AN EVOLUTIONARY ALGORITHM FOR THE NURSE SCHEDULING PROBLEM WITH CIRCADIAN RHYTHMS

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AN EVOLUTIONARY ALGORITHM FOR THE NURSE SCHEDULING PROBLEM WITH CIRCADIAN RHYTHMS

by

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LIST OF ACRONYMS

AHP	-	Analytic Hierarchy Process
AI	-	Artificial Intelligence
AO	-	Annual Off-day
BT	-	Binary Tournament
BTS	-	Binary Tournament Selection
CH	-	Constructive Heuristics
COS	-	Cost
COV	-	Coverage
CP	-	Constraint Programming
CPU	-	Central Processing Unit
CSP	-	Constraint Satisfaction Problem
DOW	-	Day of Week
DSS	-	Decision Support System
DT	-	Double Tournament
DTS	-	Double Tournament Selection
E	-	Evening
EA	-	Evolutionary Algorithm
EC	-	Evolutionary Computation
EM	-	E-Mutation
EN	-	Enrolled Nurse
ES	-	Expert System
FLE	-	Flexibility
GA	-	Genetic Algorithm

GP - Goal Programming

GUI - Graphical User Interface

H - Heuristic

HG - Human Generated

HT - Hybrid Technique

ILP - Integer Linear Programming

IP – Integer Programming

IT - Information Technology

J - Junior

LGP - Linear Goal Programming

LP - Linear Programming

LPN - Licensed Practical Nurse

M - Morning

MA - Memetic Algorithm

MCDM - Multi-Criteria Decision Making

MIP – Mixed-Integer Programming

MP – Mathematical Programming

N - Night

NA - Nurse Aide or Nurse Assistant

NO - Night Off

NP - Network Programming

NSP – Nurse Scheduling Problem

O - Off-day

OR – Operations Research

QUA - Quality

PO - Public Off-day

RFM - Requirement-Fitness Mutation

RM - Redundant Modeling

RN - Registered Nurse

RW - Roulette Wheel

RWS - Roulette Wheel Selection

S - Senior

SA - Simulated Annealing

SCN - Special Care Nursery

SN - Staff Nurse

SOM - Split-Off Mutation

ST - Search Technique

TOD - Time of Day

TS - Tabu Search

WO - Weekly Off-day

ABSTRACT

This thesis investigates the use of memetic algorithm (MA) for solving the nurse scheduling problem. The problem involves the assignment of shift duties and off days in such a way that several hard organizational and soft preferences constraints are satisfied. MA, which is also considered an evolutionary algorithm (EA), offers an efficient and successful alternative technique to solve this problem. An MA framework to solve the semi-cyclic nurse scheduling problem in a special environment is presented. The objective of this study was to come out with an efficient solution technique, which also is a better approach to the existing human generated technique. The approach offers some added values, which simultaneously include the circadian rhythm elements, the prolonged off days or rest periods, and fairness in shifts distributions. One of the key aspects of this approach is the use of specially designed representations that cater for the circadian ordering in shifts distribution. The approach involves several major components, such as the declaration of special environment constraints, the construction of an evaluation function, and the usage of evolutionary operators in generating sets of candidate solutions. Successful results are demonstrated following the implementation of the prototype incorporating all inputs in several evolutionary phases. The approach also relies for its success on the use of specially designed mutation operators as parts of the evolutionary operators, which greatly improve the overall performance of the solutions. The solutions obtained show that the proposed MA technique is effective and able to improve the solution quality, while satisfying the main objective of providing continuous patient care services. This is reflected in the evaluation analysis, which utilized the analytical hierarchy process (AHP) technique to evaluate and select based on four criteria. The scheduling framework can readily handle a variety of manpower scheduling problem constraints, especially those with similar domains.

Keywords: Manpower scheduling, nurse scheduling problem, nurse rostering problem, evolutionary algorithms, memetic algorithms, analytic hierarchy process, human resource management, and health care application.

SATU ALGORITMA EVOLUSI UNTUK MASALAH PENJADUALAN JURURAWAT DENGAN RENTAK 'CIRCADIAN'

