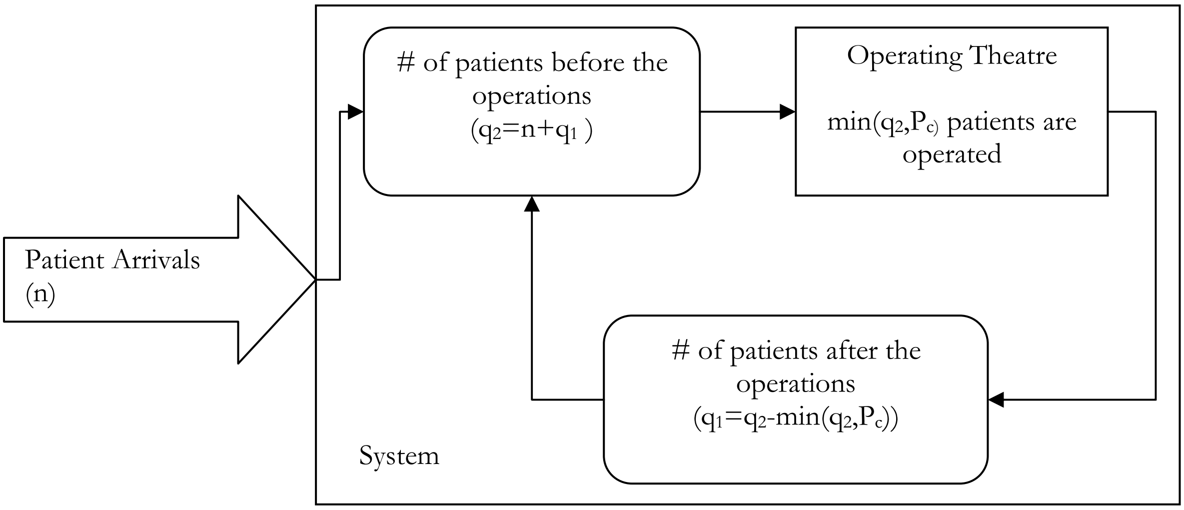


Figure 4: Number of patients waiting for the operation in a small cycle

In order to calculate the average number of cycles that a patient should wait, first the average number of patients before the operations (q2) is found for the steady state. As shown in the Figure 4, the number of patients just before the operations is q2, and the probability that there are q2 patients before the operations is Q2(q2). Similarly, the probability that there are q1 patients just after the operations is Q1(q1), while the number of patients arrived before the operations is shown with n, and the arrivals occur according to a Poisson distribution in this case with a probability of P(n). These steady state probabilities are found by running the model, which is illustrated above in Figure 2, until there is no more change in the values of the Q1 and Q2 probabilities. In other words, for a given value of ε, which is close to 0, the simulation is run until the condition given below is reached.

$$\left|Q1_y(q_1) - Q1_{y+1}(q_1)\right| \leq \varepsilon \text{ and } \left|Q2_y(q_2) - Q2_{y+1}(q_2)\right| \leq \varepsilon$$

Note that, the y value represents the number of periods that the model is run, and the maximum value that it should take for a patient category is y_{max}, at which the conditions given above are met. Thus, to reach the steady state, the model is run for at least y_{max} periods, which may differ for each patient category

After reaching the steady state values of Q1 and Q2, the average number of patients just after the operations took place is calculated by $\sum Q_1(i) \times i$ for all patient types. Note that if there are less amount of patient than the number of operations scheduled for a cycle for any patient category, than the number of operations occurred is equal to the number of patients, who are in the system, for that patient category. Again, it is assumed that there is no flexibility between the operations of different patient categories for the tactical planning.

With the help of these calculations, some analyses are done to see the effect of small cycles on the average number of periods that patients wait to be operated. It is observed that the average number of cycles gets higher when the cycle length is decreased as can be expected. However, to see the real effect of the planning with small cycles, thus with a smoother allocation, on the waiting time of the patients, further calculations and analysis should be made with the waiting times in terms of days, since the main effect of small cycles is expected to occur in that part.

2.5.2 AVERAGE WAITING TIME: AVERAGE NUMBER OF DAYS

As the main reason behind the equal allocation of the operations is to decrease the time between each operation and also reduce the variation of the time between operations, the main influence and the improvement of this approach is expected to be at the average number of days that patients wait for the operation.

To observe the effect of this approach, first the mathematical model is solved with and without the additional small cycles' constraints. Then the resulting schedules for each operation of each patient category are considered to calculate the average waiting time of a patient from each category. The calculation of the waiting time is similar to the one for the periods, but more detailed since it takes the days of the operations within a period into account.

Again, note that this waiting time calculations is also done for each patient category separately, since they are assumed to be independent from each other. It is not allowed to use the operation capacity of a non-occurred patient from a certain category for a patient from another category.

As illustrated in Figure 5 below, there are n patients arriving in a day with a probability P(n), which makes the number of patients before the operations on day j equal to q_{2j} with a probability of $Q2_j(q_{2j})$. There are $S_c(j)$ operations scheduled on day j for the patient category c, which brings the number of patients after the operation on day j to q_{1j} with the probability of $Q1_j(q_{1j})$. The values of j are from 1 to T, and after the T^{th} day, the cycle continues with the planning of the 1^{st} day. Again the model is run until the $Q1_j$ and $Q2_j$ values reach the steady state. Note that, the number of patients operated on day j, depends on the number of patients before the operations on day j-7. Thus, the decisions about the operational planning of the operations are done one week before the operations take place.

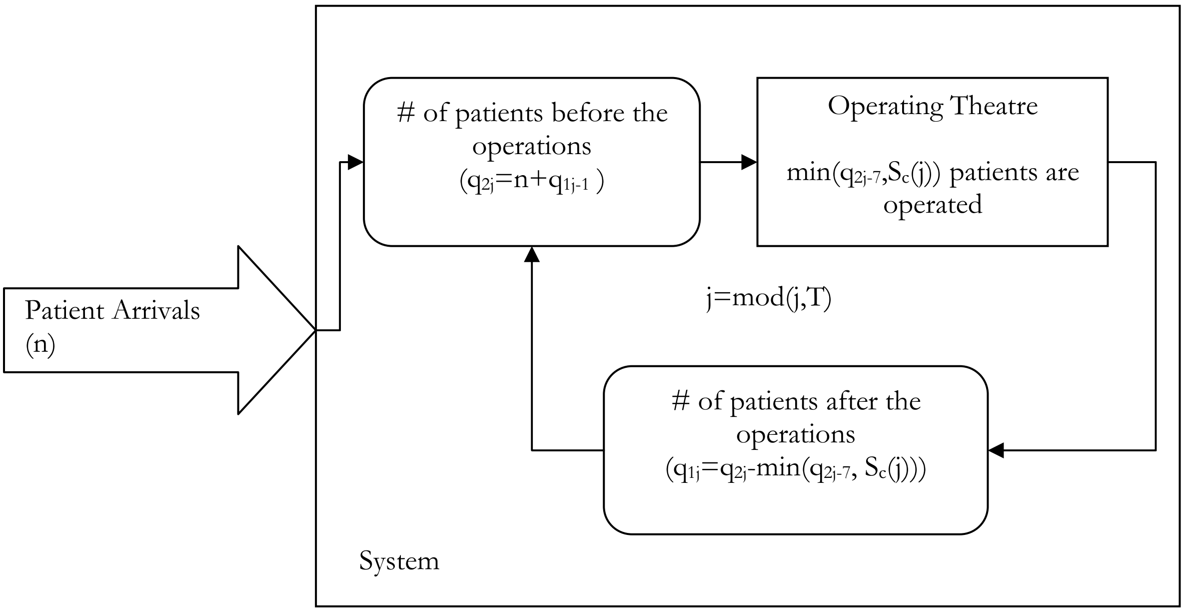


Figure 5: Number of patients waiting for the operation in one day

Obtaining the steady state probabilities of number of patients for each day for each patient category, now the average waiting time of each patient category can be calculated. The average waiting time of patients can be considered as two parts. One part consists of the average waiting time of the patients, who will be operated within that period, until the first operation day. The second part, on the other hand, considers the probability that the patients who should wait until the next operating day. Thus the equation for average waiting time of patients can be written as:

Average waiting time = WT_1+WT_2, where the calculations WT_1 and WT_2 will be explained below.

As mentioned above, WT_1 is the average waiting time of patients until the first day that an operation takes place. Let d_i be the number of days between two consecutive days, at which operations are scheduled, and let λ be the arrival rate of patients per day. Thus, there will be $\lambda x d_i$ patients arrived on average, and the average waiting time of a patient will be $d_i/2$ days. When these values are considered for the whole planning horizon, T, with several d_i values, then the WT_1 is found to be:

$$WT_1 = \frac{\frac{1}{2}\lambda \sum_i d_i^2}{\lambda \sum_i d_i}$$ for each patient category.

WT_2 considers the average waiting time of the patients who cannot be operated at the first operating day. Thus, it considers the probabilities that there will be more patients than the number of scheduled operations on the first operating day. For WT_2 calculation, let N_i be the number of scheduled operations on the operating day i for that patient category and λ be the arrival rate of patients for the planning horizon T, instead of per day as in WT_1 calculation. Again, let d_i be the number of days between two consecutive operating days i and i+1, and q_{2i} the number of patients before the operations on day i, with a probability of $Q2_i(q_{2i})$. So, if there are more patients before the planning day of the operation (q_{2i-7}) than the number of scheduled operations (N_i) on the operating day i, the surplus patients (q_{2i-7}-N_i) will wait until the next operating day i+1, thus for d_i days. Again, when these are combined for the whole planning horizon, T, for all i values, then the WT_2 can be calculated as:

$$WT_2 = \frac{\sum_i \sum_{q_{2i}>N_i} (q_{2i-7} - N_i) \times Q2_{i-7}(q_{2i-7}) \times d_i}{\lambda}$$ again for each patient category.

Also, note that, for this waiting time calculation, there is not any exchange of scheduled operations for patients from different patient categories. If there are less patient than the number of operations scheduled for that day for any patient category, then the number of operations occurred is equal to the number of patients, who are in the system before the planning time of that operation, for that patient category. For instance, if there are two operations for patient category c scheduled on day t, but there is only one patient one week before from that category c, then there will be only one operation done, and the remaining capacity for the other scheduled operation will remain idle.

After considering the effect of smooth allocation on patient satisfaction via waiting time calculations, its effect on resource efficiency will be illustrated in the next section by several calculations about the utilization levels of the resources.

2.6 DISTRIBUTION OF RESOURCE USAGE LEVELS

In the previous section, the steady state probabilities of number of patients for each patient category for each day are obtained. In addition to the average waiting time calculations, these steady state probabilities can also be used to determine the usage levels of the scarce resources like intensive care unit, nursing hours for intensive care unit and the medium care unit. In this section, the distribution for the usage levels of these resources will be obtained. First, the IC unit will be considered as it is the first place that patients utilize after the surgery. Next, depending on the results of the IC unit, the usage levels of NH and MC will be considered as well.

2.6.1 THE INTENSIVE CARE UNIT

In order to find the distribution of the intensive care unit usage, first the system for the IC unit should be explained in more detail. After the surgery, patients stay at the IC unit for several days depending on their patient category. For instance a patient from category c can stay at the IC unit at most t_1 days; however another patient from another category can stay at most t_2 days. Moreover, for each patient category, each day has a different probability that a patient will continue to stay at the IC unit or not. In other words, for a patient from category c, the probability that he or she stay at the IC unit on the day of operation is $p_{IC,c,0}$, but the probability that he or she will stay at the IC unit t days after the surgery is $p_{IC,c,t}$.

As mentioned before, it is assumed that there is no exchange of operations scheduled between patients from different patient categories. Thus, it is possible to find the IC unit usage of each patient category separately, independent of the others. Then, the general total usage level of IC unit can be calculated by combining the separate ones that obtained for each patient category.

To find the distribution of the IC unit usage for each patient category, the steady state probabilities of the number of patients for each day for that patient category is considered as calculated in the previous part. First, the distribution of the IC unit usage of each patient category is calculated separately to find the total usage of IC unit. As the patient categories are assumed to be independent from each other for the tactical planning, it again brings the ease of calculation of the separate IC usage levels.

For IC usage of each patient category:

Several steps are followed for the calculation of usage levels of IC unit, which are explained in detail below.

<u>Step 1.</u>

Let $sur_c(n,t)$ be the probability of n operations taking place on day t according to the number of patients arrived for each patient category c.

For $\forall$ n and $\forall$ t=1,2,..,T, If n < N_t ➔ $sur_c(n,t) = Q2_{t-7}(n)$

Else ➔ $sur_c(n,t) = 1 - \sum_{n=0}^{N_t - 1} Q2_{t-7}(n)$

where N_t is the number of operations scheduled at tactical level on day t for that patient category.

Step 2.

