OPTIMISATION OF STAFF LEVEL PLANNING AND SCHEDULING FOR NURSING HOMES

LEUNG PO LING

PhD

The Hong Kong Polytechnic University

2021

THE HONG KONG POLYTECHNIC UNIVERSITY

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

Optimisation of Staff Level Planning and Scheduling for Nursing Homes

LEUNG Po Ling

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

June 2020

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

__________________________ (Signed)

LEUNG Po Ling (Name of Student)

ABSTRACT

Personal planning efficiency and effectiveness are regarded as the most critical issues in enhancing the capacity of residential care homes for the elderly. After reviewing the previous studies of staff level planning and scheduling in nursing homes, some deficiencies of the studies were noted. First, the previous studies of staff level planning and scheduling in nursing homes mostly consider a single objective/criterion, such as staff level and staffing cost. In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff level planning and scheduling. Second, the previous studies of staff level planning and scheduling did not consider skill mix, skill substitution and consequence of skill quantitatively in their optimisation models. Third, in the previous studies, staff level planning and scheduling were tackled in two separate phases and in a sequential approach. However, staff level planning and scheduling are highly interrelated and separate consideration of them would result in strategic and operational conflicts.

Accordingly, three main research objectives have been identified and addressed: i) To perform staff level planning of nursing homes' nursing staff using a multi-objective optimisation approach; ii) To perform staff scheduling of nursing homes' nursing staff using a multi-objective optimisation approach.; and iii) To develop a methodology for performing the integrated staff level planning and scheduling problem with the consideration of skill mix, skill substitution and consequence of skill.

To cope with the ever increasing residential care services demand associated with ageing population, managers of residential care places strive to enhance their service capacity by providing good service quality, especially to those fragile ones. However, good personnel planning practice, in literature, is usually defined by i) total staffing cost, ii) total staffing level or iii) total overtime work required. All evaluation criteria have drawbacks. Therefore, this study proposes a multi-objective optimisation model to consider these factors simultaneously.

Skill related concepts are also investigated in this study driven by the practical needs for better nursing staff utilisation and that in real elderly care homes setting. In literature, skill mix, skill substitution and consequence of skill are addressed qualitatively without formally taken into consideration in the planning stage. Thus, personnel planning without considering skill related concepts may cause inaccurate estimation of staffing levels and the associated staffing costs. Therefore, a personnel planning model with skill related concepts is proposed to bridge the research gap.

Ultimately, an integrated staff level planning and scheduling problem for nursing staff in nursing home with regarded to the skill related concepts is oriented in this study.

In literature, rather than integrating decisions in one planning problem, staff level planning and scheduling are often addressed in two consecutive phases in the personnel planning process. Meanwhile, researchers believe that it is much more beneficial to integrate both decisions into one. Staff level planning and scheduling are highly interrelated that traditional distinction between them may result in strategic and operational conflicts. To illustrate the limitations, this study firstly formulates and solve the staff level planning problem and scheduling problem as two distinctive and consecutive phases. Effectiveness of applying optimisation technique to solve the model and limitations of separating the staffing and scheduling decisions are demonstrated with numerical experiments. In this regard, this study deals with the integrated staff level planning problem and scheduling problem (ISLPSP) by firstly decomposing the integrated problem into the staff level planning problem (master problem) and the staff scheduling problem (sub-problem), and solve them in an iterative approach. The algorithm starts with the staff level planning problem because it directly confines the number and the mix of nursing staff required for each shift, and thus affects the total staffing levels and total staffing costs. Solution of staff scheduling will provide feedback for the master problem for further process. Accordingly, a Two-level Non-dominated Sorting Genetic Algorithm-II (TLNSGA-II) for ISLPSP is proposed. A case study of a subvented nursing home in Hong Kong is conducted to illustrate the proposed

model and methodology. Experimental results demonstrate that the proposed model with skill related concepts reduces the total staffing costs while increases staffing levels remarkably.

PUBLICATIONS

Journal Papers (in chronological order)**:**

1. Wu, C.H., **Leung, P.P.L.,** Dong, N., Ho, G.T.S., Kwong, C.K. and Ip, W.H. (2019). Optimization of terminal serviceability based on chaotic GA-based method. *Malaysian Journal of Computer Science*, 32(*1*), 62-82.

2. **Leung, P.P.L.**, Wu, C.H., Kwong, C.K. and Ching, W.K. (2020). Nursing shortage in the public healthcare system: an exploratory study of Hong Kong. *Enterprise Information Systems*, 14(7), 913-931.

3. **Leung, P.P.L**., Wu, C.H., Kwong, C.K., Ip, W.H. & Ching, W.K. (2021). Digitalisation for optimising nursing staff demand modelling and scheduling in nursing homes [Special issue in *Digitalization Adding Value to Healthcare*]. *Technological Forecasting and Social Change*, 164(1): 120512.

4. **Leung, P.P.L.**, Kwong, C.K., Ip, W.H., Ching, W.K., & Wu, C.H. Wu. Nursing staff demand modelling for nursing homes. *Computers and Industrial Engineering* (Under revision).

Conference Papers (in chronological order)**:**

1. **Leung, P.P.L.**, Wu, C.H., Ho, G.T.S., Ip, W.H. and Mou, M.L. (2015). Modelling, analysis and projections: A case study on nursing workforce demand in a local nursing home. In proceedings of *World Conference on Business and Management 2015*. Seoul: People and Global Business Association.

2. **Leung, P.P.L.**, Wu, C.H., Ho, G.T.S., Ip, W.H. and Mou, W.L. (2015). Workforce modelling, analysis and planning: A feasibility study in a local nursing home. *2015 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 6 December 2015, Singapore, 1337-1341.

3. **Leung, P.P.L.**, Ip, W.H., Ching, W.K., Wu, C.H. and Wu, J.W. (2018). Designing remote diagnosis solutions in China. In proceedings of *World Conference on Business and Management*, 27-30 June 2018, Jeju Island, South Korea.

4. **Leung, P.P.L.**, Wu, C.H., Kwong, C.K., Ip, W.H. and Ching, W.K. (2019). Multi-objective optimization for determining nursing staff demand in nursing home. In proceedings of *International Conference on Digital Health and Medical Analytics (DHA2019)*, 23-25 August 2019, Zhengzhou, China.

ACKNOWLEDGEMENTS

Firstly, I would like to express my greatest gratitude and deep appreciation to my supervisors, Dr C.K. Kwong and Dr W.H. Ip. Thank you very much for their guidance and support throughout my PhD study over these six years. With their excellent knowledge in the area of industrial engineering, optimisation and decision support systems, they provided me useful knowledge and inspired me in the area of resources optimisation and nursing management.

In addition, I would also like to express my sincere gratitude to my senior colleagues and research teammates, Dr George T.S. Ho and Dr Jack C.H. Wu. Thank you very much for their time and support all the time. Their immense knowledge on the area of scheduling and metaheuristics supported me over these years.

Last but not least, my thanks go also to all the staff in the Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, for their support and help over these years, especially the lecturers who have taught me when I was in undergraduate and PhD.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CR	Crossover Rate
DCD	Dynamic Crowding Distance
EN	Enrolled Nurse
GA	Genetic Algorithm
HW	Health Worker
ICP	Individual care plan
ISLPSP	Integrated Staff Level Planning and Scheduling Problem
MOEA	Multi-objective Evolutionary Algorithm
MR	Mutation rate
NP	Non-deterministic Polynomial Time
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
PCW	Personal Care Worker
RCHEs	Residential care homes for the elderly
RCSs	Residential care services
RN	Registered Nurse
SGA	Simple Genetic Algorithm
SLPP	Staff Level Planning Problem
SSP	Staff Scheduling Problem

S/N	Signal to Noise ratio
TLNSGA-II	Two Level Non-dominated Sorting Genetic Algorithm-II

Chapter 1 - INTRODUCTION

1.1 Research Background

Advanced healthcare technologies have brought benefits to the ageing society. The population of the elderly aged 65 or above, in almost every developed region is growing at a much faster rate than any other age groups due to the declining fertility rates and longer life expectancy (World Health Organization, 2012). The ageing population is becoming a major concern in Hong Kong. According to the Census Department, the elderly population has risen continuously from 12% in 2001 to 15% in 2014 (Research Office of Legislative Council Secretariat, 2015).

Healthcare is an indispensable component of human welfare in our modern society (Griffiths et al., 2012). Residential care homes for the elderly (RCHEs) worldwide are experiencing challenges due to the severe shortage of nursing staff that is expected to increase in the future (Chang & Cheng, 2013; Feldman, 2001). However, due to the shrinking working population and decelerated economic growth, the Hong Kong public healthcare system and its service capacity are on the verge of saturation, and its health expenditures are growing at a much faster rate than economic growth (Department of Community Medicine and School of Public Health, 2008; Food and Health Bureau, 2008). The demand for subsidised residential care places in Hong Kong is skyrocketing (Social Welfare Department, 2011). Indeed, the thirst for service is not just restricted to the escalating number of patients or the rapidly ageing population, but also due to the ‘increasing complexity of illnesses and [the] variety of procedures’ (Hospital Authority, 2014, p. 93). The growth in the number of patients, compounded by the increasing complexities of illnesses and varieties of procedures, poses a heavy workload on the frontline staff.