IKHTISAR

Tesis ini menyiasat penggunaan algoritma 'memetic' (AM) untuk menyelesaikan masalah penjadualan jururawat. Masalah ini melibatkan pengagihan tugasan syif dan hari cuti sebegitu rupa agar beberapa kekangan organisasi yang keras dan kekangan berkaitan kehendak kakitangan dapat dipenuhi. AM yang ditakrifkan sebagai suatu algoritma evolusi, menawarkan satu penyelesaian alternatif yang berjaya dan efisien untuk masalah ini. Satu kerangka algoritma 'memetic' untuk menyelesaikan masalah penjadualan jururawat dalam persekitaran kerja khas dipersembahkan. Objektif kajian ialah untuk menghasilkan satu teknik penyelesaian yang efisien, yang juga merupakan satu kaedah yang lebih baik berbanding teknik janaan manusia yang sedia ada. Beberapa nilai tambah yang ditawarkan oleh kaedah 'memetic' ini termasuklah elemen rentak 'circadian', pemanjangan hari cuti atau tempoh masa tidak bekerja, dan perlakuan adil dalam pengagihan syif. Salah satu daripada aspek penting kaedah ini ialah penggunaan reka bentuk perwakilan khas yang mampu menangani jujukan 'circadian' dalam pengagihan syif. Kaedah ini melibatkan beberapa komponen penting seperti pernyataan kekangan khusus bagi persekitaran kerja, pembinaan satu fungsi penilaian, dan penggunaan berbagai operator evolusi dalam menjana calon penyelesaian. Keputusan yang membanggakan diperolehi selepas proses implimentasi prototaip yang menggabungkan semua input dalam beberapa fasa evolusi. Keberjayaan kaedah ini juga bergantung pada penggunaan beberapa operator mutasi yang direka khas sebagai sebahagian dari operator evolusi, yang mana ianya dapat meningkatkan lagi pencapaian keseluruhan setiap penyelesaian itu. Penyelesaian yang diperolehi

menunjukkan bahawa kaedah AM yang diusulkan ini adalah efektif dan mampu meningkatkan lagi kualiti penyelesaian, sambil memenuhi objektif utama iaitu menyediakan perkhidmatan berterusan yang berkualiti kepada pesakit. Ini digambarkan oleh analisa penilaiannya yang menggunakan teknik Proses Hiraki Analitik (PHA) dalam proses menilai dan memilih berdasarkan empat kriteria. Kerangka proses penjadualan ini seterusnya dapat diaplikasikan juga kepada beberapa jenis masalah penjadualan kakitangan, terutama yang mempunyai 'domain' serupa.

Katakunci: *Penjadualan kakitangan, masalah penjadualan jururawat, algoritma evolusi, algoritma 'memetic', proses hiraki analitik, pengurusan sumber manusia, dan aplikasi kesihatan.*

CHAPTER ONE

INTRODUCTION

The human service organization is characterized by multiple and often conflicting goals (Ignizio, 1980). One example is in hospital organization. Hospitals are expected to provide high quality care and at the same time attain maximum efficiency in their operations. They are normally expected to emphasize on aspects such as community responsibility and consumer satisfaction. Hospitals have to provide twenty-four-hours-a-day and seven days-a-week of service. At the same time, personnel job satisfaction needs must also be fulfilled.

Parker & Kaluzny (1982) stress that the routes to achieve these (multiple) goals are by streamlining the staffing and scheduling patterns in each single unit, which in turn will indirectly determine the operational efficiency of the whole organization. In addition, design as either a process or set of arrangements is important in human service organizations for at least two reasons: First, the provision of human services is a collective activity. Thus, organizations, rather than individuals, provide the framework for an ever-increasing set of complex human service technologies. Secondly, increasing evidence indicates that aspects of organizational design, rather than individual characteristics of personnel, are the critical factors affecting organizational performance. In an organization like hospitals, staffing and scheduling processes of nurses are the important designs or components that affect organizational performance. Therefore,

nurse personnel management should be the prime target in the move towards organizational improvement.

As one of the phases in a management system, the scheduling process may involve different entities. The application domain of scheduling varies widely but at the highest abstraction, it can be classified into three classical types: production scheduling, route scheduling and personnel scheduling (Van Wezel & Jorna, 1996). The distinction in different scheduling types can be depicted by the differences in objects that are arranged within each type. Therefore, event allocation, of which the timetabling problem is an example, can be considered a class by itself. However, the focus of this thesis is in personnel scheduling with emphasis on the nurse workforce. The thesis work is on the scheduling process of nurses' shift duties wherein the service organization is the hospital, which provides nursing services around the clock. In a nurse management system, staffing process is the initial phase, while scheduling process is the second. The final phase is the allocation process, which takes place in real time implementation of scheduling. The scheduling process may involve nurses of different skill categories such as enrolled nurses (ENs), nurse aides or assistants (NAs), licensed practical nurses (LPNs), and registered nurses (RNs) or staff nurses (SNs).

1.1 What is Scheduling?

Scheduling is in essence a resource allocation problem. As defined by Baker (1974), scheduling is the allocation of resources over time to perform a collection of tasks. However, Wren (1996) further defines it as the arrangement of objects into a pattern in time or space in such a way that some goals are achieved, or nearly achieved, and that constraints on the way objects may be arranged are satisfied or nearly satisfied. In

production scheduling, it deals with the process of product manufacturing using machinery wherein all kinds of characteristics of the process are considered (Bowers & Jarvis, 1992; Bugnon et al., 1995). On the other hand, route scheduling or also known as vehicle routing, deals with the assigning of vehicles and their routes in transporting different products from one or more sources to specified destinations (Van Wezel & Jorna, 1996). However, in term of personnel or manpower scheduling, it is the act of balancing customer and/or organizational demand, personnel work requests and profitability (Thompson, 1998). In a similar definition, Lau (1996) stated it as the scheduling of manpower resources to meet temporal operational requirements in ways that satisfy the goals and policies imposed by the managements, labor unions and governments.