Let $P_c(n,t,j)$ show the probability that there are n patients staying at the IC after j days from their surgery, which took place on day t for the patient category c.

For ∀ n, ∀ t=1,2,..,T and ∀ j=0,1,2,.., $L_{IC,c}^{max}$

$$P_c(n,t,j) = sur_c(n,t) \times p_{IC,c,j}$$

where $p_{IC,c,j}$ is the IC stay probability j days after the operation and $L_{IC,c}^{max}$ is the maximum length of IC stay of patients from category c as mentioned before.

Step 3.

Since the number of operations on the previous days also has an effect on the IC usage of following days, a recursive calculation is needed to combine the usage of IC by patients who are operated on different days, but from the same patient category. Let $R_c(n,t)$ be the probability that there will be n patients staying at the IC on day t from patient category c, and $Tp_c(n,t,j)$ be a temporary variable which has. a similar meaning to the $P_c(n,t,j)$. However instead of indicating the single probabilities, $Tp_c(n,t,j)$ shows the cumulative probabilities for the number of patients in the IC unit.

For ∀ n and ∀ t=1,2,..,T

$$R_c(n,t) = Tp_c(n,t,0)$$

$$Tp_c(n,t,j) = \sum_{k=0}^{n} Tp_c(n-k, t-1, j+1) \times P_c(k,t,j)$$

For the starting point, let $Tp_c\left(n, t - L_{IC,c}^{max}, L_{IC,c}^{max}\right) = P_c\left(n, t - L_{IC,c}^{max}, L_{IC,c}^{max}\right)$ for all n values possible.

After obtaining the probabilities of IC usage levels for each patient category, in order to find the overall usage of IC unit, these probabilities may now be combined.

For overall IC usage of all patient categories:

The function to find the overall IC usage by the patients from all categories is similar to the one used per patient type. Since there are several patient categories, again a recursive function will be used to find the total IC utilizations.

Now, let R(n,t) the probability that there are a total of n patients at the IC unit at day t. Again, a temporary variable will be used for the recursive function which is Tr(n,t,c). Here, the c value refers to the category number and C is the total number of patient categories. For instance, if the c value is 2, then only the first two patient categories are considered until the calculation of the Tr probability. Again the recursive function to get the R(n,t) values is as follows:

For ∀ n and ∀ t=1,2,..,T

$$R(n,t) = Tr(n,t,C)$$

$$Tr(n,t,c) = \sum_{k=0}^{n} Tr(n-k,t,c-1) \times R_c(k,t)$$

For the starting point, let $Tr(n,t,1) = R_1(n,t)$ for all n values possible.

After calculating each value until the category C, then the overall IC levels are obtained given the probabilities that a patient will stay at the IC j days after the surgery for each patient category.

2.6.2 THE NURSING HOURS OF THE INTENSIVE CARE UNIT

Another important resource that is considered for the efficiency of the hospital is the nursing hours spent in the intensive care unit. Thus, it is also crucial to see the effect of smoother allocation on the utilization levels of the nurses. The usage of nursing hours is similar to the IC stays, since the nursing hours are required only if the patient stays at the IC. However, for each patient category, the number of nursing hours required is different. Moreover, within a patient category, the required nursing hours can also vary among the duration of their IC stay. For instance, for a patient from category c, the number of nursing hours required at the IC unit on the day of operation is $w_{c,0}$, but the necessary number of nursing hours at the IC unit t days after the surgery is $w_{c,t}$.

Again, as in the IC calculations, it is assumed that there is no exchange of operations scheduled between patients from different patient categories, which brings the ease of calculation since the patient categories can be considered separately again, and then combined to see the over all usage levels.

To find the distribution of the NH usage for each patient category, the steady state probabilities of the number of patients for each day for that patient category is considered as well.

For NH usage of each patient category:

Similar steps to the IC usage are followed for the calculation of the NH, thus only the differences will be mentioned for the NH. Since step 1 is exactly same with the one in IC usage, step 2 will be explained first.

<u>Step 1.</u>

Calculate $sur_c(n,t)$ ∀ n, ∀ t=1,2,..,T

Step 2.

Let $N_c(h,t,j)$ show the probability that there are h hours of nursing required for the patients staying at the IC after j days from their surgery, which took place on day t for the patient category c.

For $\forall$ n, $\forall$ t=1,2,..,T and $\forall$ j=0,1,2,.., $L_{IC,c}^{max}$

$$N_c(h,t,j) = N_c(n \times w_{c,j}, t, j) = sur_c(n,t) \times p_{IC,c,j}$$

where $w_{c,j}$ is the number of NH required j days after the surgery per patient from category c as mentioned before.

Step 3.

Step 3 is also same as the third step of IC usage except some differences in notation. Again, $R_c(h,t)$ is the probability that h hours of nursing will be required on day t and Tn_c is the temporary variable.

For $\forall$ h and $\forall$ t=1,2,..,T

$$R_c(h,t) = Tn_c(h,t,0)$$

$$Tn_c(h,t,j) = \sum_{k=0}^{h} Tn_c(h-k, t-1, j+1) \times N_c(k,t,j)$$

For the starting point, let $Tn_c\left(h, t-L_{IC,c}^{\max}, L_{IC,c}^{\max}\right) = N_c\left(h, t-L_{IC,c}^{\max}, L_{IC,c}^{\max}\right)$ for all h values possible.

For overall NH usage of all patient categories:

To combine the NH requirements of all patient categories, a similar recursive function will be used to the one used for IC usage.

For $\forall$ h and $\forall$ t=1,2,..,T

$$R(h,t) = Tr(h,t,C)$$

$$Tr(h,t,c) = \sum_{k=0}^{h} Tr(h-k, t, c-1) \times R_c(k,t)$$

For the starting point, let $Tr(h,t,1) = R_1(h,t)$ for all h values possible.

After calculating each value until the category C, then the overall NH levels are obtained given the probabilities that a patient will stay at the IC and the amount of nursing hours needed j days after the surgery for each patient category.

2.6.3 THE MEDIUM CARE UNIT

The usage of the medium care unit varies among the patient categories. To be able to find the usage level distribution of this unit, the possible usage ways should be understood. Some of the patient categories stay at the MC unit just after their operation, while some others visit MC unit after their stay at the IC unit. Moreover, some of the patient categories may stay at the MC unit just before their surgeries. Moreover, the maximum length of MC stays can differ among patient categories as it was for IC unit as well. Also, for MC unit, for each patient category, again each day may have a different probability of staying at the MC unit or not.

The approach to find the usage level distribution of MC unit is very similar to the approach used for IC unit, except that there are some pre-operation stays at the MC. However, to make it similar, this pre-operative stay can be taken as a post-operative stay with a j value of -1. Thus, for j=-1, it is meant that the MC stay is before the scheduled surgery.

Since, it is again assumed that there is no exchange of operations between different patient categories, it is possible to find the MC usage of each patient category separately and independent of the other patient categories' usage levels, which brings the ease of calculation. After obtaining these MC usage levels, then it is possible to combine the usage levels of each patient category in order to find the total usage distribution of MC unit.

To find the distribution of the MC unit usage for each patient category, the steady state probabilities of the number of patients for each day for that patient category is considered as calculated in the previous part.

For MC usage of each patient category:

Since the steps for the MC usage are very similar to the steps of IC and NH usage, only the differences will be explained in detail.

Step 1.

Calculate $sur_c(n,t)$ $\forall$ n, $\forall$ t=1,2,..,T

Step 2.

For $\forall$ n, $\forall$ t=1,2,..,T and $\forall$ j=-1,0,1,.., $L_{MC,c}^{max}$

$$P_c(n,t,j) = sur_c(n,t) \times p_{MC,c,j}$$

where $p_{MC,c,j}$ is the IC stay probability j days after the operation and $L_{MC,c}^{max}$ is the maximum length of IC stay of patients from category c as mentioned before. Note that, the minimum value of j is -1 because of the pre-operation stays at the MC.

Step 3.

For $\forall$ n and $\forall$ t=1,2,..,T

$$R_c(n,t) = Tp_c(n,t+1,-1)$$

$$Tp_c(n,t,j) = \sum_{k=0}^{n} Tp_c(n-k, t-1, j+1) \times P_c(k,t,j)$$

For the starting point, let $Tp_c\left(n, t - L_{MC,c}^{\max}, L_{MC,c}^{\max}\right) = P_c\left(n, t - L_{MC,c}^{\max}, L_{MC,c}^{\max}\right)$ for all n values possible.

For overall MC usage of all patient categories:

The function to find the overall MC usage by the patients from all categories is the same with the one used for IC. Since there are several patient categories, again a recursive function will be used to find the total MC utilizations.

For ∀ n and ∀ t=1,2,..,T

$$R(n,t) = Tr(n,t,C)$$

$$Tr(n,t,c) = \sum_{k=0}^{n} Tr(n-k, t, c-1) \times R_c(k,t)$$

For the starting point, let $Tr(n,t,1) = R_1(n,t)$ for all n values possible.

After calculating each value until the category C, then the overall MC levels are obtained given the probabilities that a patient will stay at MC after j days of its surgery, for each patient category.

PART III NUMERICAL RESULTS

3.1 INTRODUCTION

In this chapter, the issues discussed in the previous chapters will be illustrated by using sample data that is borrowed from the Thorax Center Rotterdam, also used in the study of Dellaert and Jeunet [8]. In the first part, the mathematical model developed by Dellaert and Jeunet will be solved with the given data, which can be found in Appendix I. Then, the proposed heuristics and additional constraints will be used and their performance will be tested with the waiting time calculations and resource usage level distribution calculations obtained in the previous chapter. After that, the emergency patients will be considered in order to see the overall performance of the system. Finally, the operational strategies will be considered for the given data.

3.2 TACTICAL PLAN OBTAINED WITH THE BASIC MATHEMATICAL MODEL

The mixed integer program developed by Dellaert and Jeunet [8], and explained in section 2.2.1 is solved with the data given in Appendix I using GAMS with a fixed computation of 1000 seconds.

For these sample data, the planning period for the tactical planning (T) is taken as 28 days, and again it is assumed that there should not be any operation scheduled on weekends. Moreover, the arrival of the patients were simulated as a Poisson process as mentioned before. Considering the other relevant data for the tactical planning, the following schedule, shown in Figure 6 is obtained for 8 patient categories given in the data with an optimality gap of 2.8%.

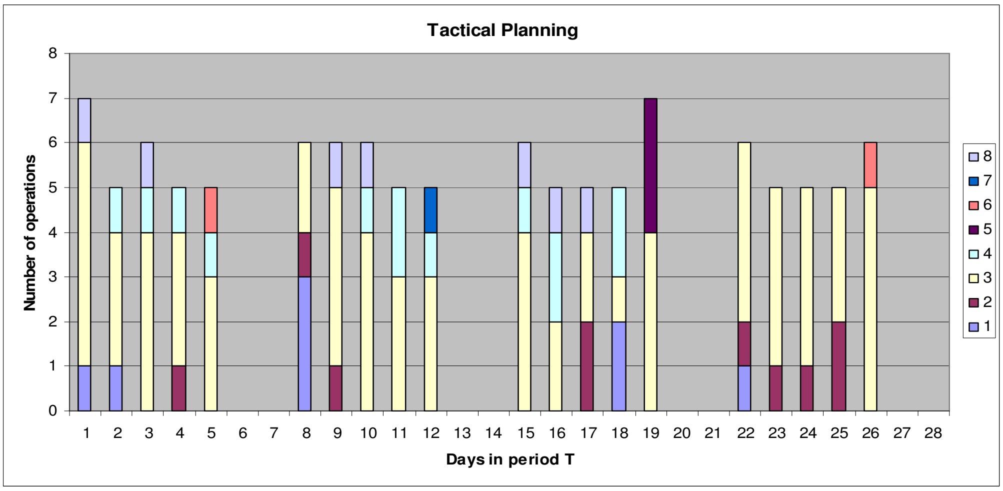


Figure 6: Tactical planning obtained with the basic mathematical model

3.3 THE EFFECT OF SMOOTH ALLOCATION

As mentioned in the previous chapter, to obtain a smooth allocation of the operations required, first small cycle lengths are defined according to total number of planned operations per patient category. Thus, for the given data, the small cycle lengths are defined as follows, given in Table 1:

Table 1: Small cycle lengths and average number of operations per small cycle per patient category

	Patient Group (c)	Operation duration (S_c)	Small cycle length (working days)	average # patients /small cycle
1	Child simple	4	5	2
2	Child complex	8	2	1
3	Adult, short OT, short I	4	20	67
4	Adult, long OT, short IC	8	5	3.25
5	Adult, short OT, middle IC	4	10	1.5
6	Adult, long OT, middle IC	8	10	1
7	Adult, long OT, long IC	8	20	1
8	Adult, very short OT, no IC	2	10	3.5

Note that, although the patient category 3 has 67 patients planned, its small cycle length is not different from the whole period length. The reason behind this is that, since it has a huge number of operations planned, using small cycles for that category would not make a significant difference for the whole planning. Because, in order to satisfy the total number of operations, the basic mathematical model itself assigns operations for that category almost everyday.