As Hong Kong moves steadily to an ageing society, elderly care continuously ranks high on the government’s policy and action agenda. In the face of the challenges brought by the over flowing ageing population, the government has decided to increase the capacity of the healthcare system and enhance its service quality (Hong Kong Special Administrative Region Government, 2014). The government also continues to implement a host of diversified measures and initiatives to enhance elderly care. In particular, the Labour and Welfare Bureau has implemented the initiatives of increasing the provision of subsidised residential care places in the long run (Social Welfare Department, 2011) and improve the utilisation of manpower resources through better personnel planning. Over the years, despite the ever-increasing healthcare expenditures, the service has been in short supply, and cannot meet the projected increasing needs of healthcare services associated with the ageing population. All these impose heavy workloads on the frontline staff of the public healthcare system, resulting in continual manpower shortages and high staff turnover (Hospital Authority, 2011, 2014), especially among nurses in non-governmental organisations and the elderly care industry (Association of Hong Kong Nursing Staff, 2012, 2013; Hospital Authority, 2011, 2014). These problems arise mainly from ineffective and short sighted personnel planning.

The primary resources of RCHEs are healthcare professionals. Thus, one of the possible approaches to increase the capacity of RCHEs is having better personnel planning. Personnel planning exists in various areas, such as nursing staff level determination and nurse rostering (Burke, Li, & Qu, 2010; Parr & Thompson, 2007; Petrovic & Berghe, 2012; Todorovic & Petrovic, 2013), in RCHEs. Efficient and effective personnel planning, particularly with a focus on nursing staff, is essential for RCHEs to enhance their service capacity, provide quality service for all their users at lower operational costs and share the workload of the existing staff (Petrovic and Berghe, 2012).

In practice, efficient personnel planning in a healthcare setting, such as that in RCHEs, is difficult to achieve. RCHEs typically have a very unpredictable demand for irregular services (those services that happen unexpectedly). On one hand, all demands (both for regular and irregular services) can be satisfied by employing many healthcare professionals with high staffing costs and long staff idle times. On the other hand, not all of the demands can be satisfied or they will only be satisfied beyond the time requirement if too few healthcare professionals are employed.

The nursing home sector is a rather unique part of the healthcare industry that has received little attention in the literature. As emphasised by Koeleman, Bhulai and van Meersbergen (2012), '[the majority of] the literature on [personnel planning in areas other than nursing homes, such as] home care personnel planning, is largely deterministic in nature and does not deal with the stochastic nature of the demand and service required that is perceived in practice' (p. 2). Moreover, nursing homes face challenges that other industries do not. Firstly, residents of nursing homes have demands for care and require specific service profiles. Secondly, the residents' needs vary with their changing health status. Hence, sufficient service capacity in terms of manpower is a must so that residents can receive continual care once admitted. These two stochastic features of nursing homes bring further complexity to the nursing staff planning problem in nursing homes, and make many of the modelling and solution techniques complex and difficult to apply.

Although the ageing trend has drawn both academic and political interest for better resource allocation in the healthcare sector, studies concerning nursing staff planning issues in nursing homes are limited. The majority of existing studies have focused on examining the nurse rostering and scheduling, the impact of poor staffing levels, staff assignment models or skill-mixes in hospitals. Nursing homes, which are far different, by nature, from hospitals or clinics, were relatively less considered by researchers in the past. Among the limited researches in nursing staff planning in nursing homes, researchers suggested various factors that might affect planning, such as work shifts, the resident case-mix and skill mix (Bowblis & Lucas, 2012; Ellenbecker, 2004; Flynn & Deatrick, 2003).

1.2 Research Motivation

Given the ageing trend of the population, there is an increasing demand for RCHEs, particularly nursing homes, with various care needs in Hong Kong. Nursing staff planning problem in nursing home has been identified as a significant problem in the research field of healthcare professionals planning. Given the elderly type, the different and changing healthcare needs of the elderly, the expected delivery time outlined by the service plan, the heterogeneous healthcare tasks requiring respective nursing manpower and the multi-skilled nursing manpower, nursing home managers have to carefully review the service capacity and the respective healthcare planning for multiple healthcare tasks performed by each nursing staff within the shift so as to eliminate the possibility of staff overwork and ensure a certain level of service quality.

The service capacity of nursing homes, in general, can be increased by better utilisation of existing manpower resources and devoting additional manpower and monetary resources. The primary resources of nursing homes are nursing staff. Expanding the size of manpower is possible but not preferable, given the global severe shortage of nursing staff and tremendous amount of costs involved. In this regard, accurate planning of staffing levels and better nursing staff scheduling are significant to increase the service capacity of nursing homes.

The existing approach to solve the nursing staff planning problem in the context of nursing home could be an infeasible solution. In addition, considering the complexity of the nursing care needs associated with residents, determining the reasonable and cost effective nursing staff level and assigning capable and suitable mix of nursing staff are critical in establishing residents' care plan. Moreover, the practical guidelines and constraints of assigning and scheduling nursing staff shall be taken into considerations in the optimisation model.

Motivated by a need to enhance the service capacity of nursing homes under the emerging ageing population, developing an efficient optimisation approach that tackles the integrated workforce planning and scheduling problem in the context of nursing homes is desired.

1.3 Research Scope

This study carries out an in-depth study on the integrated staffing level planning and scheduling problem related to nursing staff in nursing homes. In practice, there are tremendous resources allocation and personnel planning decisions involved in a nursing home. In the literature, many studies focused on the individual aspect of personnel planning without simultaneously considering other personnel planning decisions. However, from a practical point of view, there exists significant interactions among personnel planning decisions. Effective and appropriate determination of staffing level acts as a foundation of the subsequent staff scheduling, staff assignment and task assignment optimisation processes. The variation of residents' health status and healthcare service requirements significantly affect the levels and mixes of staff required. Therefore, staffing level planning and scheduling approach need to be flexible and integrated with one another so as to coordinate with the changing incoming healthcare service demands. Among the healthcare professionals in nursing home, the nursing staff who make up the largest proportion of the frontline staff in the public healthcare system and nursing homes (Hospital Authority, 2012, 2014), and perform majority of the healthcare and nursing care services will be the focus of this study.

1.4 Research Aims and Objectives

After reviewing the previous studies of staff level planning and scheduling in nursing homes, some deficiencies of the studies were noted. First, the previous studies of staff level planning and scheduling in nursing homes mostly consider a single objective/criterion, such as staff level and staffing cost. In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff level planning and scheduling. Second, the previous studies of staff level planning and scheduling did not consider skill mix, skill substitution and consequence of skill quantitatively in their optimisation models. Third, in the previous studies, staff level planning and scheduling were tackled in two separate phases and in a sequential approach. However, staff level planning and scheduling are highly interrelated and separate consideration of them would result in strategic and operational conflicts.

This study is in the area of healthcare resources' optimisation. This study aims to improve the efficiency and effectiveness of the staff level planning and scheduling for nursing homes. Accordingly, three research objectives are defined as shown below.

(i) To perform staff level planning of nursing homes' nursing staff using a multi-objective optimisation approach.

(ii) To perform staff scheduling of nursing homes' nursing staff using a multi-objective optimisation approach.

(iii) To develop a methodology for performing the integrated staff level planning and scheduling problem with the consideration of skill mix, skill substitution and consequence of skill.

This study mainly involves three parts. The first part is to study staff level planning and scheduling from a multi-objective optimisation perspective. The second part is to develop a methodology for performing the integrated staff level planning and scheduling with the consideration of skill mix, skill substitution and consequence of skill. The last part is to conduct a case study for evaluating the effectiveness of the proposed methodology for performing the integrated staff level planning and scheduling problem.

The proposed approach and methodology aim to assist medium- to longer-term staff level planning and scheduling for nursing staff in order to enhance both the quality and quantity of healthcare for meeting the changing and growing healthcare needs of the community, while ensuring that the resources available to nursing homes are managed in a cost-effective, wise and transparent manner. Moreover, the proposed approach and methodology will offer nursing staff more flexibility in addressing the manpower shortage, relieving the workload of frontline nursing staff, and strengthening career development.

1.5 Outline of Thesis

This thesis is divided into seven chapters. After a brief introduction of the research background, motivation, scope, problem statements and objectives in Chapter 1, the rest of this thesis is organised as follows. Related works in the field, including the personnel planning in nursing home, critical factors affecting staffing level planning and scheduling in nursing homes, and the corresponding approaches and optimisation algorithm, are reviewed in Chapter 2. Research gaps and opportunities are then discussed. Chapters 3 and 4 present the multi-objective optimisation approach to staff level planning and staff scheduling, respectively. Considering the non-deterministic polynomial-time – complete (NP-complete) and NP-hard nature of the problems, an optimisation technique namely Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is applied. Chapter 5 extends the staff level planning problem and staff scheduling problem studied in Chapter 4 and presents the development of a methodology for integrated staff level planning and scheduling of nursing staff in nursing homes. Chapter 6 presents a case study conducted for evaluating the proposed methodology for performing the integrated staff level planning and scheduling problem. Lastly, Chapter 7 concludes the contribution and limitation of this study. Suggestions for future work in nursing staff planning are also presented.

Chapter 2 - LITERATURE REVIEW

2.1 Introduction

In this chapter, review of research on staffing level planning and scheduling in healthcare industry, critical factors of staffing level planning and scheduling, and approaches to staffing level planning and scheduling are presented. Section 2.2 gives an overview of personnel planning. Section 2.3 reviews existing studies on relationship between nursing shortage, turnover and job dissatisfaction in public healthcare system. Then, Sections 2.4 and 2.5 proceed to reviews existing studies on key factors of nursing staff' job dissatisfaction, and approaches to solve nursing shortage in healthcare industry, respectively. Existing studies on staffing level planning and scheduling in nursing home settings are reviewed in Section 2.6. Various factors affecting staffing level planning and scheduling of nursing staff are then reviewed in Section 2.7. To provide more insights on how the research objectives can be achieved, a review on the heuristics and optimisation techniques applied in staffing level planning and scheduling problem are presented in Section 2.8. Finally, Section 2.9 summarises the research gaps and research opportunities identified.