Personnel scheduling has been a topic of interest in the operations research community for such a long time and can be traced back to almost four decades ago. A variety of service delivery settings have been studied such as the scheduling of airline crews (Schindler & Semmel, 1993), hotel reservation personnel (Holloran & Byrn, 1986), telephone operators (Henderson & Berry, 1976), police officers (Taylor & Huxley, 1989), and security guards (Engku, 2001) to name a few. This thesis discusses specifically the nurse scheduling problem (NSP) which relates to a specific environment.

1.2 What is Nurse Scheduling?

Personnel scheduling is a complex problem, which consumes a great deal of management time and significantly influences the efficiency and quality of departmental operations. In the nurse scheduling context, scheduling refers to the determination of the

off days and daily shift patterns of each nurse, for each nursing unit, over a period ranging from 1 to 8 weeks (Brusco & Showalter, 1993).

As mentioned earlier, scheduling is one of the phases in a nurse management system. However, before any scheduling activity is carried out one must obtain input from the staffing phase, which is the determination of the number of nurse labor hours required, of each nursing skill class, for each nursing unit over a one (fiscal) year planning horizon. This phase is normally under the control of the top management whose decision-makings are based on organizational policies. The final phase is the real time allocation which is the daily/hourly adjustment of nurses within and between nursing units, as warranted by the number and acuity of patients (Brusco and Showalter, 1993). This phase is usually done manually by the head nurse or the nurse manager as impromptu adjustments whenever an emergency arises. However, the first and third phases are not part of the thesis work.

1.2.1 Scheduling Characteristics

The nurse scheduling environment provides a complex problem because of the large number of conflicting constraints that must be balanced in order to create a schedule. The constraints cannot be prioritized because they are not independent or stable, which forces unique solutions to the scheduling problem (Jelinek & Kavois, 1992).

1.2.1.1 Problem Complexity

The configuration of the nurse schedule is generated in a particular manner so as to fulfill collective agreement requirements and the hospital staffing demand coverage

while normally, minimizing salary costs and maximizing nurse preferences as well as care quality. These collective agreement requirements are rules or constraints that help to define acceptable schedules for individual nurses in terms of seniority, workload, holidays, weekends off, consecutive assignments and possibly rotations (Jaumard et al. 1998). The demand coverage constraints specify the number of each skill level, i.e RN, LPN, NA or combination of those, required for each demand coverage requirements.

However, in this work only SNs are exclusively considered in the scheduling process. Such assumption is not unrealistic since many nursing units, particular those in critical areas (eg. surgery and intensive care), operate with strictly SNs (Venkataraman & Brusco, 1996). In addition, the scheduling of all other categories is rather regular and simple, and that is the reason why such scheduling is usually done independently of that of SNs.

The salary costs may include the regular salary of the permanent staff, overtime costs and the floating or agency staff costs. Subsequently, nurse preferences can be formulated in terms of requests such as days off, or evening versus night shifts. Care quality can be expressed through the degree of balance between experienced and less experienced nurses. All of these result in being the sources of the problem complexity.

1.2.1.2 NP-Completeness

From a theoretical perspective, the staff scheduling problem is included in the class of non-deterministic polynomial (NP) – complete problem (Garey & Johnson, 1979). An NP-complete problem is a decision problem that cannot be solved by any algorithm in polynomial time. In other words, the time required to solve an NP-complete problem is

a non-polynomial function of the problem size. This problem of generating staff schedules is a difficult combinatorial optimization problem for most staffing context. Restricting the context to staff scheduling in hospitals does not make the problem any less difficult. This remains true even when restricting it to cyclic nurse scheduling (Hare, 1997). Hence, it is not only, not practical to determine the optimal solutions for a mixed of cyclic and non-cyclic method, but also it is not practical for scheduling large problem with that approach, simultaneously.

1.2.2 Scheduling Approaches

In the general concept of staff scheduling, there are two main approaches for solving these scheduling and assignment decisions. The first approach is a two-stage solution technique. The scheduling decision is made in the first stage while the assignment decision, which is determined based upon the result of the scheduling decision, is made in the second stage. In other words, work patterns of off days and working days are generated first. Then shift duties are assigned based on the working day patterns (Ozkarahan & Bailey, 1988; Ozkarahan, 1991; Chen & Yeung, 1992; Randhawa & Sitompul, 1993). The second approach is a single-stage solution technique. In this approach, these scheduling and assignment decisions are solved simultaneously, which is also referred as tour scheduling (please see section 2.1).