Now, by using these small cycles and the average number of patients to be scheduled in each cycle, the heuristic model is used both for ascending and descending order of patients, with the operating room capacity of 36 hours per day. The following schedules, given in Figure 7 and Figure 8, are obtained.

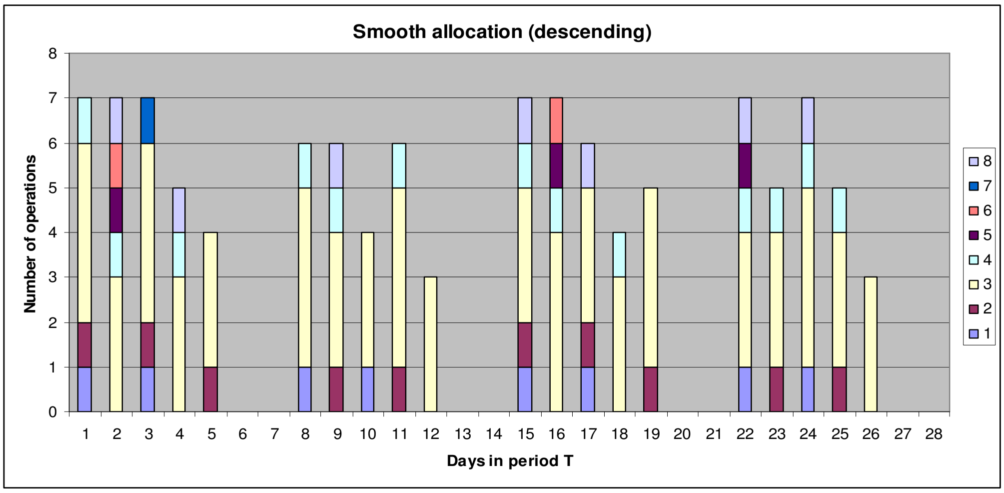


Figure 7: Tactical planning obtained with the heuristic for descending order (OT capacity=36hrs/day)

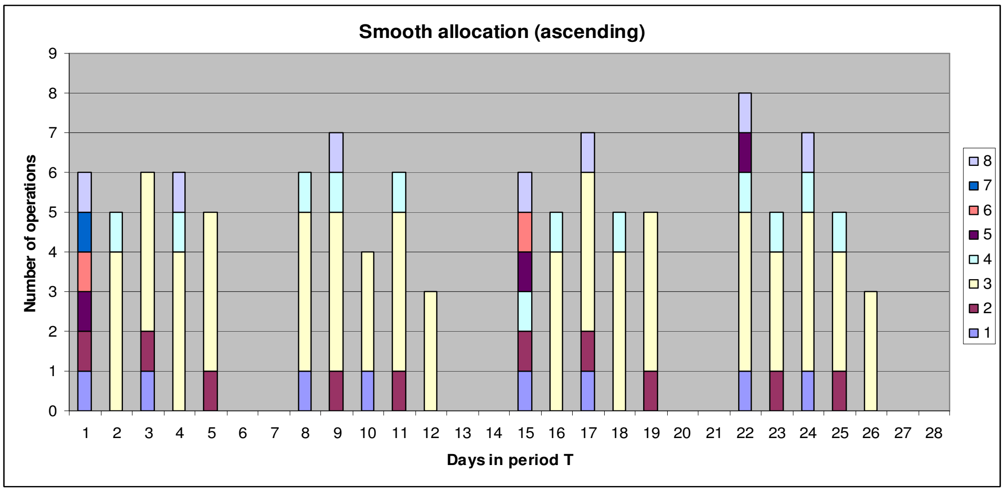


Figure 8: Tactical planning obtained with the heuristic for ascending order (OT capacity=36hrs/day)

As can be seen from these figures, the operations of each patient category are allocated more smoothly than in the schedules found by the basic mathematical model. However, this smoother allocation causes some problems for the objectives of the scheduling problem such as more deviations of utilization levels or lack of meeting the demand. Moreover, note that, because of the lack of available capacity, several operations of some patients' categories could not be scheduled since the scheduling is done according to a fixed order of patient categories. Again, note that this scheduling takes the OT capacity of 36 hours per day, which is higher than the targeted capacity level of the OT. Hence, to see the effect of this scheduling on the utilization levels, the daily utilization of each resource is found and the deviations, as well as the overuse of them are calculated, which are given below in the Table 2. Note that, for the weighted sum calculation, the penalty value for the overuse of the resources, b, is taken as 1.

Table 2: Deviations from the targeted utilization levels and the excess capacity

		Basic Mathematical Model	Smooth al. (desc., cap=36)	Smooth al. (asc., cap=36)
OT	**Overuse**	0	87.65	6.74
	Overutilization	8.86	134.66	47.13
	Underutilization	8.98	170.79	55.25
IC	**Overuse**	0	8.46	0.01
	Overutilization	7.56	24.68	16.41
	Underutilization	7.68	33.43	17.98
NH	**Overuse**	0	80.66	11.02
	Overutilization	51.31	293.92	205.26
	Underutilization	60.25	406.19	231.37
MC	**Overuse**	0.35	0	0
	Overutilization	40.20	24.89	40.06
	Underutilization	40.49	64.29	48.75
Total (weighted)		**22.65**	**164.16**	**71.35**

In the schedules obtained by the heuristic algorithm, it is seen that the maximum utilization levels of the resources are very high compared to the solution of the basic mathematical model developed for the tactical planning. One of the main reasons behind this difference is that in the heuristic approach, the capacity of OT is taken as 36 hours per day, while the target level for OT is taken as 30.19 hours for the mathematical model and for the calculations. Also note that, the values obtained by the ascending order are less than the values obtained by the descending order. Although, there is one operation that was not scheduled for the patient category 4, still the difference can be assumed to be bigger than the effect of that single unscheduled operation.

Furthermore, this heuristic approach is again used by considering the targeted utilization of the OT. Thus, this time, the capacity of OT is taken as 30 hours per day in order to minimize the OT utilization deviations from the targeted level. The schedules obtained are shown in Figure 9 and Figure 10.

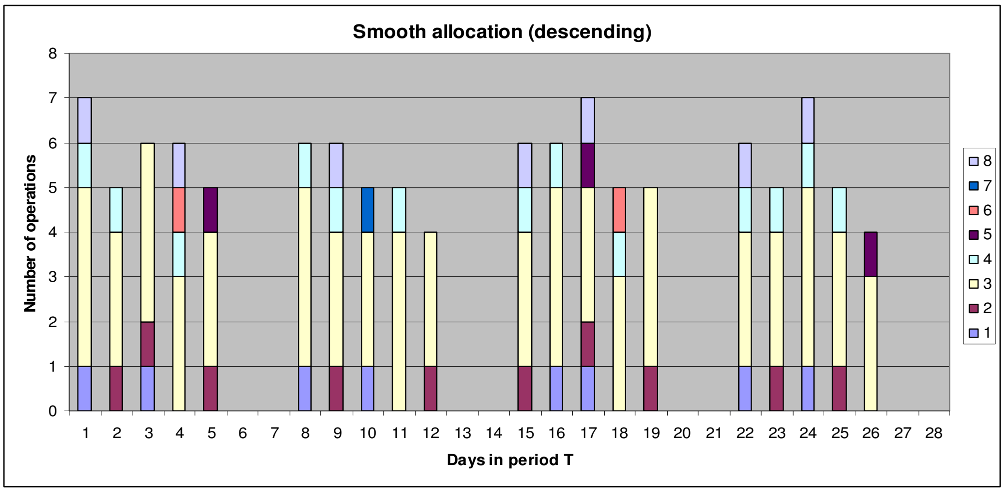


Figure 9: Tactical planning obtained with the heuristic for descending order (OT capacity=30hrs/day)

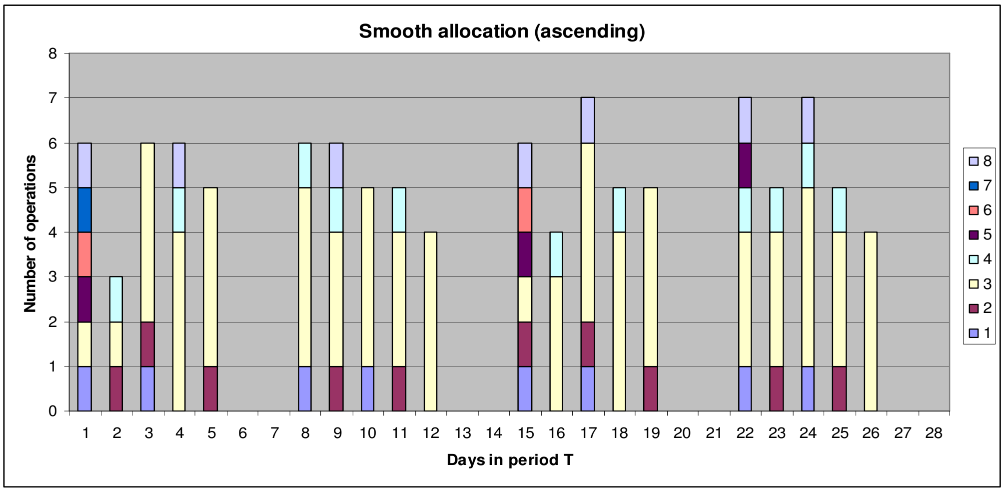


Figure 10: Tactical planning obtained with the heuristic for ascending order (OT capacity=30hrs/day)

Note that, when the heuristic algorithm is used for the ascending order of the patients, there occur some inefficient usages of OT resulting in fewer operations scheduled for higher volume patient categories, since some surgeries of some patient categories may require more hours than others. Again, to see the effect of this allocation, the same calculations are done with the penalty value equal to 1, and the results, given in the Table 3, are obtained.

Table 3: Deviations from the targeted utilization levels and the excess capacity

		Basic Mathematical Model	Smooth al. (desc., cap=30)	Smooth al. (asc., cap=30)
OT	**Overuse**	0	0	0
	Overutilization	8.86	30.76	27.13
	Underutilization	8.98	30.89	51.25
IC	**Overuse**	0	0	0
	Overutilization	7.56	10.88	10.21
	Underutilization	7.68	11.02	15.71
NH	**Overuse**	0	0	6.82
	Overutilization	51.31	110.50	138.47
	Underutilization	60.25	119.45	211.73
MC	**Overuse**	0.35	0	0
	Overutilization	40.20	38.02	26.36
	Underutilization	40.49	38.32	57.22
Total (weighted)		**22.65**	**41.64**	**54.58**

Since the capacity of the OT used in the heuristics is close to the target level of the OT, the utilization and overuse levels are found to be smaller. The weighted sum of the heuristics, with the ascending order, is greater than the one with descending order although it has several unscheduled operations, 2 for patient category 3 and 2 for patient category 4.

However, it can still be concluded that there is a difference for the utilization and overuse levels of the resources when the allocation of the operations for different patient categories become smoother.

3.4 TACTICAL PLAN OBTAINED WITH THE ADDITIONAL CONSTRAINTS

The additional constraints explained in the section 2.4 are used in order to get a smoother tactical planning of the operations for different types of patients, while taking the targeted utilization and capacity levels into account. To use these additional constraints, first the small cycles are defined based on logic similar to the one in the previous section. However, this time, instead of using small cycles in terms of days, the small cycles are selected in terms of weeks because of the ease of planning. Thus, the small cycle lengths, given in the Table 4 will be used for these mathematical models. For the patient category 3, the two options will be considered to see the effect of small cycles even if there is more than one operation per day on the average.

Table 4: Small cycle lengths and average number of operations per small cycle per patient category

	Patient Group (c)	Operation duration (S_c)	Small cycle length (weeks)	average # patients /small cycle
1	Child simple	4	1	2
2	Child complex	8	1	2.5
3	Adult, short OT, short I	4	4 (2)	67 (33.5)
4	Adult, long OT, short IC	8	2	6.5
5	Adult, short OT, middle IC	4	2	1.5
6	Adult, long OT, middle IC	8	2	1
7	Adult, long OT, long IC	8	4	1
8	Adult, very short OT, no IC	2	2	3.5

Based on these numbers, the first constraint for the fixed small cycles, introduced in section 24.1, is added to the basic mathematical model to obtain a new tactical planning of the operations. Then, the other constraints for moving small cycles, explained in section 2.4.2, are added to the basic mathematical model. The resulting schedules are shown in Figure 11 and Figure 12, and the utilization levels found are given in Table 5. Note that, the overuse penalty value (b) is taken as 1 once more.