2.2 Overview of Personnel Planning

As according to Ernst et al. (2004a, p. 5), the personnel planning process can be presented as ‘a number of modules starting with the determination of staffing requirements [staff level planning]’. The personnel planning process they have suggested is a step by step procedure, starting with staff level planning, followed by shift scheduling, days off scheduling, line of work construction, and ends with assigning individual staff members in the workforce to specific work over the planning horizon.

While there may be some flexibility concerning the workplace regulations within a personnel planning context, two staffing decisions usually occur, which are staff level planning and staff scheduling. Staff level planning, sometimes referred as workforce demand modelling or workforce planning in politics and literature, focuses more on strategic decisions than operational ones. It determines the optimal size or mix of a workforce required for the planning horizon within various constraints, especially the budgetary constraint, in order for an organisation to achieve its goals (Ernst et al., 2004b). For example, a staff level planning problem for nursing homes is to determine the number of nursing staff, such as registered nurses and enrolled nurses, required. Staff scheduling, which is usually referred as personnel scheduling and rostering in daily practice, focuses on the operational decisions that schedules staff (Li & King, 1999) and constructs ‘optimized work timetables for staff’, according to Ernst et al. (2004b, p. 1). Personnel planning problem today is far different from before. Personnel planning nowadays considers not only cost cutting, but also satisfying employees’ needs (Komarudin et al., 2013).

Also, enterprises are offering more flexible working hours and part-time contracts, and are taking into account employee preferences when creating schedules (Ernst et al., 2004; Komarudin et al., 2013).

Being the most expensive cost component in an organisation (Jorn et al., 2013; Li & Li, 2000; Zulch, Rottinger & Vollstedt, 2004) and the most flexible factor for most of the industries, such as airlines (Petrovic & Berghe, 2007), call centers (Aksin, Armony & Mehrotra, 2007) and healthcare (Burke & Petrovic, 2004; Ernst et al., 2004a, 2004b), human resources is an important factor contributing to long-term competitiveness of organisations (Zulch et al., 2004). In particular, personnel planning is a major concern for organisation facing dilemma in balancing resources, quality, productivity and time. Personnel planning is a fundamental and important part of an organisation's strategic and human resources planning processes (Ernst et al., 2004a, 2004b; Jorn et al., 2013; Zulch et al., 2004). Implementing an effective personnel plan has proven to be beneficial in reducing labour cost without sacrificing quality of care within specific time period (Erhard et al., 2018; Ernst et al., 2004a; Koeleman et al., 2012; Komarudina et al., 2013; Li & Li, 2000; Nickel, Schroder & Steeg, 2012).

Over the years, a stream of research has focused on building more cost effective staff level plan and more efficient staff schedules for healthcare professionals. For example, patient scheduling in a therapeutic clinic (Bourque, 1980), nurse and doctor scheduling in hospitals (Parr & Thompson, 2007), and physician scheduling (Erhard et al., 2018). There is also a stream of research focused on effective and efficient scheduling of healthcare resources and activities. For example, Burdett & Kozan (2018) proposed a flexible job-shop scheduling model for scheduling and rescheduling healthcare activities of an entire hospital in one integrated approach. Spratt and Kozan (2016) addressed the master surgical scheduling problem and the surgical case assignment problem in Australian public hospitals.

In fact, automated scheduling has drawn interest from the healthcare community since 1970s, particularly in nurse scheduling (Miller, Pierskalla & Rath, 1976). This interest, nurse and doctor scheduling and rostering in hospitals, has continued into recent decades (Burke et al., 2010; Parr & Thompson, 2010; Todorovic & Petrovic, 2013; Zanda et al., 2018). Zanda et al. (2018) proposed a long term nurse scheduling approach based on linear integer programming. Focus on the nurse scheduling problem in a department of a hospital, the long term scheduling problem of the shifts of a team of nurses is considered. The model deals with multi-objective while satisfying a series of constraints imposed by the contractual rules of nurses and that aims to guarantee comfortable working conditions to them. Furthermore, modelling of service demand and personnel planning problem have been conducted in different healthcare settings, such as in medical centers (Punnakitikashem, Rosenberger & Behan, 2008) and home care companies (Braekers et al., 2016; Fathollahi-Fard et al., 2018; Hiermann et al., 2015; Mankowska, Meisel & Bierwirth, 2014; Shi et al., 2017, 2018).

While there are different researches that have formulated mathematical models for medical/nursing staff staffing or scheduling problems at different organisational levels, research integrating staffing and scheduling decisions is much scarcer and only a few studied their interaction (Maenhout & Vanhoucke, 2013; Marchesi et al., 2020). Researchers highlighted that 'when staffing and scheduling are performed separately, the scheduling phase may become infeasible, since service requirements and contractual agreements may render impractical finding a scheduling that meets the established staffing levels', according to Marchesi et al. (2020).

Among the limited research studying the staff level planning and scheduling in an integrated manner, Maenhout and Vanhoucke (2013) presented a branch-and-price-based methodology to solve an integrated nurse staffing and scheduling problem. Results indicate that staffing multiple nursing departments simultaneously and integrating nurse characteristics (i.e. skill category of nurse) into the integrated staffing decision lead to significant improvements in schedule quality in terms of cost, staff' job satisfaction, and effectiveness in providing high-quality care. Kim and Mehrotra (2015) presented a two-stage stochastic integer program for integrated nurse staffing and scheduling. In the first stage, decisions regarding initial staffing levels and schedules are made to minimize overall labour costs. In the second stage, the initial schedules are adjusted at a time closer to the actual date of implementation. Results show that when compared with a deterministic model, the two-stage stochastic model leads to significant cost savings. Volland et al. (2017) presented a mixed-integer program and a column generation based solution approach for the integrated shift and task scheduling problem of logistics assistants in hospitals. Results show that flexibility in shift and task scheduling contributes to significant decrease of the required workforce. Marchesi et al. (2020) presented a two-stage stochastic programming model with fixed resources that solve the physician staffing and scheduling problems in the Emergency Department in an integrated manner

Despite the increasing life expectancy and nursing care demand in developed regions, the supply of hospitals and residential care homes for the elderly have not been grown at the same rate. In addition, many elderly people prefer to grow old in the privacy of their homes rather than in an elderly home (Braekers et al., 2016). Accordingly, the demand for home health care services is growing significantly (Fathollahi-Fard et al., 2018; Fikar & Hirsch, 2017). These give rise to the rapid development of home health care companies in western countries such as France and Germany (Golden et al., 2008; Mankowska et al., 2014; Shi et al., 2017), and contributed to an increasing number of publications dealing with the home health care routing and scheduling problem in the recent years (Braekers et al., 2016). In the recent five years, the vehicle routing and scheduling problem in home health care companies has become one of the most explored sectors in healthcare resources planning (Shi et al., 2018). Home health care routing and scheduling problems can be regarded as a special case of the skilled vehicle routing and scheduling problem, and of the resource constrained routing and scheduling problem (Paraskevopoulos et al., 2017). Specifically, home health care routing and scheduling problem involve the assignment and scheduling of skilled workforce, such as nurses, to customers' location for the execution of healthcare tasks within specific time frame (Fikar & Hirsch, 2017). Not only multi-period in nature, the home health care routing and scheduling problem also involves service requirements of customers, skill requirement of tasks, heterogeneous resources, cost and other considerations (Paraskevopoulos et al., 2017). Fikar and Hirsch (2017) reviewed the current work in the field of home health care routing and scheduling with a focus on problem settings considered, such as single-period and multi-period problems. Their review highlighted that the research field of home healthcare is highly heterogeneous in terms of the objectives studied, and the settings considered.

Lanzarone and Matta (2014) derived an analytical structural policy to deal with the nurse-to-patient assignment problem in the home healthcare context, taking into account the stochasticity of new patient's demand and workload of nurses. Hiermann et al. (2015) solved a real-life home care scheduling problem of an Austrian home health care provider. Their model considers various constraints, such as time windows and patient satisfaction levels, as penalty terms in the objective function. Four metaheuristic algorithms were applied to solve and improve the quality of solutions. Issaoui et al. (2015) addressed a bi-objective home healthcare problem, with the objectives of minimising the distance travelled by nurse and maximising patient satisfaction. A three-phase metaheuristic is proposed to solve the problem. Braekers et al. (2016) formulated the home care routing and scheduling problem as a bi-objective optimisation problem, aiming at minimising total costs while minimising client inconvenience. A neighbourhood search heuristic based metaheuristic algorithm is proposed to solve the problem. Chen, Thomas, and Hewitt (2016) studied the multi-period technician routing problem with experience-based service times. In their model, the learning effect is taken into consideration that technicians can learn from experience and increase their productivity by decreasing service time. The objective is to minimise the total daily makespan over a finite horizon. Chen et al. (2017) further extends the multi-period technician scheduling problem with experience-based service times and stochastic customers, wherein the tasks to perform are unknown until the day they are to be performed. A Markov decision process model was formulated for the problem and an approximate dynamic programming-based solution approach was applied to solve the model. Shi et al. (2017) formulated a fuzzy chance constraint model for the home healthcare routing problem with time window and fuzzy demand. Their model aims to optimise the cost of transportation. A hybrid genetic algorithm integrated with stochastic simulation methods was proposed to solve the proposed model. Shi et al. (2018) considered a home health care routing problem with stochastic travel and service times and proposed a Stochastic Programming model with Recourse (SPR model). Fathollahi-Fard et al. (2018) formulated a bi-objective optimisation model and developed four fast heuristics to deal with the green home health care routing problem taking into consideration the environmental pollution.

2.3 Relationship between Nursing Shortage, Turnover and Job Dissatisfaction in Public Healthcare System

Nursing shortage in the public healthcare system is mainly due to the undersupply of nursing staff resulting from the reformation of nursing education (Au, 2009), the increased intention to leave nursing profession caused by the encouragement of early retirement of senior and experienced staff (Baumann, 2006), and the high turnover rate (Food and Health Bureau & Hospital Authority, 2011).