With knowledge on scheduling characteristics, one can direct the problem-solving efforts toward those approaches that have the greatest likelihood of leading to useful algorithms. Therefore, this thesis focuses on the enhancement of the scheduling methodology in the quest of a balanced and high quality schedule, through the adoption of artificial evolutionary strategies. In this case, the tour scheduling approach will be

followed due to its challenging nature. This initial chapter will lay out the overall picture of the thesis in the following subsections. Considerations on nurse scheduling system are made based on the research motivation discussed in the next section.

1.3 Research Motivation

There are numerous factors, which affect the overall efficiency of any organization, but it is expected that improved capacity (resource) utilization would result in enhanced service sector productivity (Bectold et al., 1991). One resource in an organization is manpower. Research published on the problem of manpower scheduling is relatively little if compared with the literature on production scheduling (Engku & Razamin, 2000). Manpower scheduling is considerably important as well, since an over capacity of employees will lead to direct losses of resources through staff idle time (Browne, 1997) whereas, an over production of goods can be inventoried for later use. On the other hand, if the resources are insufficient to meet demand, service may be delayed. As a result, low quality of service shall be expected in such a service organization. In addition, customer satisfaction and responsibility to community will also be greatly affected. In hospitals, nursing personnel is one of the key resources that make the hospital operable. Thus, providing efficient work schedules for them would be very beneficial to hospital operations.

A good schedule can improve operations by providing better coverage with identical or reduced staffing levels (Randhawa & Sitompul, 1993). On the other hand, the opposite is usually perceived as being unfair. Moreover, scheduling personnel efficiently is also crucial since nurses' salaries make up the largest single item in a hospital's operating cost (Kao & Queyranne, 1985). From previous statements, we can understand that the

act of scheduling is an important thing because it affects many aspects. Therefore, scheduling personnel has been shown to play an important role in hospital's operation, and this has been the initial element in motivating the research work.

Although the interest in solving the NSPs can be traced back to several decades ago, there are still ongoing efforts to create effective and efficient schedules. This can be attributed to the fact that the problem is real and important; that it has widespread application in other industries; that the constraints vary from one institution to another institution; that it is a challenging combinatorial problem known to be NP-complete; and that there appears to be no consensus on how to approach it (Millar & Kiragu, 1998). Moreover, NSP is itself complex with many objectives to fulfill. These characteristics contribute to the scheduling difficulties and become part of the complexities of hospital organization. These special and distinct characteristics are part of the underlying reasons for this on-going search in creating good schedules.

As is known, the problem of scheduling nursing staffs may differ from one hospital unit to another depending on the kind of hospital and also from one country to another. At the time when this thesis was started in 1999, the nurse scheduling process in Malaysian hospitals was still done manually. This of course, may invite the inefficiency of the services provided. Typically, the head nurse of a unit or ward is involved in the construction of schedules, which may take from several hours to several days to complete. That too depends on her experience in tackling this complicated task. It is not an uncommon practice that head nurses bring home their scheduling duties. Other disadvantages are that the head nurses often overlook details about individual nurses, which may be construed as being unfair and that no impromptu replacement of the

scheduler with equal capability is possible if she leaves the service. If this happens, it can cause great difficulty until a replacement can develop the experience and judgment necessary to construct a schedule (Franz et al., 1989). On the other hand, our Western counterparts have advanced to automated systems (Harmeier, 1991) and other sophisticated concepts of scheduling during the last few decades. This big gap in scheduling approaches reflects the lack of awareness amongst top managements as to the significance of the scheduling role as discussed earlier, and has provided further motivation for this thesis.

From the Gantt chart used in early NSPs to sophisticated evolutionary techniques used in recent scheduling work, computing technologies have evolved rapidly in a relatively short time (details and examples are further discussed in chapter 2). Hence, the enhancement of scheduling systems can be made possible by powerful computing technologies and the difficulties of nurse scheduling are further reduced, especially with the introduction of intelligent systems. Furthermore, automation of scheduling systems can help save 4 - 10 hours (Warner et al., 1990; Darmoni et al., 1994) of labor in a 4-week schedule. Consequently, vast improvements in computing technologies have become another factor to tackle this combinatorial problem and which are capable of generating comparable or better results than non-automated approaches.

1.4 Research Questions

Evidently, some research work has to be done in this area. However, some research questions arise, these are:

1. Which type of scheduling model can be developed with certain advantages?

2. What are the constraints and objectives that should be considered while designing the model?
3. Why are these constraints and objectives chosen?
4. What is the methodology needed to design an efficient model?
5. How do we evaluate the effectiveness of the model?

As is known from the literature, there is no consensus on which model or schedule that solves the NSP most efficiently and optimally. Schedules produced by way of optimization techniques often consider the hard constraints only. Moreover, in depth and lengthy mathematical formulations are needed in exploiting these techniques. Even for problems that can be mathematically formulated, these techniques or their hybrids are not opted for (Engku & Razamin, 2000). This is due to reasons such as the complexity and size of the problems. Consequently, not all NSP can make use of these techniques since in reality soft constraints are important as well. These soft constraints are rather difficult to formulate mathematically. Most solutions of NSP are problem-specific, so constraints considered in the models can be varied. Recent work similar to this research such as by Abdennadher & Schlenker (1999), Vouluxis & Housos (2000), Burke et al. (2001) present variations of the techniques used as well as in various environments. It is obvious that there is ample room for enhancement of the design methodology and strategy.