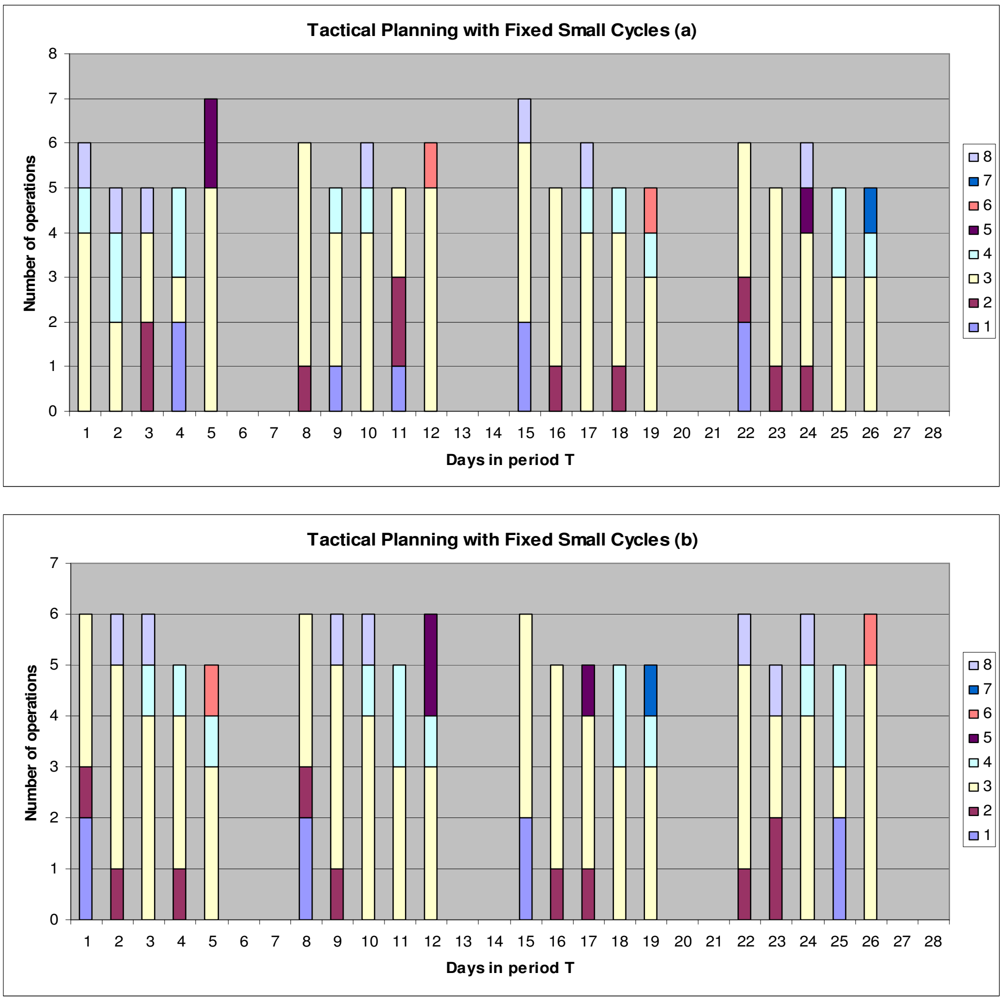
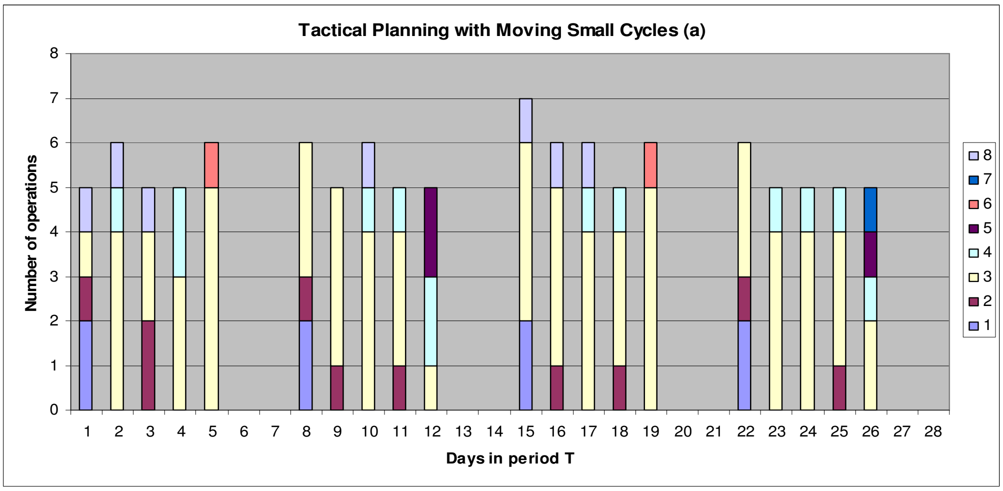


Figure 11: Tactical planning obtained with the fixed small cycles (small cycle length of 3rd category is (a) 4 weeks, (b) 2 weeks)



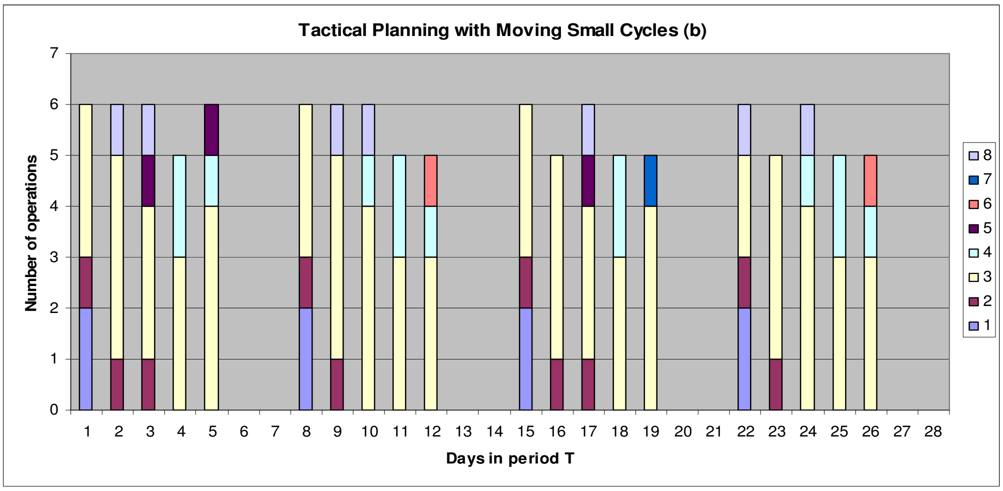


Figure 12: Tactical planning obtained with the moving small cycles (small cycle length of 3rd category is (a) 4 weeks, (b) 2 weeks)

Table 5: Deviations from the targeted utilization levels and the excess capacity

		Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
OT	**Overuse**	0	0	0	0	0
	Overutilization	8.86	8.68	9.03	8.86	9.18
	Underutilization	8.98	8.81	9.16	12.98	9.30
IC	**Overuse**	0	0	0	0	0
	Overutilization	7.55	7.54	7.55	7.22	7.75
	Underutilization	7.69	7.68	7.69	8.61	7.89
NH	**Overuse**	0	0	0	0	0
	Overutilization	51.31	53.94	54.60	40.67	61.67
	Underutilization	60.25	62.88	63.54	64.61	70.62
MC	**Overuse**	0.34	0.51	1.05	0.36	1.08
	Overutilization	40.20	42.33	41.57	41.51	45.12
	Underutilization	40.49	42.62	41.86	48.68	45.41
Total (weighted)		**22.65**	**22.65**	**23.16**	**23.75**	**24.46**

As can be seen from the figures, the tactical plan with the moving cycles constraint has a smoother allocation of the operations compared to the others. However, since there is a negative relation between this allocation and the utilization levels, the weighted sum of deviations from target utilization levels and the overuse of resources is higher than the others for this tactical plan.

Furthermore, same analyses are done for the two overplanning options, which are based on the study of Dellaert and Jeunet [8], to see the effect of smooth allocation for these strategies as well. The schedules and the results of the utilization levels can be found in Appendix A.2.

To see the effect of these allocations on the performance measures numerically, the waiting times of the patients and the usage levels of the resources will be calculated to compare the performance of the tactical plans obtained by these three models.

3.5 WAITING TIMES OF PATIENTS

In the previous chapter, it was mentioned that the main objective of smooth allocation is to increase patient satisfaction by reducing the average waiting time of the patients. To obtain a tactical planning with a smoother allocation of the operations, some additional constraints are used in the previous section 3.4. By using these schedules, and the average waiting time calculation in terms of days, which was explained in section 2.5.2, the effect of small cycles on the performance of patient satisfaction will be illustrated in this section.

Note that, 5 alternative scheduling methods explained before, are used for 3 planning options which are normal planning, intermediate overplanning and large overplanning.

Using the average waiting time calculations mentioned before, the following results are obtained for each patient category for all 15 schedule alternatives.

Table 6: Average waiting time of each patient category for normal planning

Patient Category	Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
1	21.88	21.48	21.58	21.25	21.25
2	21.58	20.30	20.40	20.11	20.18
3	10.84	10.73	10.60	10.80	10.64
4	29.35	28.33	27.55	27.55	27.71
5	41.18	38.12	38.33	37.15	36.34
6	31.81	31.81	31.81	30.65	30.66
7	21.88	21.88	21.88	21.88	21.88
8	43.65	42.83	43.14	43.40	42.45
Average	17.96	17.50	17.36	17.41	17.26

Table 7: Average waiting time of each patient category for intermediate overplanning

Patient Category	Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
1	11.69	10.26	9.93	9.39	9.68
2	9.76	9.69	9.15	9.89	9.69
3	7.39	7.68	7.52	7.48	7.22
4	12.16	12.56	11.96	12.03	12.03
5	12.62	11.77	11.16	10.34	10.29
6	10.16	10.16	10.16	10.16	10.16
7	21.88	21.88	21.88	21.88	21.88
8	17.13	15.01	14.41	13.89	13.41
Average	9.31	9.27	8.98	8.93	8.75

Table 8: Average waiting time of each patient category for large overplanning

Patient Category	Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
1	11.32	9.93	9.93	9.92	9.92
2	10.26	10.12	10.05	9.45	9.56
3	4.52	4.64	4.51	4.40	4.41
4	8.07	7.51	7.60	7.52	7.29
5	18.08	12.29	12.29	10.49	10.74
6	13.51	13.51	13.51	11.81	11.81
7	10.05	10.05	10.05	8.54	8.54
8	9.62	9.67	9.32	8.40	9.94
Average	6.73	6.49	6.39	6.13	6.22

As can be seen from these results, the average waiting time of the schedules obtained by moving small cycles is lower than the schedules obtained by the basic mathematical model and fixed small cycles. However, in the Figure 13 below, the average waiting time of the patients found are compared with the result of the objective function, the deviation of the average utilization from targeted levels plus the excess use of resources. As seen in that figure, and also as mentioned in the previous section, this deviation gets higher when the small cycle constraints are added. Also note that, the main difference for both the average waiting time and the utilization deviation occurs when different planning options are considered.

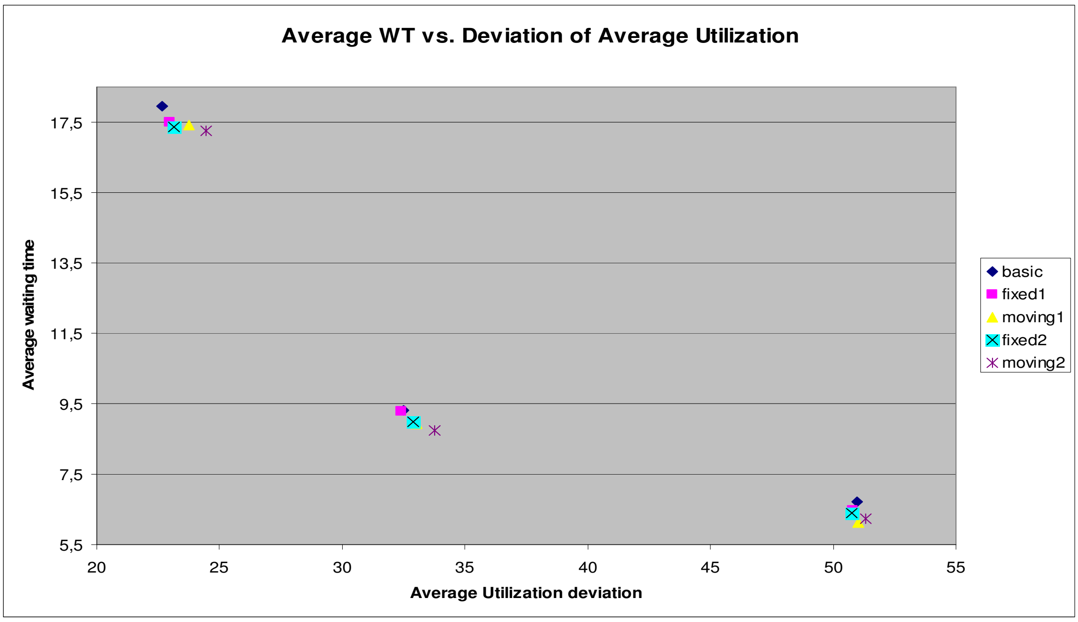


Figure 13: The trade-off between the average waiting time and the deviation of average utilization levels from the targeted level plus the overuse of resources

3.6 USAGE LEVELS OF RESOURCES

In the previous sections, to see the performance of the schedules obtained, from the efficiency point of view, the average utilization levels of the resources were used. However, to see the effect better, instead of the average values, the distribution of the usage levels of the resources are obtained. Thus, the variation of the resource use is also taken into account. Moreover, in the previous one, the average utilization was calculated based on the assumption that all of the surgeries scheduled take place, thus the number of patients operated is known. However, as mentioned before, it is possible that there are fewer patients than the number of scheduled operations for that patient category.