According to Chikanda (2005) and Hayes et al. (2006), turnover among nursing staff is defined as the withdrawal of nursing staff from an organisation, and includes those who move to other organisation. Studies summarised that it is costly to have a high nursing staff turnover which also has negative impacts for both nursing staff and patient outcomes, such as lowered services quality, increased administrative work, and weakened physical and mental wellness of patients (Hayes et al., 2006). With such economic and other negative impacts due to nursing staff turnover, concerns have been expressed globally for sustainable solutions (Hayes et al., 2006). Hence, further research can study the key factors contributing to turnover of nursing staff so as to reduce the occurrence of negative impacts.

The tendency of nursing staff to withdraw from their jobs is positively related to their job dissatisfaction (AbuAlRub et al., 2009; Cai & Zhou, 2009; Chen et al., 2008; El-Jardali et al., 2009; Flinkman et al., 2008; Hayes et al., 2002; Mrayyan, 2005; Shields & Ward, 2001; Tzeng, 2002; Zeytinoglu et al., 2007). The model of job satisfaction focuses on an individual's feelings towards his/her job (Lu et al., 2005). From the survey data of the British National Health Service (NHS), job dissatisfaction was found to be the most important determinant of the intention to leave among NHS nursing staff (Shields & Ward, 2001).

2.4 Key Factors of Nursing Staff' Job Dissatisfaction

Job dissatisfaction, in general, is determined by workload stress, and pay and benefits.

Workload is claimed as the major stressor in most public healthcare systems, as well as in the Hong Kong public healthcare system (Chan et al., 2013; Chen et al., 2008; Jourdain & Chenevert, 2010; Sellgren et al., 2009; Zeytinoglu et al., 2007). According to a longitudinal study of turnover factors, it was found that workload is highly associated with the intention to leave, and a significant predictor for actual turnover of Chinese nursing staff (Chen et al., 2008). In the case of the Hong Kong public healthcare system, a poor nurse-to-patient ratio of 1:16 can be an indicator of inadequate staffing, which places a burden on the nursing staff in managing patient care needs. Under inadequate manpower, junior nursing staff are required to take up the jobs of senior nursing staff or tasks that they are not familiar with, which further mounts pressure on junior nursing staff.

In the aspect of job dissatisfaction among nursing staff in Hong Kong, pay and benefits were reported as the main reasons for moving from the public to private healthcare system (Chan et al., 2012), which is consistent with the research outcomes by Reeves et al. (2005). In an empirical investigation in Taiwan, the results indicated that satisfaction with pay was a significant predictor of nursing staff intention to leave (Tzeng, 2002). Further, nursing staff stated that the inequitable pay and benefit between the public and private healthcare system is one of the motivations for them to leave the public for the private sector. Leaving nursing staff pointed out that they would prefer to work in public hospitals to private hospitals if the salaries of public and private ones were equitable (Chan et al., 2012).

Apart from the key factors discussed above, studies have examined other detrimental factors contributing to nursing staff' intention to leave nursing profession or to the intention to leave their current workplace. Those factors can be categorised as organisational variables, individual variables and economical variables. These variables include work schedules (Flinkman et al., 2008; Tzeng, 2002), opportunity for advancement/ promotion (Flinkman et al., 2008; Hayes et al., 2012), organisational commitment (Hayes et al., 2012; Liou & Cheng, 2010), empowerment and autonomy (Cai & Zhou, 2009), and management style/supervisor (AbuAlRub et al., 2009; Chen et al., 2008; Hayes et al., 2012; Sellgren et al., 2009).

2.5 Approaches of Solving Nursing Shortage in Healthcare Industry

According to Buchan (2004), there is no single way that one can solve nursing shortages in healthcare industry. It is necessary to consider whether the personnel planning is contingent upon the context, characteristics and also priorities of the particular organisation involved. To achieve continued improvements in organisational performance, personnel planning is important. Commonly, identifying the best ways based on dealing with nursing shortage is one issue; however, translating them into sustained personnel planning is another issue.

Approaches for solving nursing shortages include addressing either or both the supply and demand sides (Buchan & Aiken, 2006). Examples of approaches addressing the supply side issues include attracting people, retaining people (Aiken et al., 2008) and motivating people (Aiken et al., 2008; Buchan, 2006). Studies show that nursing staff are interested to work and remain in work due to gaining autonomy, participating in decision making, as well as being fairly rewarded (Buchan, 2006). Organisational factors, such as a de-centralised style of management and flexible employment terms, can be crucial for increasing nursing staff retention (Aiken et al., 2008).

For tackling the demand side challenges, it is important to enable nursing staff to utilise their skills and expertise effectively. For sustainable solutions, policy interventions like enhancing and aligning manpower capacity with workload is important (Buchan, 2004, 2006). Flexibility in terms of working patterns should also be given to nursing staff for maintaining a work-life balance (Buchan, 2006).

In the recent years, there is a new stream of research utilising latest technology to complement the nursing shortage and to lessen the workloads of nursing staff in nursing homes (Kuramoto et al., 2016; Shi et al., 2019; T’Jonck et al., 2019). Chen et al. (2016) developed a ZigBee hased wireless monitoring system for night off-bed detection and bathroom accident monitoring. Khera et al. (2016) developed an Android based wireless smart home and nurse calling system to assist the differently abled. Kuramoto et al. (2016) developed a smartphone-based wearable technology that can monitoring swallowing of elderly in real-time to enhance safety of eating in nursing homes. Mendoza et al. (2017) developed a wearable tracking system for patients with Alzheimer’s disease, who are unable to respond to their environment and demand extensive monitoring. Instead of an external wearable device, Ansefine et al. (2017) and Fong et al. (2018) proposed the use of smart clothing for elderly monitoring in nursing home. Ansefine et al. (2017) proposed a smart wearable technology in the form of a wristband for monitoring health conditions and movement information of the elderly in a nursing house. Fong et al. (2018) proposed the use of active low-power transceivers embedded in smart clothing for the dynamic short-range tracking of residents of a nursing home. Fook et al. (2018) proposed a Fiber Bragg Grating (FBG)-based monitoring and alert system to monitor vital signs of residents in nursing homes and alert staff whenever necessary. T’Jonck et al. (2019) proposed a sensor system attaching to the bed for monitoring and detecting incontinence events.

2.6 Staff Level Planning and Scheduling in Nursing Homes

Over the recent decades, demand of local subsidised nursing home places has experienced substantial increase. As population rapidly ageing, further and significant increase in the demand has been predicted. Meanwhile, nursing home managers always encounter dilemma in balancing manpower resources, service quality, staff productivity and staff workload during personnel planning. These give rise to the interest of better staff level planning, scheduling and nursing home management in practice.

While staffing and scheduling medical staff in hospitals has been widely studied, the literature on staffing and scheduling medical/nursing staff in nursing home is much scarcer. Nursing home, which provides residential and nursing care services for the frail elderly, is far distinct from hospital and clinic in nature and is a rather unique part of the healthcare industry. As emphasised by Koeleman et al. (2012), '[the majority of] the literature on [personnel planning in areas other than nursing homes, such as] home care personnel planning, is largely deterministic in nature and does not deal with the stochastic nature of the demand and service required that is perceived in practice' (p. 2). Moreover, nursing homes face challenges that the other industries do not. Firstly, residents of nursing homes demands for care and require specific service profiles. Secondly, the residents' needs vary with their changing health status. Hence, sufficient service capacity in terms of manpower is a must so that residents can receive continual care once admitted. These two stochastic features of nursing homes bring further complexity to the personnel planning of nursing staff in nursing homes, and make many of the modelling and solution techniques complex and difficult to apply.

An increasing amount of papers have been published dealing with personnel planning related issues in nursing homes since 2000s. The majority of existing studies have focused on examining the nurse rostering and scheduling, impact of poor staffing levels or staff assignment models. Researchers believed that 'mathematical driven staffing approaches can greatly support nursing homes in their search for ways to further reduce their costs while maintaining an appropriate quality level of care,' according to Bekker et al. (2019). Examples of recent research including nurse rostering conducted by Burke, Li, and Qu (2010), Parr and Thompson (2007), Petrovic and Berghe (2012) and Todorovic and Petrovic (2013); staff level planning of care workers conducted by Moeke, Koole and Verkooijen (2014); and staff assignment conducted by Rahman, Straker and Manning (2009). Bekker et al. (2019) formulated a Mixed-Integer Linear Programming model to determine the appropriate capacity level of nursing home across the day, such that waiting times of patients are minimized. Instead of constructing actual workforce plain or staff schedule, their model considers only capacity planning and neglect the assignment of qualified care workers to tasks.

2.7 Considerations Involved in Personnel Planning in Nursing Homes

Researchers have addresses the difficulties of determining appropriate nurse staffing levels, such as restrictions due to budget constraints and nursing shortages (American Nurses Association, 2010a, 2010b; Hodge et al., 2004). Although some researchers suggested various factors that affect staff level planning and scheduling in nursing homes, such as the workload of staff, staffing levels and the skill mix (Bowblis & Lucas, 2012; Ellenbecker, 2004; Flynn & Deatrick, 2003), existing mechanisms and approaches proposed by researchers always ignore those critical factors. In this section, the commonly studied critical factors of staff level planning and scheduling of nursing staff are reviewed and insights obtained are summarised.

2.7.1 Work shift

In healthcare organisations, where all-day-round nursing and medical cares are needed, the issue of work shift emerges. Nursing homes, where residents generally require staff assistance to complete many daily activities and all-day-round nursing and medical cares are needed, raise both research and operational interest.