1.5 Research Objectives

In the light of all the reasons discussed earlier, there is an acute need for the design and development of an efficient nurse scheduling system that can be adapted to different aspects of specialized environment problems. It is hoped that the system, which

incorporates artificial intelligence (AI) concepts and techniques, shall provide efficient decision-making regarding nurse management systems and thus strive towards optimizing workforce and service. The main objective of this thesis is to suggest a design methodology for a nurse scheduling model using an evolutionary approach such that, it is able to solve the semi-cyclic type of nurse scheduling problem exists in hospitals. The aim subsequently, is to construct a prototype model utilizing that methodology. In order to achieve that, some specific objectives have to be fulfilled simultaneously. They are as follow:

1. To assign shift duties and off days in a scheduling period to each nurse such that the hard requirements and soft preference constraints are fulfilled, and thus promote job satisfaction as well.
2. To implement a new parent selection procedure, that is the Double Tournament Selection, which is able to produce acceptable best-so-far solutions faster.
3. To implement a row-wise crossover operator that works in the natural structure of two dimensional matrix, and which is able to maintain the circadian rhythm orderings.
4. To implement three smart mutations operators which suit the specifics of the problem, so as to overcome certain complexities and thus, improve on the convergence rate.
5. To evaluate the model through the incorporation of qualitative and quantitative criteria, that is using the analytic hierarchy process (AHP).

1.6 Definitions

Definitions adopted by researchers are often not uniform, so key and controversial terms may need clarification. On the other hand, some terms are so defined due to their specialized use in the field. Likewise, personnel scheduling especially for nursing staff has its own specialized terms.

- A schedule at a nursing unit is the arrangement of duties and off days and is usually prepared for a short duration of time normally on a weekly, fortnightly or monthly basis.
- 'Roster' and 'schedule' are synonymous but roster is the much preferred term among nursing personnel.
- Personnel or manpower is a basic unit of resource in the scheduling process and in this case, it refers to a nurse.
- A ward is a nursing unit where nurses work and it makes up part of a hospital.
- A planning period or horizon is the long term temporal period for which personnel staffing is done. It is normally one (fiscal) year.
- A scheduling period is the short term temporal period for which a personnel scheduling is done and ranges from 1 to 8 weeks. It is a subset of the planning period.
- A work shift or simply shift is a period of time within a day for which personnel will perform work or duties.
- An off or rest day is a day during which personnel will not perform any work.
- A work stretch is a continuous chain of work shifts between any two off days.
- A feasible schedule is one that satisfies all the hard requirements of staffing and scheduling which apply to the entire workforce.
- A cyclical schedule is one which repeats a specified work pattern in a cycle of

"n" scheduling periods indefinitely into the future.

- A non-cyclical schedule is one which is newly generated each time for each scheduling period with the available resources and policies.
- Operation research (OR) is a scientific approach to problem-solving that provides executives with a quantitative and rational basis for taking decisions, especially those dealing with the allocation of resources.
- Artificial intelligence (AI) may be defined as a branch of computer science that is concerned with the automation of intelligent behavior. Its emphases are on perception, reasoning, action and computation.

1.7 Research Approach

It can be concluded that almost all the techniques used to solve NSP are problem specific. Thus, any system developed for this purpose tends to be from scratch. Adapting from systems designed for other similar NSPs is difficult due to variations of constraints and regulations (eg. part time or agency nurses are not allowed here). These differences have made it impossible to utilize other similar systems directly. Although commercial software is available, some of them are quite general in nature such that they can be used for other types of staff scheduling as well. This is of course, their commercial goal. As quoted from Dowsland (1997), a general algorithm is like a 'size 48 cloth'. It will cover everybody but it doesn't fit any one very well. Moreover, they are designed from the management viewpoints and do not consider special constraints, like the ergonomic criteria. Thus, redeveloping or reengineering of the software is necessary for our NSP since certain constraints, which follow the ergonomic guidelines have to be integrated into the system. However, this could be as tedious as doing it from

scratch when it comes to encoding the steps. These considerations underpinned our decision to tackle this problem from a problem-specific approach or perspective.

One important consideration in choosing a method for solving NSP is that the method should produce quality schedules. Quality schedules are designed to overcome frustration and fatigue due to stressful working situations amongst nurses. There have been studies that focused on ergonomic criteria for scheduling shift work (Bosch & De Lange, 1987; Chen & Yeung, 1992). Shift work scheduling is evaluated based on the following criteria: 1) psychological adjustment; 2) well-being (eg. sleep, fatigue and appetite); 3) health (eg. gastrointestinal and nervous disorders); 4) personal and social problems; and 5) performance and accidents (Chen & Yeung, 1992). Hence a scheduling method that prioritized quality in terms of ergonomic values is essential.