Thus, to see the effect of alternative scheduling methods and planning options on the resource efficiency better, the approaches described in section 2.6 is considered. As a result of these, the following values are obtained for the resources under different schedules. However, for these calculations, only the elective patients are considered. Note that, for the weighted sum value, the weights of the overutilization, underutilization and overuse are chosen as 1, 0 and 5, since it is believed that the excess capacity is the most important criteria and the underutilization is not so important as the overutilization of the resources.

Table 9: Expected values of overutilization, underutilization and overuse of IC unit

		Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
Normal Planning	Over utilization	9.00	8.71	8.61	8.54	8.15
	Under utilization	48.52	48.71	47.99	49.39	48.32
	Overuse	1.24	1.19	1.12	1.19	0.94
	Weighted Sum	15.19	14.48	14.22	14.48	12.86
Intermediate Over Planning	Over utilization	9.53	10.04	9.32	9.95	9.63
	Under utilization	51.28	50.44	50.91	50.22	49.06
	Overuse	2.04	2.23	1.94	2.32	2.05
	Weighted Sum	19.70	21.20	19.02	21.53	19.86
Large Over Planning	Over utilization	11.28	11.04	10.72	10.02	9.72
	Under utilization	52.71	51.90	51.69	54.93	53.37
	Overuse	2.38	2.29	2.06	2.09	1.76
	Weighted Sum	23.16	22.51	21.02	20.45	18.50

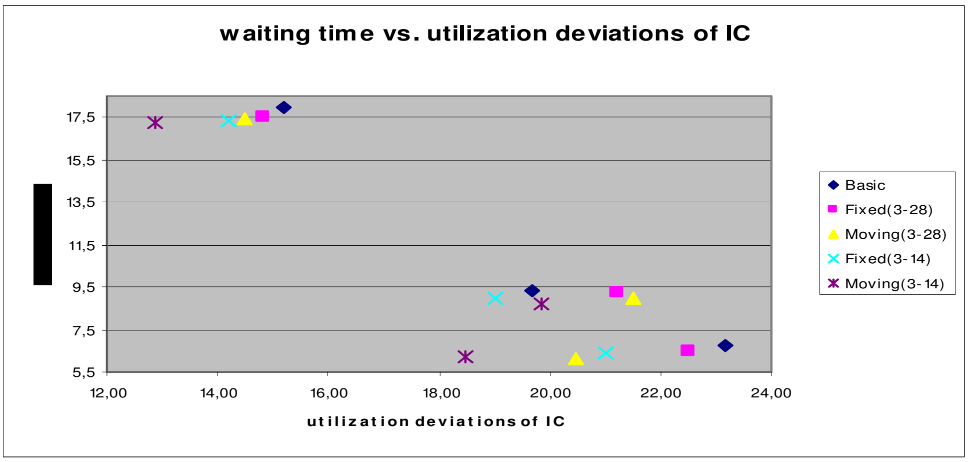


Figure 14: The trade-off between the average waiting time and the weighted sum of average deviation of utilization levels from the targeted level and the overuse of IC

As can be seen from the Table 9 and Figure 14, as the amount of overplanning increases, the weighted sum of overutilization and overuse gets higher while the average waiting time of patients decreases. For the normal planning and large overplanning options, the schedules obtained with the moving small cycles (b) gives the lowest value; while for the intermediate overplanning option the fixed small cycles (b) gives the lowest value. However, note that these results are based on the weights given before. Also when combined with the least average waiting time objective, the schedule obtained with the moving small cycles (b) has the lowest value as well for the normal planning option. For the intermediate overplanning option, again the moving small cycles (b) has the lowest average waiting time value, while the moving small cycles (a) is the best option in terms of average waiting time for the large overplanning option. Separate figures for average waiting time vs. overutilization, underutilization and overuse of IC can be found in Appendix 3.1.

Similar results are obtained for the NH and MC unit as well. The results of the MC unit are given below in Table 10 and Figure 15. Again separate figures for overutilization, underutilization and overuse of NH and MC vs. average waiting time can be found in Appendix 3.2 and 3.3.

Table 10: Expected values of overutilization, underutilization and overuse of MC unit

		Basic Mathematical Model	**Fixed Small Cycles (a)**	**Fixed Small Cycles (b)**	**Moving Small Cycles (a)**	**Moving Small Cycles (b)**
Normal Planning	**Over utilization**	8.84	8.73	8.32	7.46	6.86
	Under utilization	158.76	160.90	158.64	164.98	161.26
	Overuse	0.27	0.27	0.23	0.20	0.16
	Weighted Sum	10.21	10.07	9.45	8.47	7.64
Intermediate Over Planning	**Over utilization**	10.43	10.66	8.60	10.72	11.26
	Under utilization	168.06	164.98	171.39	167.68	163.47
	Overuse	0.49	0.50	0.32	0.51	0.53
	Weighted Sum	12.87	13.15	10.18	13.27	13.89
Large Over Planning	**Over utilization**	11.82	11.39	9.98	9.54	8.14
	Under utilization	171.99	172.17	173.03	186.68	177.93
	Overuse	0.69	0.61	0.46	0.49	0.30
	Weighted Sum	15.28	14.46	12.25	11.99	9.66

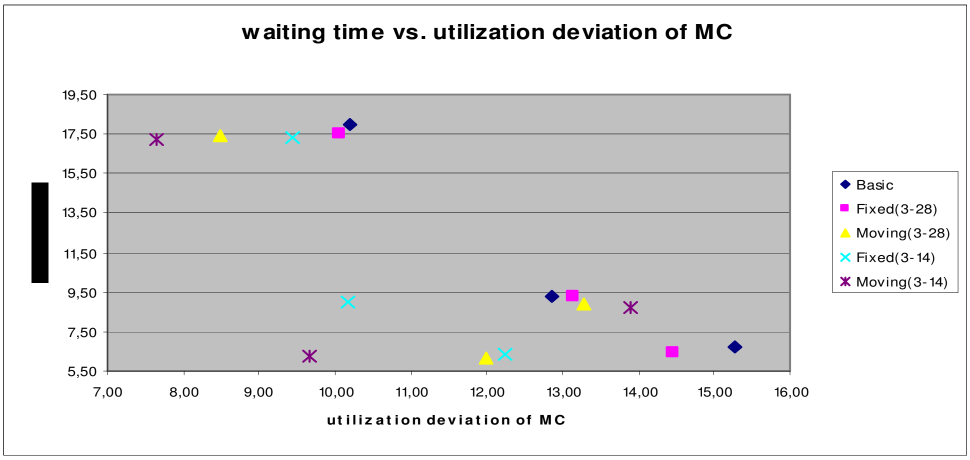


Figure 15: The trade-off between the average waiting time and the weighted sum of average deviation of utilization levels from the targeted level and the overuse of MC

The decision of the best option in terms of both the average waiting time and the utilization levels depends on the trade-off between them and how the stakeholders weight these two objectives.

Again note that, these values are obtained without taking the emergency patients into consideration. Thus, it is expected that the overuse and overutilization levels would be higher while the underutilization values would be lower when the emergency patients are considered. However, since it will make the same effect on all alternatives, only a shift in all values will occur and the relative values will not be affected from the existence of the emergency patients.

3.7 CONCLUSION AND RECOMMENDATIONS

In this study, the tactical planning of elective patients was considered. It was observed that, there are two main concerns about the scheduling of operations, which are the patient satisfaction and the hospital efficiency. First, for the hospital efficiency, a mixed integer program, with the aim of minimizing the deviations of average utilization levels from targeted levels, was used. Then in order to consider the patient satisfaction, a heuristic model was used to get lower average waiting time of patients via smooth allocation of operations. Finally, some additional constraints, which are moving and fixed small cycles, are added to the initial mathematical model to combine these to objectives by obtaining relatively smoother allocation to decrease average waiting times of the patients while minimizing the deviations of average utilization levels from targeted levels.

To see the effect of different scheduling models on the hospital efficiency and patient satisfaction, several alternatives are combined with three planning options, normal planning, intermediate overplanning and large overplanning.

The numerical results obtained show a trade-off between hospital efficiency and patient satisfaction. However, when the weighted sum of average deviation of resource utilizations from targeted levels are considered, it can be concluded that the tactical plans obtained with the additional constraints perform better than the initial mixed integer program in terms of both average waiting time of patients and the hospital efficiency.

In this study, the tactical planning was considered only with an operational strategy with no flexibility. Thus, for further studies, the result combined with more operational strategies may be taken into account to compare different tactical planning alternatives and more improvements may be done for the operational planning strategies by considering the trade-off between patient satisfaction and hospital efficiency. Moreover, for the operational level, it was assumed that there is no exchange between the operation capacities of different patient categories. In other words, although the patient from a category did not show up, the resources allocated for that operation cannot be used for an extra operation for a patient from a different category. Thus, for further studies, this option can also be considered in order to get a higher patient satisfaction and hospital efficiency.

APPENDICES

A.1 SAMPLE DATA

Table A.1: Patient groups, use of OT, # of pre-op days and 4-week volumes

	Patient Group (c)	Operation duration (S_c)	Pre-op days (l_c)	# of planned operations	average # of patients
1	Child simple	4	0	8	7.36
2	Child complex	8	0	10	9.36
3	Adult, short OT, short I	4	1	67	66.00
4	Adult, long OT, short IC	8	1	14	12.73
5	Adult, short OT, middle IC	4	1	3	2.64
6	Adult, long OT, middle IC	8	1	2	1.55
7	Adult, long OT, long IC	8	1	1	0.36
8	Adult, very short OT, no IC	2	1	8	6.91

Table A.2: Resource capacities and target levels

	OT hours		IC beds		MC beds		IC nursing hours	
Day	Capacity	Target	Capacity	Target	Capacity	Target	Capacity	Target
Monday	36	30.19	10	7.22	36	29.13	133	88.92
Tuesday	36	30.19	10	7.22	36	29.13	133	88.92
Wednesday	36	30.19	10	7.22	36	29.13	133	88.92
Thursday	36	30.19	10	7.22	36	29.13	133	88.92
Friday	36	30.19	10	7.22	36	29.13	133	88.92
Saturday	0	3.01	4	3.61	36	29.13	52	43.46
Sunday	0	3.46	4	3.61	36	29.13	52	45.46

Table A.3: Length of stay distribution at IC per patient group

Patient group	Probability of length of stay IC (days)									
	0	1	2	3	4	5	6	7	8	9
1	0.93	0.07	0.05	0.02	0	0	0	0	0	0
2	1	0.09	0.02	0	0	0	0	0	0	0
3	0.99	0.16	0.05	0.02	0.01	0.01	0.01	0	0	0
4	1	0.19	0.09	0.04	0.04	0.03	0.01	0.01	0.01	0.01
5	1	0.2	0.13	0.07	0.07	0.07	0.07	0	0	0
6	1	1	0.86	0.43	0.29	0.14	0.14	0.14	0	0
7	1	1	1	1	1	1	1	0	0	0
8	0.21	0	0	0	0	0	0	0	0	0

Table A.4: IC nursing workload required for a patient of category c, t days after the operation

Patient group	**IC nursing workload required (hours)**									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	12	12	12	12	12	12	12	12	12	12
2	12	12	12	12	12	12	12	12	12	12
3	12	12	12	12	12	12	12	12	12	12
4	12	12	12	12	12	12	12	12	12	12
5	12	24	12	12	12	12	12	12	12	12
6	12	24	12	12	12	12	12	12	12	12
7	12	24	24	12	12	12	12	12	12	12
8	3	3	3	3	3	3	3	3	3	3

Table A.5: Length of stay distribution at MC after the operation per patient group