Work schedules and shift pattern is highly related to staff and patient outcomes. Work schedules, especially those involving long work hours (e.g. 12h shifts), can lead to nurse fatigue (Querstret et al., 2020). In addition, research suggests that schedules without sufficient time off between shifts are associated with increased medication errors (Rogers, 2008) and patient mortality (Trinkoffet al., 2011). Previous research suggested that turnover is significantly lower for morning shifts than evening shifts (Helmer, Olson & Heim, 1993; Waxman, Carner, & Berkenstock, 1984) while the majority of studies examined the effect of work shifts together with other confounding factors, yielding mixed results.

In response to the potential benefits and harms of work shifts to both residents and staff, Burgio et al. (2004) examined the isolated and combined effects of work shifts (i.e. day and evening shifts), in addition to the isolated effects of the type of staff assignment model (i.e. consistent assignment and rotating assignment) on various quality-of-care indicators by direct observations. Significant statistical differences were found between groups of residents in nursing homes with different staff assignment models and shifts (i.e. staff assignment × shift interaction effect) concerning both staff and resident outcomes, such as amount of staff burnout, and staff turnover rates, etc. As anticipated, morning shifts had considerably lower turnover rates and less resident disorderly behaviour.

2.7.2 Staff task flexibility

The staff level planning and scheduling problem in the healthcare industry has many characteristics, such as non-inventoriable services and time-varying demand, which makes it far more distinct from traditional ones in manufacturing or other service industries (Li & King, 1999).

In order for the nursing home to meet the peak demand, some researchers have employed a floating nurse pool or, more recently, by increasing staff flexibility through on-the-job training (Leshner & Browne, 1993; Lyons, 1992). In spite of the importance of staff task flexibility, research with the consideration of staff flexibility in the healthcare field is scarce.

Brusco, Johns, and Reed (1998) examined the effects of cross-training in service organisations and discussed the benefits of full-scale cross-training. However, the full-scale training creates a homogeneous workforce which cannot be used in healthcare organisations. Most important, registered or qualified staff must perform certain tasks that cannot be substituted simply through on-the-job training in healthcare sector. Ozkarahan and Bailey (1988) developed a staff scheduling model that considered nursing staff shift scheduling flexibility. Their model, though being able to satisfy both the hospital and nurses' desired schedules, did not consider staff task flexibility and was only at the staff scheduling level. Li and King (1999) have examined the effects of staff cross-training on staff task flexibility and staff level planning for a clinic. Unlike Brusco et al. (1998), their work has taken into consideration the legal requirement of labour skills for job substitution. The staff planning model they proposed tried to balance the cost and benefits of staff task flexibility through cross-training.

The details of skill related concepts will be discussed in the next section.

2.7.3 Skill

Staff level planning problem and scheduling problems are known to be very difficult to solve, and the difficulties further increase when skills are incorporated in the problems. De Bruecker et al. (2015) conducted a review on the staff level planning problem incorporating skills, and pointed out the importance of combining sound technical methodologies and real life implications for the model to perform well in management.

Staff level planning incorporating skills can be categorised into the managerial aspects and technical aspects. From the managerial points of view, defining different skill types and analysing the impact of different skill types are important.

In theory, when staff is allowed to perform the tasks of other staff, flexibility of workforce increases. In reality, this can happen in a nursing home when nursing staff with a certain nurse grade is allowed to perform tasks that are normally assigned to staff with a lower nurse grade. This is referred as 'substitution of hierarchical skills' according to De Bruecker et al. (2015, p.5).

Further to flexibility, there are also other consequences of skill. De Bruecker et al. (2015) identified five main elements that can be affected by the skills and/or skill level of a staff: the labour costs, the speed of work, the quality of work, the tasks that a staff can perform (task restriction), and the resulting flexibility.

Despite the consequences of skills perceived in reality, most of the previous studies failed to consider consequences of skills quantitatively in their models. For example, previous studies either failed to incorporate the higher labour costs resulting from higher skilled staff (Lagodimos & Mihiotis, 2006), or made unreasonable assumption that assuming temporary staff have less skills than the regular staff and therefore requiring lower labour costs (Carlos, Sanchez & Martorell, 2011; Corominas, Lusa & Olivella, 2012).

2.7.4 Skill Mix

Mixes of nursing staff in a nursing home, in a hospital, in a hospital unit or on a hospital ward can be expressed in terms of the skill mix (Butler et al., 2011). Skill mix, which is sometimes used interchangeably with staff mix and hereafter referred as skill mix for simplicity, is a broadly-used concept that varies within and across countries. For example, skill mix refers to the mix of ‘licensed’ and ‘unlicensed’ nursing staff in United States (Kane et al., 2007); ‘registered’ and ‘unregistered’ nursing staff in Australia and United Kingdom, and even ‘the proportion of different nursing grades, and levels of qualification, expertise and experience’ in other countries, according to Ayre et al. (2007, p. 56).

It has been argued that nursing skill mix is directly linked to quality of care, cost effectiveness and staff workload. Currie et al. (2005) found that there is an association between a lower proportion of registered nursing staff in the nursing workforce and an increased patient length of stay, incidence of hospital acquired infections, and prevalence of pressure ulcers. Mitchell et al. (2018) conducted a systematic review to understand and synthesize the relationship between hospital staffing and health care-associated infections. They concluded in their paper that in spite of the lack of consistency of the prior studies, the overall results demonstrate that increased hospital staffing, either or both of nurse-to-patient ratio, skill mix or nursing hours per patient-day of nurse staffing and non-nurse staffing, is related to decreased risk of acquiring health care-associated infections. Some of the other researchers found skill mix in forms of mixing registered and unregistered nursing staff significant in improving cost effectiveness and quality, but others claimed that there were decreases in the care quality, heavier workload for registered nursing staff, and higher absenteeism and turnover (Buchan & Calman, 2006).

Despite the potential importance of skill mix and the debates in evidence for positive outcomes, most of the existing studies focus on identifying and examining the impact of poor staff levels or skill mixes, rather than providing sufficient practical guidance (Flynn & McKeown, 2009; Masterson, 2004).

2.7.5 Nurse-to-patient ratio

Nurse-to-patient ratio, refers to the minimum, specific and guaranteed nursing staff staffing ratio (De Bruecker et al., 2015). Shin et al. (2020) reviewed, compared and analysed the expected nurse-to-patient ratio, the actual number of patients for each work shift per nurse, penalties for violating these regulations, and the laws enacted. They highlighted that nurse staffing should be based on the actual number of patients for each work shift per nurse, i.e. nurse-to-patient ratio instead of beds-per-nurse ratio.

Issues related to mandatory nurse-to-patient ratio are widely controversial (Douglas, 2010). Supporters believe that regulating nursing staff level and ratio can increase positive patient and staff outcomes, such as decreasing intention to leave, decreasing nursing shortages, decreasing staff turnover rates, and increasing nursing staff recruitment as well as job satisfaction (Aiken, Clark & Sloane, 2002; Dall et al., 2009; Kane et al., 2007; Shin et al., 2020; Unruh, 2008).

A considerable amount of study has associated increased nursing staff level with an increase in patient safety, quality of care, and patient satisfaction (Aiken et al., 2002; Dall et al., 2009; Kane et al., 2007), as well as a decrease in patient length of stay, staff burnout and turnover (Douglas, 2010). Hodge and his colleagues (2004) found that better nurse staffing leads to better patient care quality, such as decrease in hospitalisation.

However, the premise behind the positive outcomes of mandatory nurse-to-patient ratio has not been proven (DeVandry & Cooper, 2009). The American Nurses Association (ANA) opposed to mandatory nurse-to-patient ratio and addressed that the determination of appropriate nurse staff levels is problematic due to budget constraint, nursing shortages, and apparent lack of data to guide and make adequate staffing decisions (American Nurses Association, 2010a; Rajecki, 2009). They acknowledged that mandatory nurse-to-patient ratio do not consider many critical factors, such as patient acuity. Implementing legislation with a single focus does not empower nursing staff to use their expertise for best patient outcomes (American Nurses Association, 2010b; DeVandry & Cooper, 2009). Instead, the American Nurses Association supports legislation with recommended guidelines for establishing nursing staff ratios and levels based on critical factors.

The mixed opinions towards mandatory nurse-to-patient ratio, indeed, refers to the concerns which researchers located and recommended further study. Firstly, there is no empirical evidence supporting the specific number of patients assigned to each staff through mandatory ratio with better patient outcomes (Hodge et al., 2004). Passing legislation without sufficient evidence is potentially dangerous to any stakeholders involved. Another major concern with mandatory nurse-to-patient ratio is ignorance of critical factors, such as nurse education, skills, knowledge, and years of experience. For example, in California Assembly Bill 394, which mandates minimum, specific and numerical nurse-to-patient ratio in hospitals, only 50% of the mandated nurses must be registered nurses with the implication of minimal differentiation between licensed professional nurses and registered nurses (Chapman, 2009). Finally, mandatory ratio is inflexible and do not allow for the dynamic changing patient needs (Douglas, 2010).

2.8 Heuristics and Optimisation Techniques

Staff level planning problem and scheduling problem, in general, are very difficult to solve. Different variation of the problems and their sub-problems have been proved by various researchers for their NP-hardness and NP-completeness (Bartholdi, 1981; Di Gaspero et al., 2007; Lau, 1996; Lee & Vairaktarakis, 1997; Vairaktarakisa, Cai & Lee, 2002). Even for a simplified staff level planning problem containing only a single criterion and homogenous skill (Cai & Li, 2000; De Bruecker et al., 2015), the problem is still very difficult to solve.