1.7.1 Constraints Gathering

Before proceeding to build a model, all constraints relevant to the problem have to be collected. Literature search is necessary to gain insights on the constraints normally used. But most importantly, a series of discussions with the management assisted in gaining understanding about the constraints needed and their necessity.

1.7.2 The Evolutionary Model

A prototype for the nurse scheduling system is developed based on the acquired constraints and variables. The paramount objective of this prototype is to provide efficient schedules and ensure that these are feasible ones. Some strong points in evolutionary computation (further details discussed in chapter 3) have been the deciding

factors as to why an evolutionary model is adopted in this work. The model is designed into modules with each having their own functions. This whole structure consists of several main modules to exhibit the evolutionary approach used. These are the initialization of population, evaluation, selection, crossover and mutation modules. They satisfy the relevant constraints and rules. The process must possess in-depth problem specific knowledge in nurse scheduling and can be achieved by using heuristics. Detailed descriptions of the modules involved are discussed in chapter 4. However, the following diagram summarizes the overall approach taken.

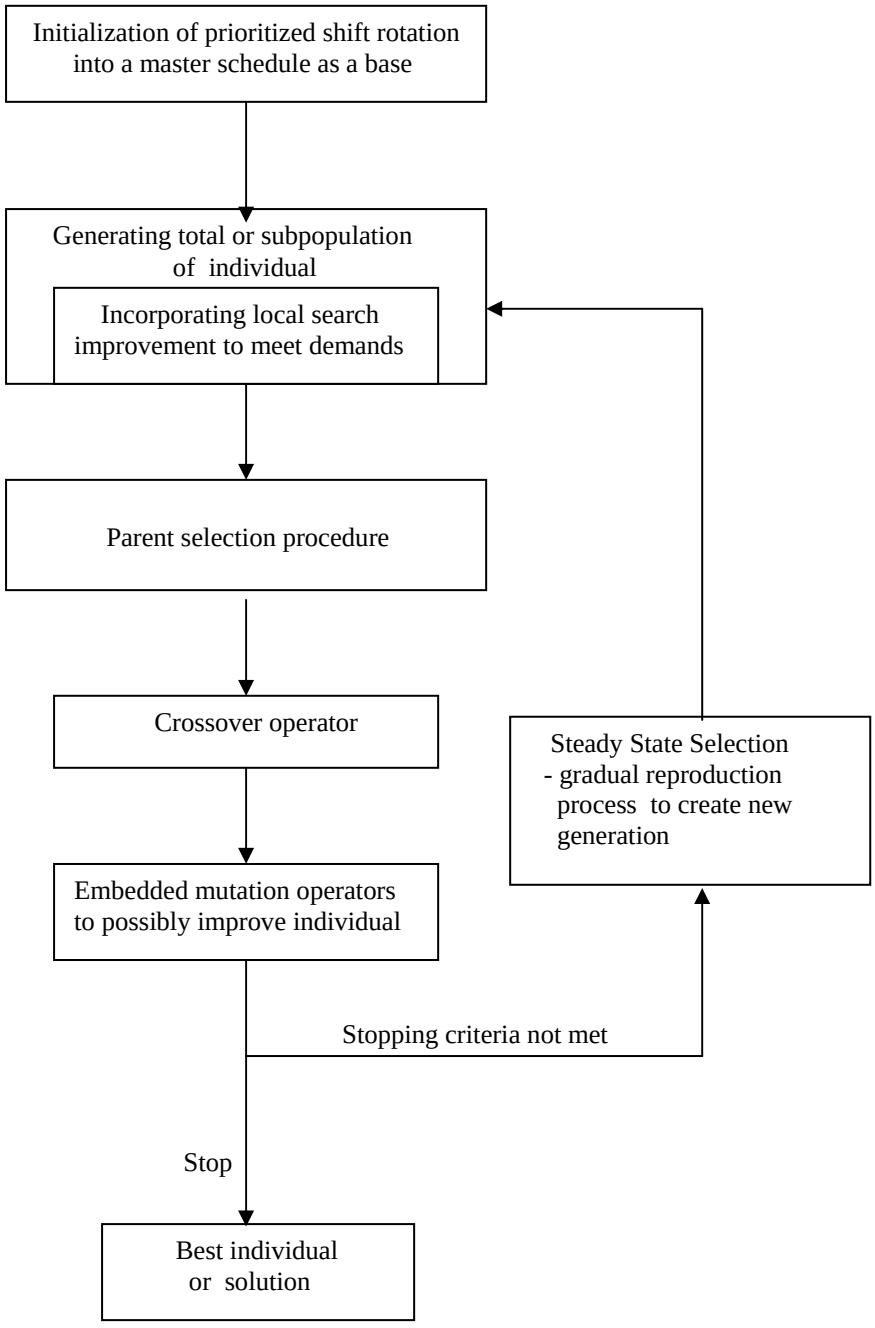

Figure 1.1 : The evolutionary strategy for the nurse scheduling problem

1.8 Research Contributions

This research focuses on the nurse scheduling model with primary focus on the design of the scheduling methodology. In designing and solving this scheduling model, significant contributions have been made and are given as follow:

- **Major Contributions**

1. The main contribution of this research is the package of methodology design based on the memetic approach for the nurse scheduling problem, with semi-cyclic scheduling and circadian rhythms priority. The memetic methodology introduces structures within the framework such as the parent selection, crossover and specialized smart mutations, which contribute towards producing high quality schedules. Some of these techniques exploit the nature of the problem, while the mutation rates fluctuate depending on the nature of the solution. Furthermore, this approach is able to satisfy nurse preferences and at the same time fulfill the organizational constraints. The integration of hill-climbing search and certain heuristics have made it possible to overcome certain complexities in the problem.

2. With respect to the framework, a new parent selection procedure, which differs from the standard procedures, is introduced. It is called *Double Tournament* selection, and is able to produce acceptable best-so-far solutions faster. Comparisons with standard selection schemes are presented as well.

3. A different crossover technique, which is able to maintain the circadian rhythm orderings is presented. This is a row-wise crossover that is feasible in the natural structure of two-dimensional matrix.

- **Side Contributions**

4. In further improving the solution quality, smart mutation operators are implemented. These operators are special local search that are adaptive and also help to speed up the solution process. The *E-Mutation* helps to increase the number of preferred shift instances; the *Split-Off Mutation* takes care of the undesired split off days through efficient management of annual leave; and the *Req-Fit Mutation* tackles any infeasibility and possibly mutates them into feasible ones.

5. The evaluation of our proposed nurse scheduling approach and the human-generated approach were carried out using the analytical hierarchy process (AHP) instead of just the qualitative style. The usage of this unique technique, which incorporates the qualitative and quantitative criteria, is rather a new introduction to the nurse scheduling environment (in term of evaluation). The AHP thus, quantified preferences based on the established scheduling criteria. The results are clear and transparent but above all, without compromising quality.

6. A different classification of the solution techniques as discussed in chapter two is presented. The classification describes recent trends and developments in the nurse scheduling arena. Thus, it provides future researchers with new directions into the solution space.

1.9 Outline of the Thesis

Chapter Two discusses the overview of past nurse scheduling solutions. It describes the changing trends in this section of healthcare delivery systems. Some classifications of solution techniques are discussed, which function is to put this thesis in perspective.

Chapter Three examines the foundation of the approach to be undertaken for this nurse scheduling problem. It looks at the attributes, characteristics, principles and benefits of the evolutionary algorithms in detail. Eventually, these have provided a base for one of the contributions of this research.

Chapter Four discusses on the methodology of the proposed solution with semi-cyclic scheduling approach to the nurse scheduling problem. Discussions on how constraints gathering are done and the objective functions applied are presented. Criteria for the evaluation of the solution are also given. The chapter ends with several highlighted recent similar work.

Chapter Five describes the implementation of the proposed scheduling algorithms to solve nurse scheduling problems. This implementation was then tested on a real-life extensive nurse scheduling problem at a Malaysian general hospital. Evaluation of the model was done using qualitative and quantitative methods as well.

Chapter Six as the final chapter presents the conclusion to the thesis. It summarizes the proposed evolutionary strategy to the problem, discusses its implications, limitations and how further work might be best directed.

CHAPTER TWO

A REVIEW OF NURSE SCHEDULING PROBLEMS

The need to look for effective and efficient scheduling is becoming important. In profit making hospital organization, this is important because hospital costs could be controlled efficiently through nursing salaries. Technology has also played its role with powerful tools and emerging effective techniques with automation in AI areas. Hence, this chapter will concentrate on the review of related issues and a range of solution techniques in nurse scheduling as evidenced by published articles. It begins with the descriptions of scheduling types. It continues with brief discussions on the objective function and constraint criteria adopted by previous researchers, which are multiple and varied. Then the review will roughly segregate the research arena into two timeframes, namely prior to 1990's and post 1990's, and at the same time describes past solution approaches trying to be as exhaustive as possible.

2.1 Scheduling Types

Personnel scheduling work can be classified into three types as suggested by Baker (1976), that is, days-off, shift and tour scheduling.

2.1.1 Days-off Scheduling

Days-off is the simplest form of the scheduling type. Its objectives are to determine each personnel's work and non-work days during the operating scheduling period (Brusco &

Johns, 1995) and to ensure a fair distribution of off days (Lau, 1996). The main concern is on the development of methods for environments where personnel off days are required to be consecutive (Bechtold, 1981). There is also setting where the off days are unconstrained (Bechtold,1988).