	Probability of length of post-op stay MC (days)													
Patient group	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	0.05	0.26	0.26	0.26	0.26	0.21	0.14	0.07	0	0	0	0	0	0
2	0	0.13	0.17	0.17	0.17	0.17	0.17	0.13	0.09	0.08	0.06	0.06	0.06	0.06
3	0.01	0.84	0.94	0.97	0.95	0.66	0.42	0.29	0.21	0.15	0.11	0.09	0.07	0.05
4	0	0.78	0.88	0.93	0.93	0.84	0.68	0.53	0.35	0.25	0.22	0.19	0.18	0.13
5	0	0.8	0.87	0.93	0.93	0.87	0.8	0.6	0.6	0.4	0.33	0.33	0.13	0.07
6	0	0	0.14	0.57	0.71	0.86	0.86	0.86	1	1	0.86	0.86	0.86	0.86
7	0	0	0	0	0	0	0	1	1	1	1	1	1	1
8	0.64	0.54	0.41	0.26	0.13	0.1	0.08	0.08	0.03	0.03	0	0	0	0
	Probability of length of post-op stay MC (days)													
Patient group	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.06	0.04	0.02	0.02	0.02	0	0	0	0	0	0	0	0	0
3	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0	0	0	0	0	0	0
4	0.1	0.06	0.06	0.06	0.04	0.04	0.04	0.03	0.03	0.01	0.01	0.01	0.01	0.01
5	0.07	0.07	0	0	0	0	0	0	0	0	0	0	0	0
6	0.71	0.71	0.71	0.71	0.57	0.57	0.57	0.43	0.43	0.29	0.14	0	0	0
7	1	1	1	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.6: Arrival rate of emergency patients of category c on day t

Patient group	**Probability emergency arrivals**						
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
1	0.1	0.1	0.05	0.05	0.08	0.06	0.12
2	0.1	0.12	0.15	0.05	0.08	0.16	0.12
3	0.5	0.7	0.45	0.44	0.5	0.3	0.4
4	0.1	0.12	0.11	0.09	0.08	0.1	0.12
5	0.01	0.02	0.04	0.02	0.02	0.01	0.01
6	0.01	0.02	0.03	0.02	0.02	0.01	0.01
7	0	0	0.01	0	0	0	0
8	0.01	0.05	0.05	0.05	0.04	0.06	0.1

Moreover, the probability qc,t, that an emergency patient of category c arrives during the day shift t is equal to 0.8 for all categories and all days.

The α_r values, which indicate the relative weight of each resource is defined considering the capacity of the resources and the absolute weight of resources, g_r, assigned by the stakeholders in the hospital. The g_r values are 8, 10, 3 and 5 for the resources OT, IC, MC and NH respectively. Hence, the α_r values can be found as

$$\alpha_r = \frac{\dfrac{g_r}{\sum_{j=1}^{T} C_{r,j}}}{\sum_r \dfrac{g_r}{\sum_{j=1}^{T} C_{r,j}}}$$ where $C_{r,j}$ values stand for the maximum capacity of the resources.

A.2 OVERPLANNING OPTIONS

Table A.7: Number of operations to be scheduled in two overplanning options

	Patient Group (c)	# of planned operations Intermediate Overplanning	Large Overplanning
1	Child simple	9	9
2	Child complex	11	11
3	Adult, short OT, short I	68	70
4	Adult, long OT, short IC	14	15
5	Adult, short OT, middle IC	4	4
6	Adult, long OT, middle IC	3	3
7	Adult, long OT, long IC	1	2
8	Adult, very short OT, no IC	8	9

A.2.1 INTERMEDIATE OVERPLANNING

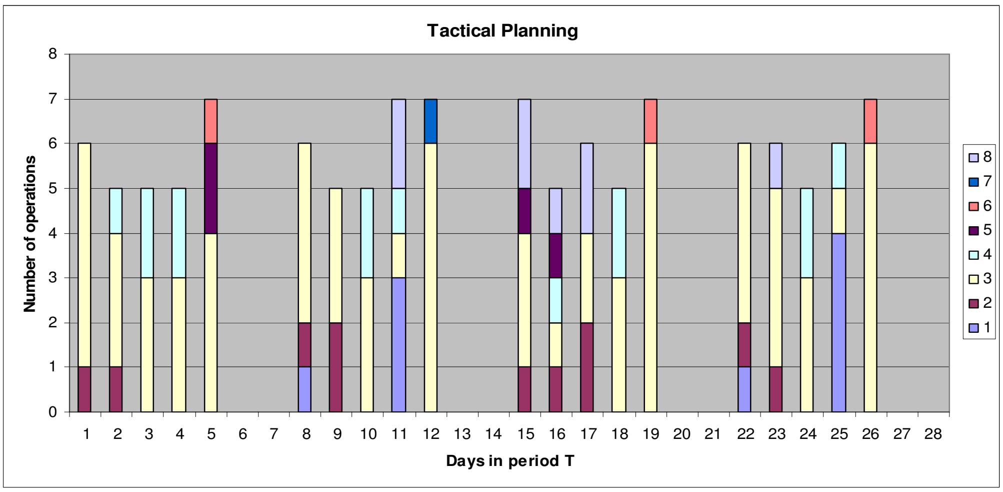
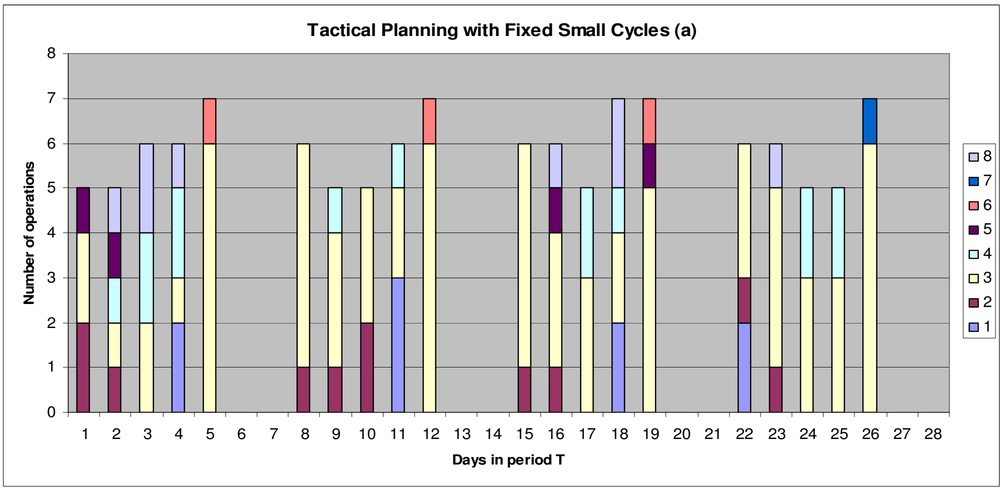


Figure A.1: Tactical planning obtained with the basic mathematical model



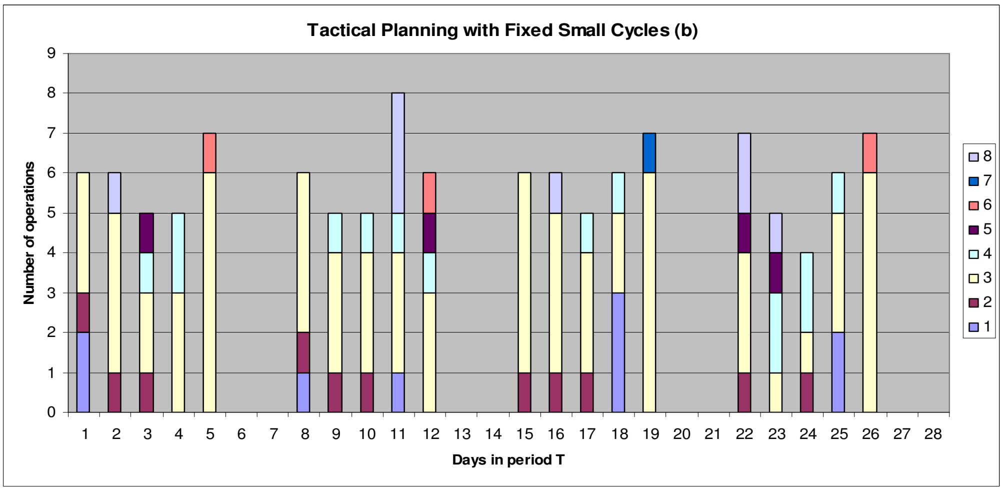
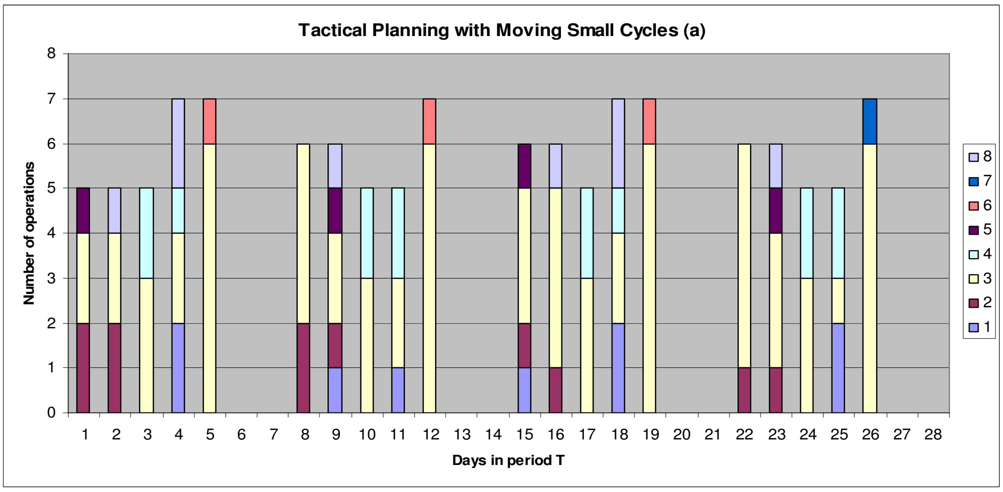


Figure A.2: Tactical planning obtained with the fixed small cycles (small cycle length of 3rd category is (a) 4 weeks, (b) 2 weeks)



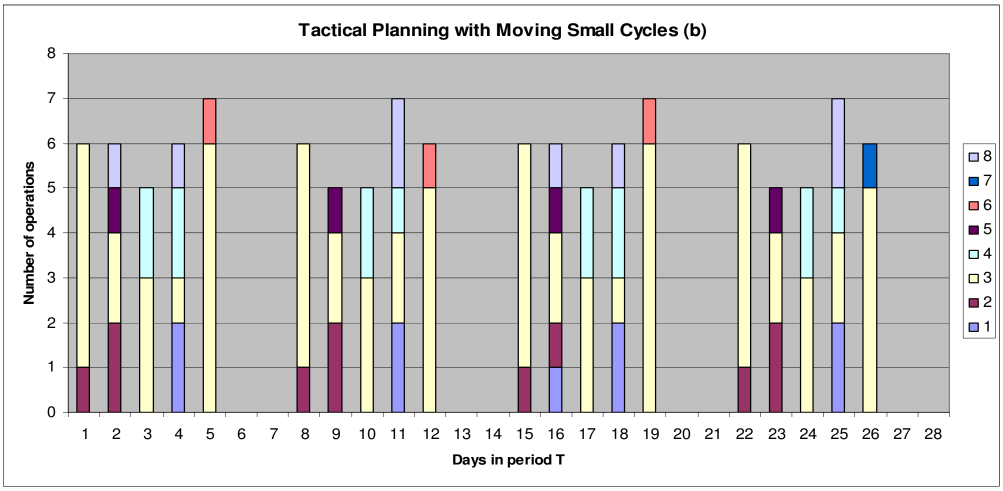


Figure A.3: Tactical planning obtained with the moving small cycles (small cycle length of 3rd category is (a) 4 weeks, (b) 2 weeks)

Table A.8: Deviations from the targeted utilization levels and the excess capacity

		Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
OT	**Overuse**	0	0	0	0	0
	Overutilization	37.90	37.90	37.90	37.90	37.90
	Underutilization	0.02	0.02	0.02	0.02	0.02
IC	**Overuse**	0	0	0	0	0
	Overutilization	15.16	15.16	15.33	15.18	15.54
	Underutilization	4.62	4.62	4.79	4.64	5.00
NH	**Overuse**	0	0	0	0	0
	Overutilization	144.40	143.09	145.90	147.31	150.01
	Underutilization	15.19	13.88	16.70	18.10	20.80
MC	**Overuse**	7.15	7.62	6.36	7.64	4.91
	Overutilization	66.17	66.70	66.05	68.61	68.94
	Underutilization	19.62	20.15	19.50	22.05	22.38
Total (weighted)		**32.52**	**32.42**	**32.90**	**33.00**	**33.76**