The integrated staff level planning and scheduling problem becomes even more difficult to solve when multiple criteria and mixed skills are considered. When multiple skills are incorporated into integrated planning, a heterogeneous workforce is resulted and remove the symmetry. The absence of symmetry eliminates the possible speed up in computation time. In practice, it is sometimes more important to get a sensible feasible solution quickly than to obtain an optimal or near optimal solution with a great deal of computational effort. Thus, management in reality prefer a fast and good solution to the optimal solution and these give rise to the heuristics solution methods and evolutionary optimisation techniques instead of exact approaches. Literature concerning four commonly used heuristics and optimisation techniques, including Constructive Heuristic, Simulated Annealing, Tabu Search, Genetic Algorithm (GA), and Non-dominated Sorting Genetic

Algorithm-II (NSGA-II) are reviewed.

Constructive Heuristic refers to the group of simple but fast heuristic algorithms providing feasible solutions to the problem (Ernst et al., 2004a, 2004b). As refer to Ernst et al. (2004a, 2004b), manual solutions for scheduling and rostering can be categorised as Constructive Heuristic. Feasible solutions from Constructive Heuristic often offers a good starting point for obtaining better solutions when other algorithms are used in the later stages.

Simulated Annealing and Tabu Search are two popular meta-heuristic algorithms. Simulated Annealing attempts to find global optimal solutions by employing complicated moving strategies (Ernst et al., 2004a, 2004b). Examples of application of Simulated Annealing include highly nonlinear models (Busetti, 2003), financial instruments (Busetti, 2003), and complex portfolio selection model, (Busetti, 2003) For Tabu Search, being trapped in cyclic moves is avoided by maintaining the recent solution regions in a dynamically updated Tabu list and forbidding or penalising moves in the Tabu list (Ernst et al., 2004a). Tabu Search has been applied to solve frequency assignment problem (Montemanni, Moon & Smith, 2003) and course timetabling problem (Lu & Hao, 2010).

GA is a special meta-heuristic algorithm under the umbrella of evolutionary algorithm. It is firstly proposed by John Holland in 1970s (Holland, 1975) and is based on the mechanics of evolution and natural genetics (Srinivas & Patnaik, 1994). Through the natural search and selection, only the fittest individuals can survive and reproduce and this phenomenon is usually referred to as 'survival of the fittest'. It can yield near optimal or even optimal solution (Huang et al., 2014), improve the search process (Kim, Abraham & Cho, 2007), and is applicable to solve problems that are non-linear (Marczyk, 2004) It is applied widely for solving scheduling problems in healthcare system (Ernst et al., 2004a, 2004b), such as nurse rostering (Huang et al., 2014) and nurse scheduling (Landa-silva & Le, 2008). The application of GA has demonstrated effective and satisfactory performance in cost minimisation (Huang et al., 2014) and overall nurses' satisfaction maximisation (Landa-silva & Le, 2008).

NSGA-II is a multi-objective evolutionary algorithm proposed by Deb et al. (2002), which is an improved version of NSGA. NSGA-II addresses all issues of NSGA, including high computational complexity of non-dominated sorting, lack of elitism and the need for specifying a sharing parameter (Deb et al., 2002). NSGA-II uses a fast non-dominated sorting approach and crowding distance to assign ranks to individuals in the population (Roshan, Seifarghy & Pishva, 2017). NSGA-II has been one of the 'widely applied evolutionary algorithms to the design and optimisation of multi-objective problems' (Xu et al., 2015). Previous studies showed that NSGA-II outperforms other common multi-objective optimisation algorithms, such as strength-Pareto evolutionary algorithm (Zitzler, 1999), in terms of the spread of solutions and convergence near the true Pareto-optimal front.

NSGA-II is considered a promising method for multi-objective optimisation problems and has been applied successfully to solve scheduling problem.

It is found that constructive heuristic can usually act as good starting point for obtaining better solutions for scheduling and rostering. It may also provide a good starting point for obtaining a solution to the integrated staff level planning and scheduling problem. NSGA-II may be used together with constructive heuristic to solve the non-linear, multi-objective, integrated staff level planning and scheduling problem of nursing staff in nursing home, so as to improve the search process and generate near optimal or even optimal solution to the model to be proposed.

2.9 Summary and Discussion

This chapter has reviewed previous studies in personnel planning problem in healthcare industry, relationship between nursing shortage, turnover and job dissatisfaction in public healthcare system, key factors of nursing staff' job dissatisfaction, approaches of solving nursing shortage in healthcare industry, personnel planning in nursing home settings, considerations involved in personnel planning in nursing homes, heuristics and optimisation techniques. Staff level planning and staff scheduling are difficult and time consuming problems. Different variation of the problems, and even their sub-problems, are NP-hard and NP-complete (Di Gaspero et al., 2007; Lau, 1996; Lee & Vairaktarakis, 1997; Vairaktarakisa, Cai & Lee, 2002). After reviewing the previous studies of staff level planning and scheduling in nursing homes, some deficiencies of the studies were noted.

First, the previous studies of staff level planning and scheduling in nursing homes mostly consider a single objective/criterion such as staff level and staffing cost (Flynn & McKeown, 2009). In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff level planning and scheduling. Second, the previous studies of staff level planning and scheduling did not consider skill mix, skill substitution and consequence of skill quantitatively in their optimisation models. Third, in the previous studies, staff level planning and scheduling were tackled in two separate phases and in a sequential approach. However, staff level planning and scheduling are highly interrelated and separate consideration of them would result in strategic and operational conflicts (Maenhout & Vanhoucke, 2013; Savage et al., 2015, Vile et al., 2016; Marchesi et al., 2020).

To address the deficiencies of the previous studies, in this study, three major research tasks are proposed. The first research task is to perform staff level planning using a multi-objective optimisation approach. The second research task is to perform staff scheduling using a multi-objective optimisation approach. The third research task is to develop a methodology for performing the integrated staff level planning and scheduling problem with the consideration of skill mix, skill substitution and consequence of skill. Details of the first and second research tasks are described in Chapters 3 and 4, respectively, while the development of a methodology for performing the integrated staff level planning and scheduling problem is described in Chapter 5.

An integrated staff level planning and scheduling model is proposed in Chapter 5. The proposed integrated model takes into consideration essential factors and essential constraints informed by literature. Essential factors, including work shift, resident case-mix, multi-skilled workforce and a heterogeneous workforce, and essential constraints, including service requirement, working hours, rest periods, day off, split shift and overtime work, are considered in both objective functions and constraints. Further, three factors commonly ignored in previous studies of staff level planning and scheduling in nursing homes, including skill mix, skill substitution and consequence of skill, are considered quantitatively in the proposed model.

The integrated model offers an alternative approach to solve the staff level planning and scheduling problem from an integrated and simultaneous perspective.

Typically, the staff level planning and scheduling problems are seen as a multi-phase sequential planning and control process that the decisions made in each phase of this hierarchical process constrain subsequent phases. The staffing decisions restrict shift scheduling decision alternatives. The proposed model, when being solved by the proposed Two Level NSGA-II Approach, avoids the type of sub optimality that may arise in the two-step approach, as it determines staffing requirements and shift schedules simultaneously. In that sense, it is superior to the existing distinct models and two-step models.

When comparing with the limited integrated models of staff level planning and scheduling in existing literature, the proposed integrated model and the proposed Two Level NSGA-II Approach outperforms in terms of practicality. Maenhout and Vanhoucke (2013) applied a branch-and-price procedure to allocate a given workforce over multiple departments based on the hospital's nurse staffing policies, each ward's shift scheduling policies and the nurses' characteristics. Their model is able to balance, over several months, the workforce costs and the coverage of patients in multiple hospital departments. Nevertheless, the multiple objectives are handled by the use of weighted sum method, which requires the determination of weights and the quality of the solution relies on the weights. Kim and Mehrotra (2015) proposed an integer L-shaped algorithm with a prioritized branching strategy to study the integrated staffing and scheduling in two stages. Though their model is able to deal with short-term uncertainties at a time epoch closer to the actual date of demand realisation, their model is of little practicality that they assume work patterns are repeated on a weekly basis and that all possible weekly patterns are generated in advance. Similarly, the work presented by Jiang, Hyer and Kong (2020) are of limited practicality that they assume that work patterns repeat and scheduling patterns pre-exist.

The integrated model proposed in this study is highly practicable that, 1) it supports both staff level planning and scheduling decision making in an iterative approach, without the need of specifying all possible scheduling patterns or assuming work patterns repeat; 2) it allows decision makers to choose optimal solutions according to particular interest and free decision makers from determining the weights of different objectives; and 3) it is able to capture most of the strategic and operational constraints as anticipated in reality.

Table 2.1 summarises the comparison of the proposed integrated model and the proposed Two Level NSGA-II Approach with similar works.

Table 2.1 Comparison of proposed model and approach with similar works

	Proposed Model and Approach	Maenhout and Vanhoucke (2013)	Kim and Mehrotra (2015)	Jiang et al. (2020)
Objectives	To solve the multi-objective, integrated staff level planning and scheduling problem with consideration of skill mix, skill substitution and consequence of skill	To allocate a given workforce over multiple departments based on the hospital's nurse staffing policies, each ward's shift scheduling policies and the nurses' characteristics.	To study the integrated staffing and scheduling in two stages, i.e. define initial staffing levels and schedules in the initial stage, and adjust these schedules at a time epoch closer to the actual date of demand realization	To study a nursing home staff schedule optimization problem under resident demand uncertainty
Techniques/ Tools	Constructive heuristics, modified NSGA-II	A branch-and-price procedure	An integer L-shaped algorithm with a prioritized branching strategy	Implemented in Python and solved the resultant instances with the Gurobi MIP solver
Area of healthcare services	Integrated staff level planning and scheduling for nursing staff of subvented nursing home	Integrated nurse staffing and scheduling for nurse over multiple departments	Integrated nurse staffing and scheduling in hospital	Nursing home staff scheduling decision optimisation under demand uncertainty
Decision	Relatively high	Medium	Low to medium	Medium

support level	- Support both staff level planning and scheduling decision making in an iterative approach - Allow decision makers to choose optimal solutions according to particular interest - Able to capture most of the strategic and operational constraints as anticipated in reality	- Able to balance, over several months, the workforce costs and the coverage of patients in multiple hospital departments - Multiple objectives are handled by the use of weighted sum method, which requires and quality of solution relies on the weights.	- Assume that work patterns repeat from week to week during the planning horizon and that all possible weekly patterns are generated in advance	- Able to generalise the resident-level service demand, and facility-level service demand - Assume that work patterns repeat, and scheduling pattern pre-exist - Handle shift scheduling for regular nurse, and staffing level adjustment with part-time nurses at two sequential stages

.