2.1.2 Shift Scheduling

On the other hand, shift scheduling focuses on determining the daily start and finish times for personnel, as well as the placement of any rest and/or meal breaks (Brusco & Johns, 1995). It completes the whole schedule by assigning time-of-day to the chosen days-off schedule subject to demands and the shift assignment constraints. These constraints permit and forbid certain shift changes such as morning shift to afternoon shift is acceptable but not night shift to morning shift, so that personnel are not unduly affected by irregular rest periods. Shift scheduling problem becomes more complex when it involves both part-time and full-time personnel (Glover & McMillan, 1986) as well as different shift duration and shift start time.

2.1.3 Tour Scheduling

The third type is tour scheduling, which is the integration of days-off scheduling with shift scheduling over the scheduling period (Brusco & Johns, 1995). It determines the personnel off days during the period as well as personnel shift duties and break times during each work day. The combined features make it the most challenging of the three types of scheduling as experimented by Razamin et al. (2000).

2.2 Objective Function Criteria

Any organization using valuable resources and employing a large number of personnel faces the problem of ensuring efficient and productive utilization of both resources and personnel. This generally involves deciding which days/shifts/tasks are to be allocated to each member of the organization over some period of time. In doing so, a systematic procedure is developed with certain objectives to fulfill. The objective function criteria which have been used or suggested in past solutions include (1) total labor hours scheduled, (2) total number of employees, (3) labor costs, (4) unscheduled labor costs, (5) customer service, (6) overstaffing, (7) understaffing, (8) number of schedules with consecutive days off, (9) number of different work schedules utilized, or (10) some combination of the above (Bechtold et al., 1991). These criteria are not limited to nurse scheduling environment alone. Some are not appropriate for certain NSPs where part-time personnel not allowed. However, Aggarwal (1982) listed that one of the objective is to keep investment in facilities at near-minimum amount. Bechtold et al. (1991) also mentioned that total labor hours scheduled is the performance criteria, which has been used most frequently by scheduling researchers. This is true in a profit-oriented organization case. If the scheduling procedure could minimize that objective, it means less labor hours incurred thus, considered a saving. This similarly happens in privately run hospitals but not so in totally government funded ones because the number of employed personnel is solely controlled by top managements. Consequently, this number does not fluctuate very often. In recent nurse scheduling solutions (eg. Dowsland, 1998), individual preferences and request for days off are taken into consideration when formulating the objective function. This procedure is becoming favorable.

2.3 Constraint Criteria

In attempting to develop efficient and flexible schedules, organizations are bound to certain constraints at the same time. Constraints are relations between variable to be defined (Van Hentenryck, 1999). Such constraints are (1) labor requirements, (2) labor schedule duration, (3) labor schedule start time, (4) meal and rest breaks, (5) consecutive/non-consecutive days off, (6) labor productivity, (7) number of employees, (8) equipment capacity, (9) labor availability, (10) labor location site, (11) hours per day of operation, (12) schedule planning horizon, or (13) some combination of the above (Bechtold et al., 1991). As is well known, there are two types of constraint. Hard or requirement constraints are those that must be satisfied at all times, while soft constraints are those that can be over-ruled by the person in-charge at a certain cost. In the case of nurse scheduling, the person in-charge is the head nurse. Constraints adopted in nurse scheduling differ from one institution to another. This is usually due to the institution trying to incorporate flexibility in the procedures. For example, duty start time do not have to be fixed. It can vary so as to give flexibility to nurses to plan their duties and family lives. In Burke et al. (2001), the shift duties vary from 6 – 15 compared to traditionally three planned shift duties.

2.4 Overview of early work

Classification systems can be misleading when they do not uniquely describe each approach. To avoid these complications, Sitompul & Randhawa (1990) and Bradley & Martin (1990) suggested that scheduling models be classified by the type of schedule developed (i.e., cyclical and non-cyclical) and also by scheduling technique used (i.e. heuristic and optimization) in earlier literature as shown in Table 2.1. This literature was reported prior to 1990s. The table exhibits the existing classification schema whereby

the names in the table refer to references for these papers. Some scheduling models use more than one techniques for modeling different stages of the problem and thus, can actually be placed in more than one cell of the table. However, the schema chose to highlight the primary methodology used by the authors and brief descriptions of each follows.

As shown in Table 2.1, most of the heuristic models focused on solving the cyclical scheduling problem while optimization models concentrated in non-cyclical scheduling. Details of the subsections can be traced in Sitompul & Randhawa (1990) and Bradley & Martin (1990). Other collective reviews of some of the NSPs can be found in Smith-Daniels et al. (1988), Warner et al. (1990), Siferd & Benton (1992) and Hung (1995).

2.4.1 Cyclical Scheduling

Modeling of NSP with scheduling tools in the early days consisted primarily of graphical devices such as Gantt charts (Jelinek & Kavois, 1992). At that time the cyclical approach of scheduling began to evolve. In cyclical scheduling, the fixed schedule repeats itself within a given time frame which is usually the planning horizon.