A.2.2 LARGE OVERPLANNING

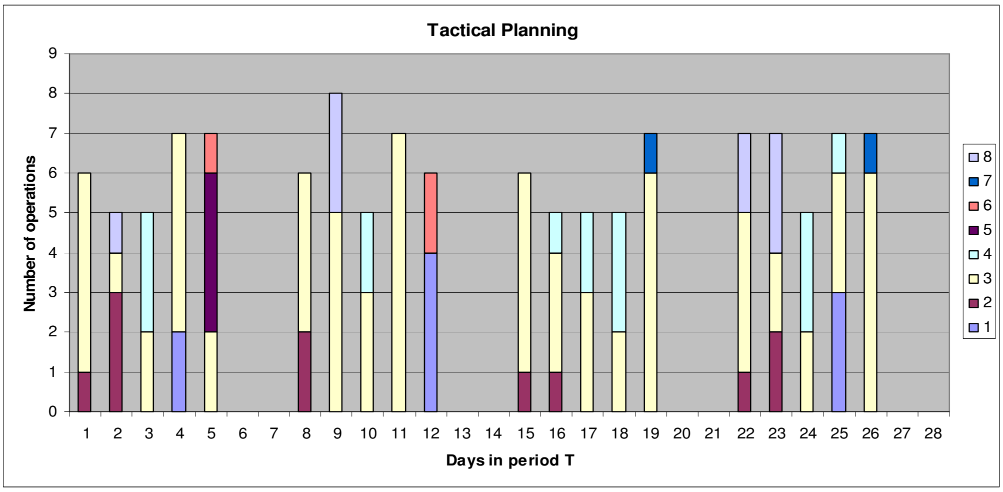
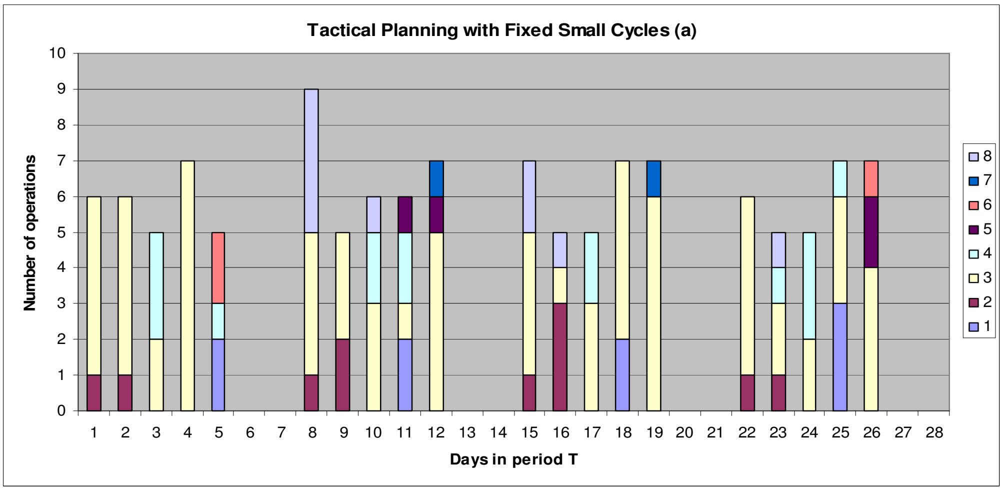


Figure A.4: Tactical planning obtained with the basic mathematical model



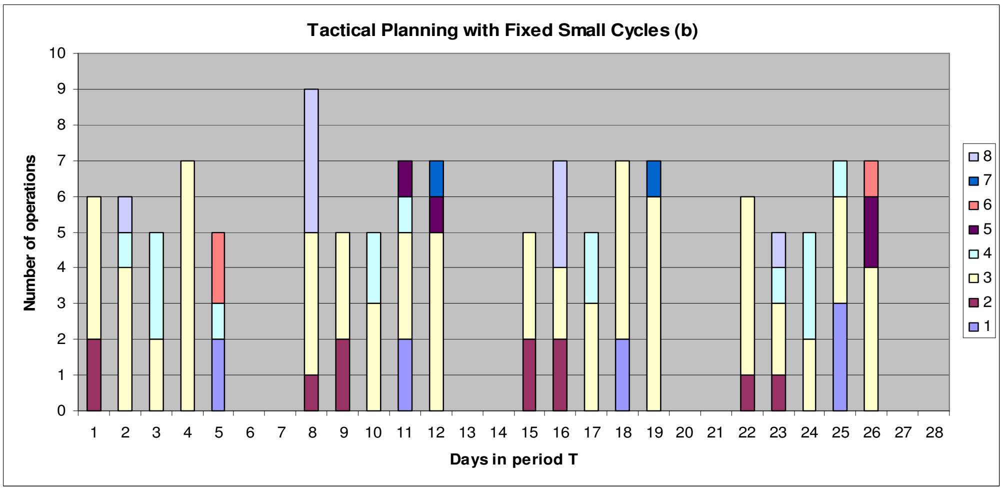
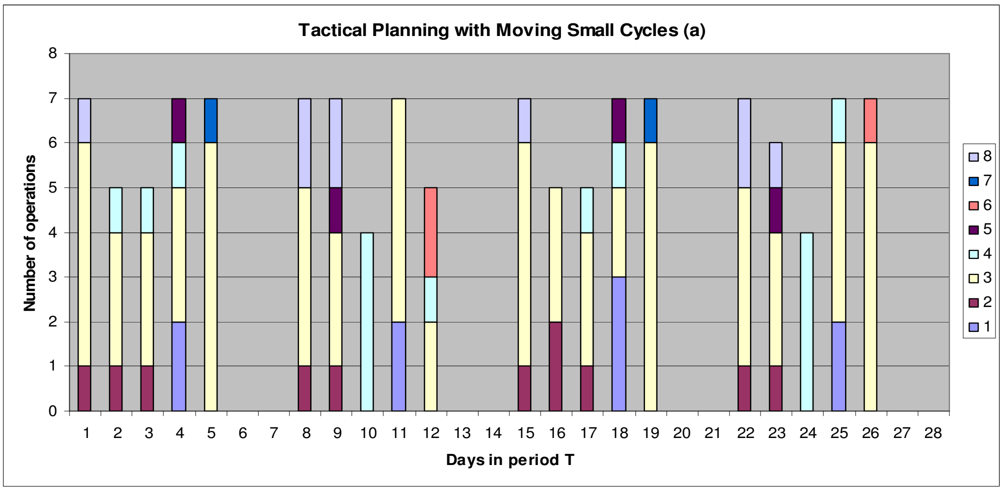


Figure A.5: Tactical planning obtained with the fixed small cycles (small cycle length of 3rd category is (a) 4 weeks, (b) 2 weeks)



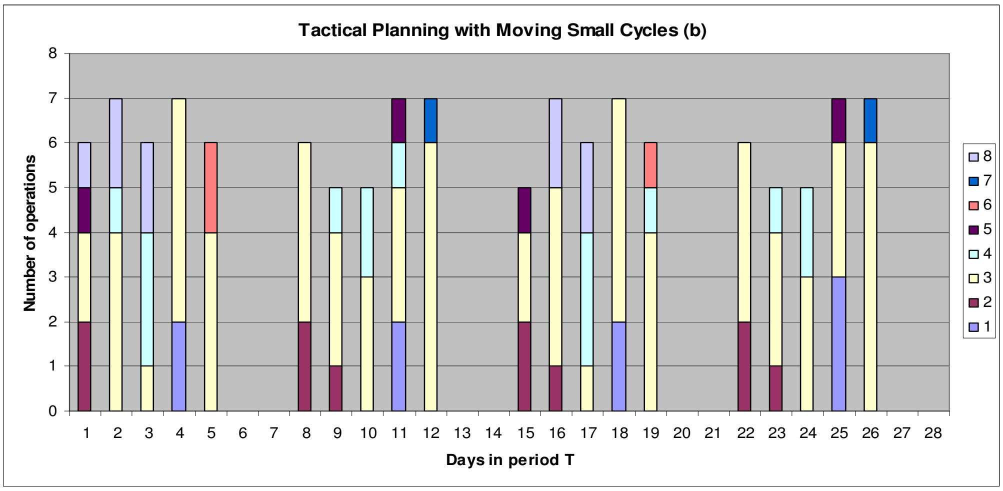


Figure A.6: Tactical planning obtained with the moving small cycles (small cycle length of 3rd category is (a) 4 weeks, (b) 2 weeks)

Table A.9: Deviations from the targeted utilization levels and the excess capacity

		Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
OT	**Overuse**	0	0	0	0	0
	Overutilization	63.90	63.90	63.90	63.90	63.90
	Underutilization	0.02	0.02	0.02	0.02	0.02
IC	**Overuse**	0	0	0	0	0
	Overutilization	24.81	24.83	24.82	24.85	25.00
	Underutilization	3.13	3.15	3.14	3.17	3.32
NH	**Overuse**	0	0	0	0	0
	Overutilization	287.27	287.15	287.36	289.31	290.17
	Underutilization	2.28	2.15	2.36	4.32	5.18
MC	**Overuse**	13.53	12.52	12.94	10.80	11.24
	Overutilization	96.60	93.10	92.35	93.17	93.31
	Underutilization	13.58	10.08	9.33	10.15	10.29
Total (weighted)		**51.00**	**50.79**	**50.77**	**51.01**	**51.34**

A.3 RESOURCE UTILIZATION DEVIATIONS

A.3.1 INTENSIVE CARE

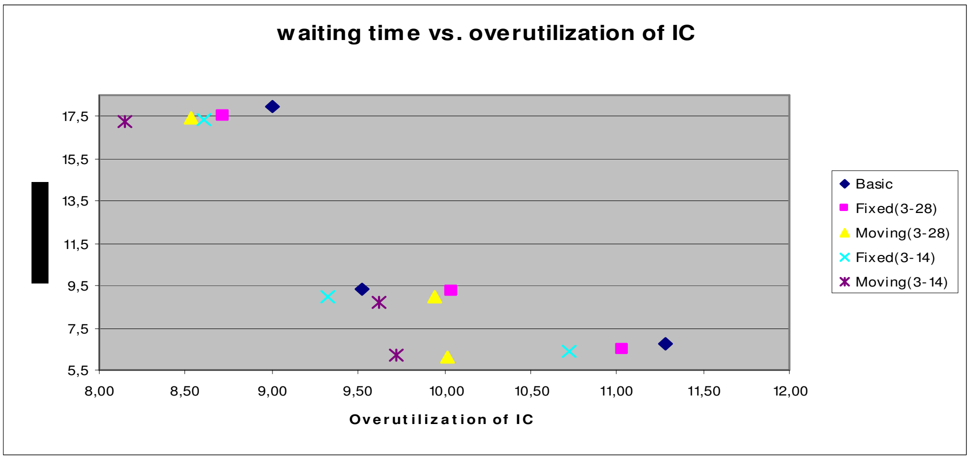


Figure A.7: The trade-off between the average waiting time and the expected overutilization of IC

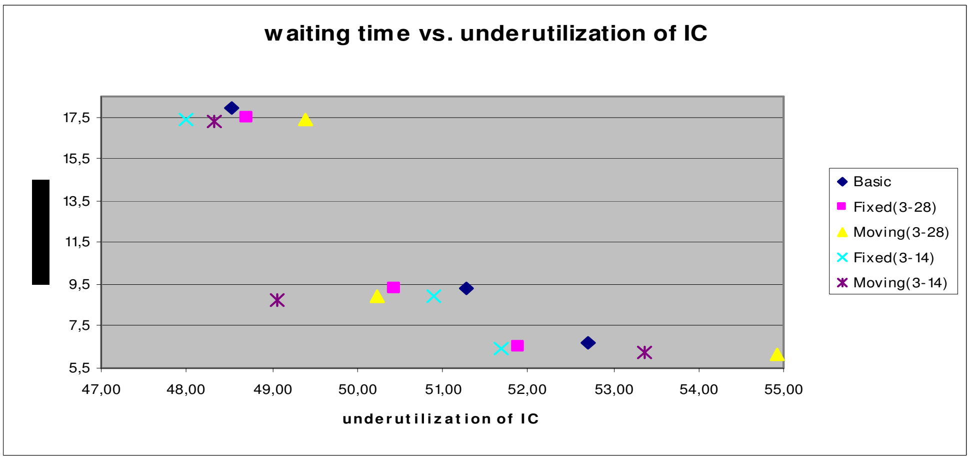


Figure A.8: The trade-off between the average waiting time and the expected underutilization of IC