Chapter 3 – A MULTI-OBJECTIVE OPTIMISATION APPROACH TO STAFF LEVEL PLANNING PROBLEM

3.1 Introduction

In this chapter, the formulation of an optimisation model for staff level planning problem with multi-objectives and criteria are presented in Sections 3.2. NSGA-II applied for solving the optimisation model is described in Section 3.3. The solving of the staff level planning problem using a case study of a subvented nursing home in Hong Kong is illustrated in Section 3.4. A summary is given at the end of the chapter.

Figure 3.1 outlines the methodology. Optimal skill mix, staff level, overtime work hours and work hours are determined based on Non-dominated Sorting Genetic Algorithm-II (NSGA-II).

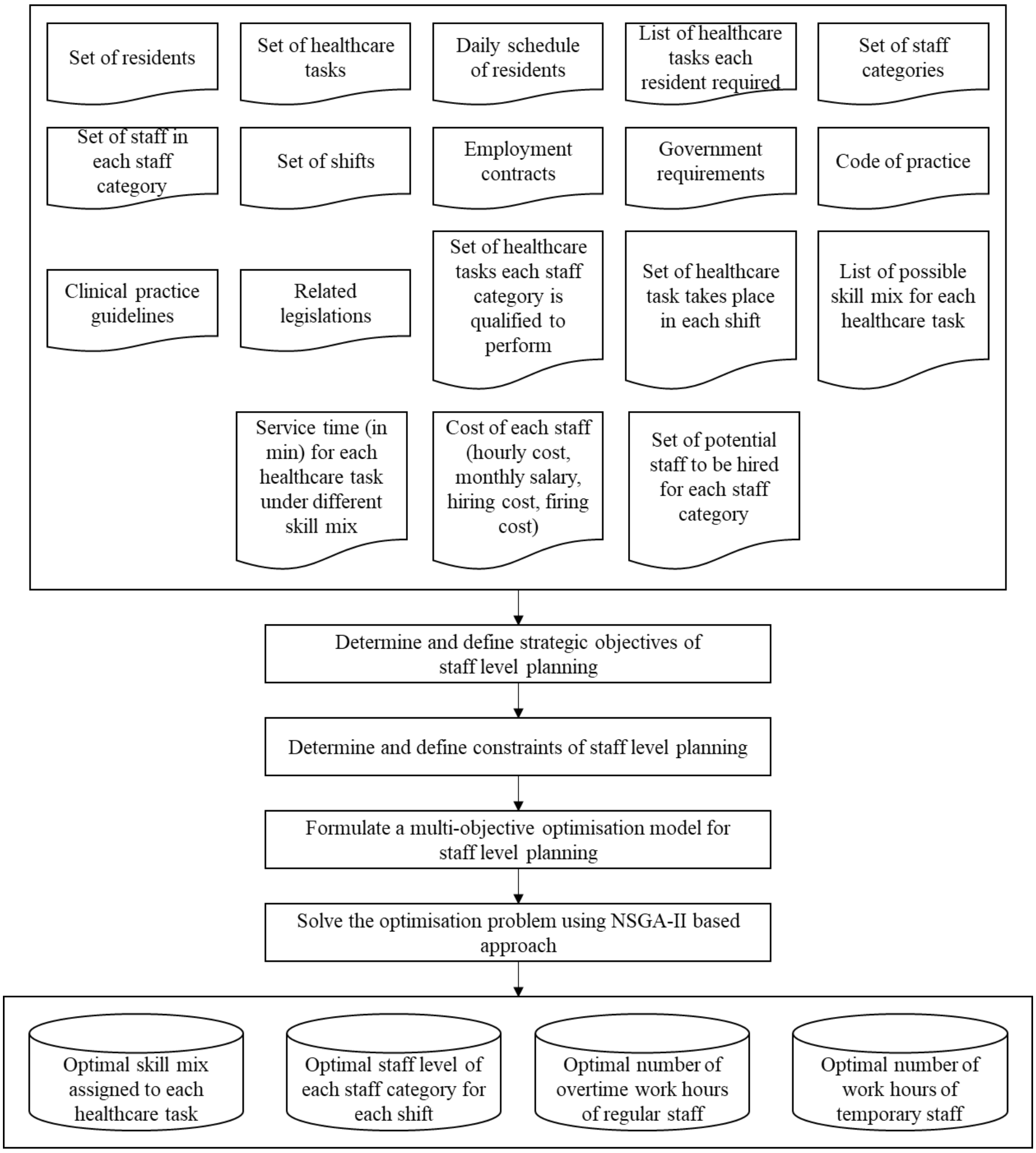

Figure 3.1 Outline of a multi-objective optimisation approach to staff level planning problem

3.2 Formulation of an Optimisation Model for Staff Level Planning Problem

The importance and research interest of staff level planning in nursing homes have been extensively reviewed (in Chapter 2), and the positive relationship between nurse staff levels and the quality of nursing home care has been demonstrated widely (Harrington et al., 2000a; Schnelle et al., 2004; Unruh & Wan, 2004; Zhang et al., 2006). As a result, the determination of the optimal nursing staff level becomes very important and receives even further attention as a solution to improve nursing home quality (Harrington et al., 2000b).

Many different evaluation criteria exist for optimal staff level planning; ever, the previous studies of staff level planning mostly consider a single objective/criterion, such as staff productivity, staffing costs and quality of care (Freeman, 1992; Hancock, Pollock & Kim, 1987; Li & Li, 2000). In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff level planning. For example, nursing home managers want to know the reasonable and acceptable minimum staff level to control costs and improve efficiency while providing quality nursing home care (Kim & Hancock, 1989; Li & Li, 2000; Pulido et al., 2014; Wright, Bretthauer, & Cote, 2006). Furthermore, staffing costs are used by both the government (Freeman, 1992) and other organisations to address the manpower shortage issue. Regarding staff outcome, the correlation among staff workload, poor nurse-to-resident ratio, nursing shortage and staff turnover have been extensively reviewed (in Chapter 2).

For the positive outcomes of nursing home manager, nursing staff and residents, this study performs staff level planning using a multi-objective optimisation approach and makes use of total staffing costs, staff level and overtime work as the evaluation criterion for staff level planning, and the optimal nursing staff level ascertained in this model is the one that minimised the total staffing costs, minimised overtime work and maximised staff level.

Staff Level Planning Problems (SLPPs) of nursing staff in nursing homes involve a nursing home with a set of healthcare services (or tasks) required by a set of residents that must be completed by a set of available nursing staff. Each nursing staff belongs to a specific category and has his/her own qualifications, skill sets and constraints. Each resident has his/her own healthcare needs (i.e. healthcare tasks to be fulfilled by the nursing staff). The nursing home has regulations that impose constraints on the assignment of nursing staff to healthcare tasks. The objectives are to minimise the shift-based staffing costs and overtime work of regular nursing staff while maximising shift-based nurse-to-resident ratio, i.e. staff level, given that all healthcare services (or tasks) requirements are satisfied.

A set of healthcare tasks $T = \{1, 2, \dots, L\}$, in the context of SLPPs, are performed during a predefined time period called a shift. A set of shifts $S = \{1, 2 \dots M\}$ are fixed in time (e.g. an overnight shift). There can be many shifts in one day without overlapping in time. Each healthcare task l for each resident requires T_{il} minutes during the shift when it is provided by either regular or temporary nursing staff of category i. There is a set of $C = \{1, 2, \dots, I\}$ of available nursing staff categories, a set of D_i = {1, 2…, J_i} nursing staff in a particular nursing staff category *i*, and a set of D_i^t = {1, 2, …, J_i^t} temporary nursing staff in a particular nursing staff category *i*. The availability of the j^{th} regular nursing staff of category *i* (hereafter referred as regular staff *ij* for simplicity) per shift is *U* hours. For reasons of cost effectiveness and healthcare task fulfilment, regular nursing staff can work overtime in case the task cannot be completed within a shift for T_{ijm}^{ot} hours. In addition, temporary nursing staff will be selected when the selection of additional regular nursing staff is unfavourable. Similarly, the j^{th} temporary nursing staff of category *i* (hereafter referred as temporary staff *ij* for simplicity) may perform a maximum number of hours (T_i^{max}) of work per shift. Nursing staff have different skills, so P_i is the set of healthcare tasks that nursing staff of category *i* is qualified to perform. In other words, a certain number of nursing staff may be chosen from the set *C* of *i* nursing staff and the subset of selected nursing staff must be capable of completing some of the jobs in the shift. The goal is to find feasible solutions that optimise the shift-based staffing costs of assigning nursing staff *ij*, either temporary or regular nursing staff, to healthcare task *l*. We refer to this model of the staff level planning problem as SLPP.

The input data, parameters and decision variables for formulating a staff level planning model are shown below.