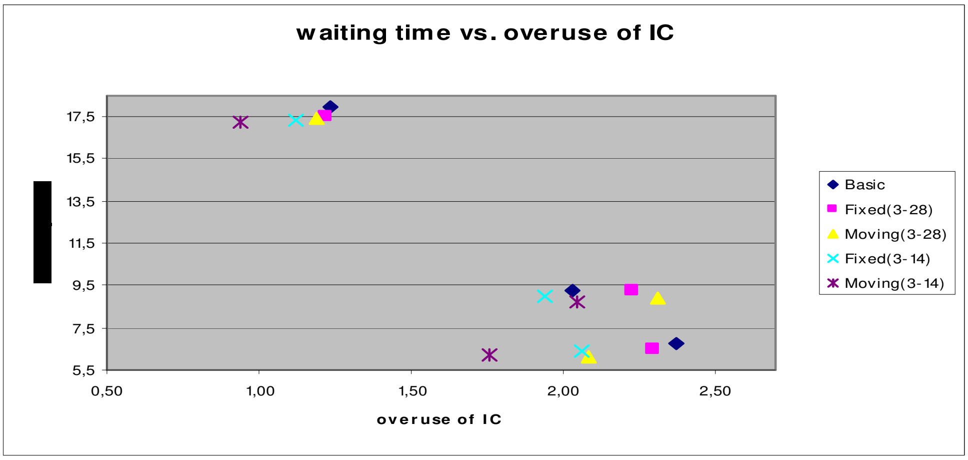


Figure A.9: The trade-off between the average waiting time and the expected overuse of MC

A.3.2 NURSING HOURS

Table A.10: Expected values of overutilization, underutilization and overuse of IC unit

		Basic Mathematical Model	Fixed Small Cycles (a)	Fixed Small Cycles (b)	Moving Small Cycles (a)	Moving Small Cycles (b)
Normal Planning	Over utilization	97.44	92.55	90.56	89.41	85.60
	Under utilization	617.53	618.18	608.42	627.97	615.76
	Overuse	9.86	9.00	8.08	8.73	6.31
	Weighted Sum	146.73	137.55	130.98	133.06	117.17
Intermediate Over Planning	Over utilization	103.51	108.24	100.17	106.49	105.43
	Under utilization	652.63	639.09	644.86	635.90	624.09
	Overuse	16.49	17.85	15.21	18.82	15.63
	Weighted Sum	185.95	197.48	176.23	200.58	183.59
Large Over Planning	Over utilization	125.34	120.91	117.36	109.20	103.56
	Under utilization	663.70	653.01	648.36	701.60	680.88
	Overuse	19.67	17.06	15.53	15.43	12.86
	Weighted Sum	223.69	206.19	195.02	186.44	167.86

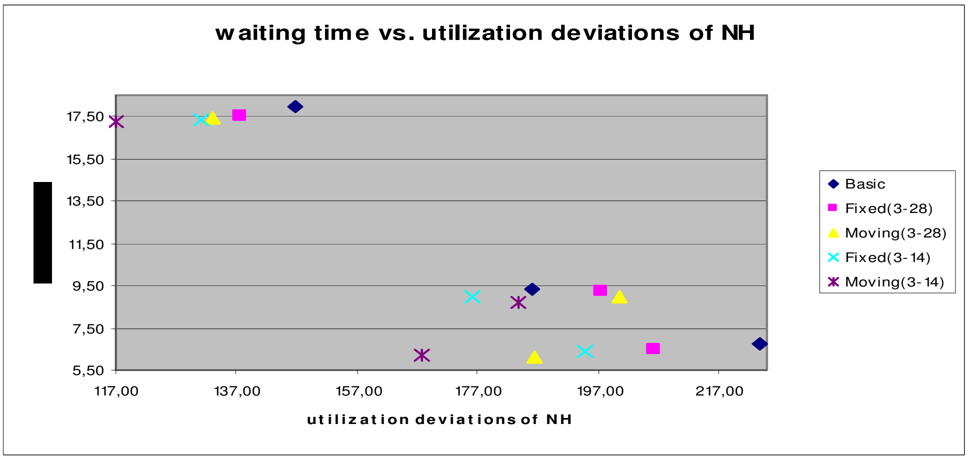


Figure A.10: The trade-off between the average waiting time and the weighted sum of average deviation of utilization levels from the targeted level and the overuse of NH

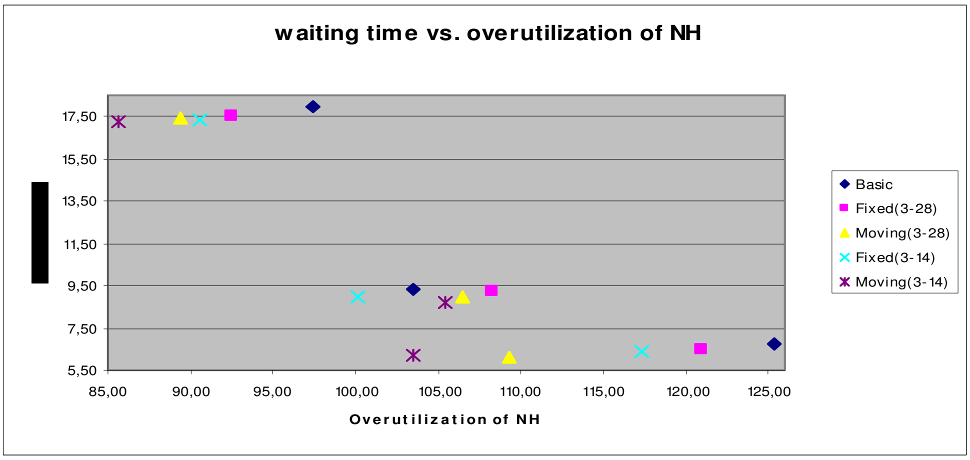


Figure A.11: The trade-off between the average waiting time and the expected overutilization of NH

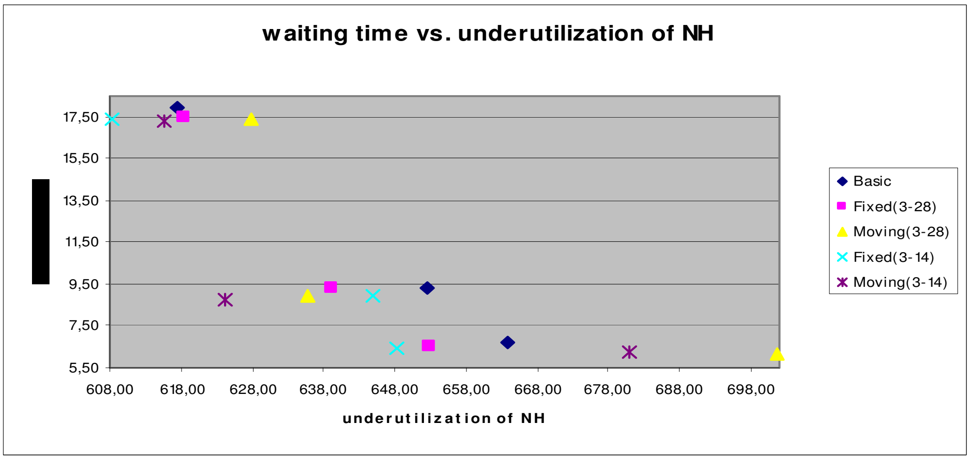


Figure A.12: The trade-off between the average waiting time and the expected underutilization of NH

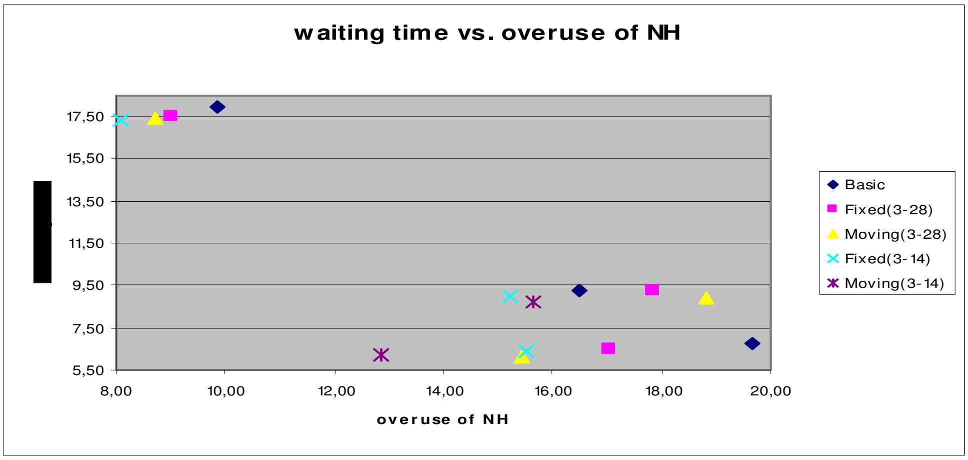


Figure A.13: The trade-off between the average waiting time and the expected overuse of NH

A.3.3 MEDIUM CARE

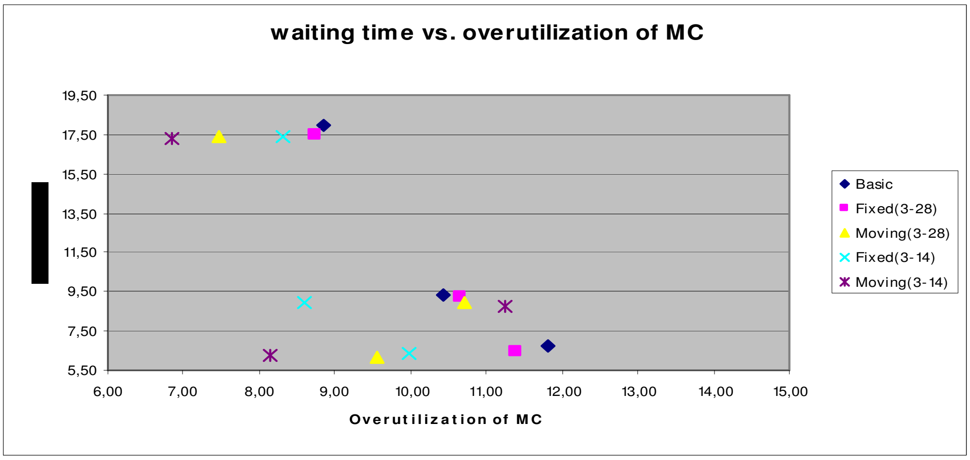


Figure A.14: The trade-off between the average waiting time and the expected overutilization of MC

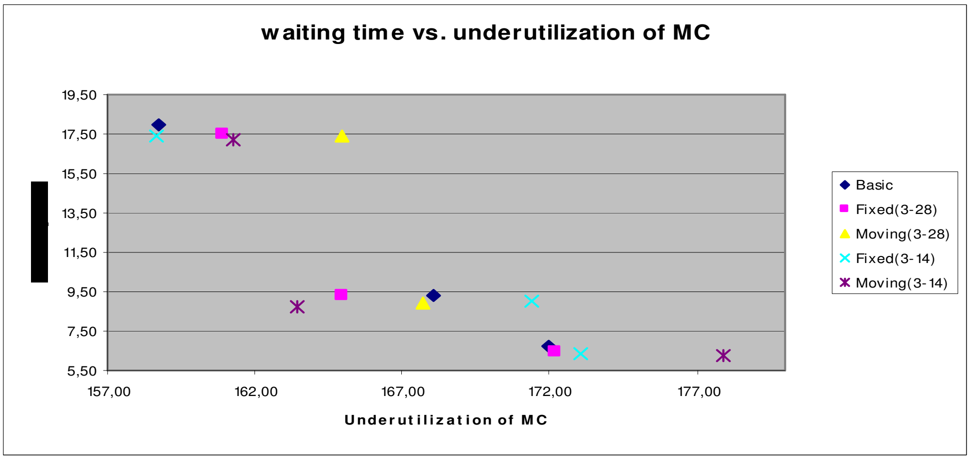


Figure A.15: The trade-off between the average waiting time and the expected underutilization of MC

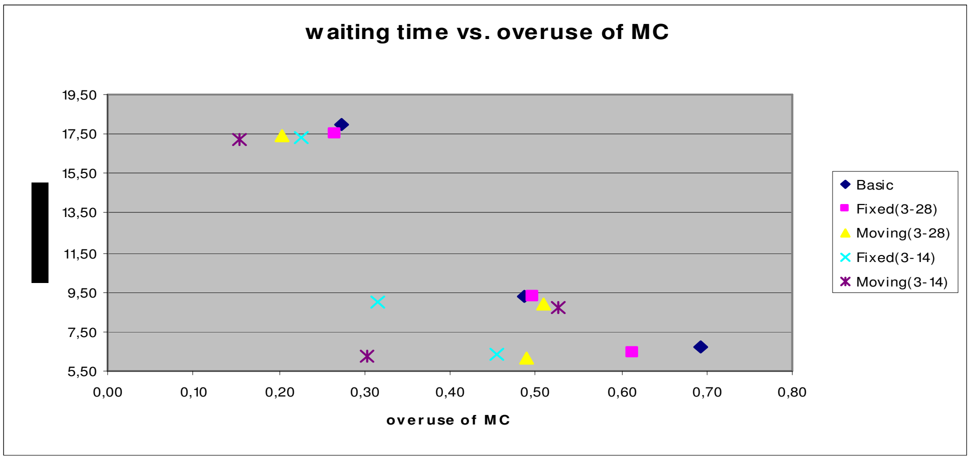


Figure A.16: The trade-off between the average waiting time and the expected overuse of MC

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