Input Data:

C Set of nursing staff categories, $C = \{1, 2, \ldots, I\}$

D_i Set of nursing staff in a particular nursing staff category i, $D_i = \{1, 2\ldots, J_i\}$ where J_i is the given maximum allowable regular nursing staff of category i to be hired

D_i^t Set of temporary nursing staff in a particular staff category i, $D_i^t = \{1, 2, \ldots, J_i^t\}$ where J_i^t is the given maximum allowable temporary nursing staff of category i to be hired

D''_i Set of potential temporary nursing staff in a particular staff category i to be hired, $D''_i = \{J_i^t + 1, J_i^t + 2, \ldots, J_i^t + J''_i\}$ where J''_i is the given maximum allowable temporary nursing staff of category i to be hired

P_i Set of healthcare tasks that nursing staff of category i is qualified to perform, $P_i = \{1, 2, \ldots, L_i\}$

S Set of shifts (in the planning horizon of 1 month), $S = \{1, 2\ldots M\}$

T Set of healthcare tasks, $T = \{1, 2\ldots L\}$

Parameters:

T_i^{max} The upper limit of working hours per shift for a temporary staff of category i

C_i^p Hourly wage of a regular nursing staff of category i

C_i^t Hourly wage of a temporary nursing staff of category i

N Number of residents

N_l Number of residents requiring l^{th} healthcare task

T_{il} Service time (in minutes) of the l^{th} healthcare task for each resident per shift if it is provided by nursing staff, either regular or temporary, of category *i*

Y_{lm} 1 if the l^{th} healthcare task is needed for resident in shift *m*; otherwise 0

U Standard working time (in minutes) for all regular nursing staff per shift

Variables:

T_i^t Total working hours of temporary staff of category *i*

T_{ijm}^{ot} Overtime work (in hours) for regular staff ij in shift m

X_{ijlm} $= \begin{cases} 1 \text{ if regular staff } ij \text{ is assigned to task } l \text{ in shift } m \\ 0 \text{ otherwise} \end{cases}$

X_{ijlm}^t $= \begin{cases} 1 \text{ if temporary staff } ij \text{ is assigned to task } l \text{ in shift } m \\ 0 \text{ otherwise} \end{cases}$

X_{ijm} $= \begin{cases} 1 \text{ if regular staff } ij \text{ is selected in shift } m \\ 0 \text{ otherwise} \end{cases}$

X_{ijm}^t $= \begin{cases} 1 \text{ if temporary staff } ij \text{ is selected in shift } m \\ 0 \text{ otherwise} \end{cases}$

N_i^h Number of additional regular nursing staff of category *i* to be hired

N_i^f Number of existing regular nursing staff of category *i* left the workforce

Decision Variables:

T_{ijlm}	Amount of time (in minutes) that regular staff *ij* is assigned to perform task *l* in shift *m*
T^t_{ijlm}	Amount of time (in minutes) that temporary staff *ij* is assigned to perform task *l* in shift *m*

A staff level planning model is formulated as follows.

$$\mathrm{F}_1 = \text{Minimise} \sum_{i \in C} \sum_{j \in D_i} \left[X_{ijm} \cdot C_i^p \cdot \max\left(\sum_{\forall l \in P_i} T_{ijlm}, U \right) \right] + \sum_{i \epsilon C} C_i^t \cdot \sum_{j \in D_i^t} \sum_{\forall l \in P_i} T^t_{ijlm} \qquad \forall m \in S \qquad (3.1)$$

$$\mathrm{F}_2 = \text{Maximise} \left(\sum_{i \in C} \sum_{j \in D_i} X_{ijm} + \sum_{i \in C} \sum_{j \in D_i^t} X^t_{ijm} \right) \qquad \forall m \in S \qquad (3.2)$$

$$\mathrm{F}_3 = \text{Minimise} \sum_{i \in \mathrm{C}} \sum_{j \in D_i} T^{ot}_{ijm} \qquad ,\forall i \in C,\ \forall j \in D_i,\ \forall m \in S \qquad (3.3)$$

, where

$$X_{ijm} = \begin{cases} 1 \text{ if } \sum_{\forall l \in P_i} T_{ijlm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C,\ \forall j \in D_i,\ \forall m \in S \qquad (3.4)$$

$$X^t_{ijm} = \begin{cases} 1 \text{ if } \sum_{\forall l \in P_i} T^t_{ijlm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C,\ \forall j \in D_i^t,\ \forall m \in S \qquad (3.5)$$

$$T_{ijm}^{ot} = \max\left[\left(\sum_{\forall l \in P_i} T_{ijlm} - U\right), 0\right] \qquad ,\forall i \in C,\ \forall j \in D_i,\ \forall m \in S \qquad (3.6)$$

Subject to

$$T_{il} \cdot N_l \cdot Y_{lm} \leq \sum_{j \in D_i} T_{ijlm} + \sum_{j \in D_i^t} T_{ijlm}^t \qquad ,\forall i \in C,\ \forall l \in P_i, \forall m \in S \qquad (3.7)$$

$$\sum_{l \in P_i} T_{ijlm} \leq \left(U + T_{ijm}^{ot}\right) \cdot X_{ijm} \qquad ,\forall i \in C,\ \forall j \in D_i \cup D_i',\ \forall m \in S \qquad (3.8)$$

$$\sum_{l \in P_i} T_{ijlm}^t \leq T_i^{max} \cdot X_{ijm}^t \qquad ,\forall i \in C,\ \forall j \in D_i^t \cup D_i'',\ \forall m \in S \qquad (3.9)$$

$$T_{ijlm} \leq \left(U + T_{ijm}^{ot}\right) \cdot X_{ijlm} \qquad ,\forall i \in C,\ \forall j \in D_i,\ \forall l \in P_i, \forall m \in S \qquad (3.10)$$

$$T_{ijlm}^t \leq T_i^{max} \cdot X_{ijlm}^t \qquad ,\forall i \in C,\ \forall j \in D_i^t,\ \forall l \in P_i, \forall m \in S \qquad (3.11)$$

$$X_{ijlm} = \begin{cases} 1 \text{ if } \displaystyle\sum_{\forall l \in P_i} T_{ijlm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C,\ \forall j \in D_i \cup D_i',\ \forall m \in S \qquad (3.12)$$

$$X_{ijlm}^t = \begin{cases} 1 \text{ if } \displaystyle\sum_{\forall l \in P_i} T_{ijlm}^t \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C,\ \forall j \in D_i^t \cup D_i'',\ \forall m \in S \qquad (3.13)$$

$$X_{ijlm} \in \{0, 1\} \qquad ,\forall i \in C,\ \forall j \in D_i\ ,\ \forall l \in P_i, \forall m \in S \qquad (3.14)$$

$$X_{ijlm}^t \in \{0, 1\} \qquad ,\forall i \in C,\ \forall j \in D_i^t,\ \forall l \in P_i, \forall m \in S \qquad (3.15)$$

$$X_{ijm} \in \{0, 1\} \qquad ,\forall i \in C,\ \forall j \in D_i\ ,\ \forall l \in P_i,\ \forall m \in S \qquad (3.16)$$

$$X_{ijm}^{t} \in \{0,1\} \qquad ,\forall i \in C,\ \forall j \in D_i^t,\ \forall l \in P_i, \forall m \in S \qquad (3.17)$$

In the model, the objective function (3.1) minimises the total staffing cost of a shift. Objective function (3.2) maximises the staff level of a shift. Objective function (3.3) minimises the overtime work of regular nursing staff of a shift. Equations (3.4) to (3.6) define X_{ijm}, X_{ijm}^{t} and T_{ijm}^{ot}, respectively.

Constraint (3.7) imposes the task requirements as specified by the amount of time required to complete each healthcare task within a shift. In a nursing home, both direct and indirect care demands of all residents (in staff hours) have to be satisfied within each shift (i.e. daytime, evening and overnight shifts), by either regular and/or temporary nursing staff, and all unserved staff hours cannot be stocked. The minimum estimated demand for resident care (in staff hours) of task *l* in shift *m*, forecasted based on historical data and seasonal characteristics, is considered during demand forecasting. Constraint (3.8) limits the number of working hours for each selected regular nursing staff. If the regular nursing staff is not selected, this constraint prohibits the model from assigning healthcare tasks or hours to this regular nursing staff. Similarly, Constraint (3.9) limits the number of working hours for each selected temporary nursing staff. If the temporary nursing staff is not selected, this constraint prohibits the model from assigning healthcare tasks or hours to this temporary nursing staff. In addition, Constraints (3.10) and (3.11) prohibit the model from assigning hours to a nursing staff that has not been selected to perform a given healthcare task in a given shift. Constraints (3.12) and (3.13) define X_{ijlm} and X_{ijlm}^{t}.

Constraints (3.14) to (3.17) define X_{ijlm}, X_{ijlm}^{t}, X_{ijm} and X_{ijm}^{t} are binary variables.

In summary, the minimisation of total staffing costs for each shift, the maximisation of staff level for each shift and the minimization of overtime work ensure a nursing home to fulfil service demand requirements at any shift and at the minimum total staffing costs and with minimum overtime work yet maximum nurse-to-resident ratio. Strategic issues of concern to nursing home managers during staff level planning are considered in this model as part of the objective function and/or as constraints.

3.3 NSGA-II Approach

A NSGA-II approach is applied to solve the multi-objective optimisation problems and determine the staff level and staff schedule. In this section, the NSGA-II algorithm for solving the optimisation models is described.

3.3.1 Description of NSGA-II

NSGA-II is an elitist evolutionary algorithm introduced by Deb et al. (2002) for solving multi-objective optimisation problems through evolution. During the reproduction process, crossover operator and mutation operator are used to generate chromosomes in the next generation. Then, members of the parent population (P_t) and offspring population (Q_t) are combined and sorted based on the non-dominance and crowding distance concepts. Higher ranked chromosomes are chosen by a selection procedure and transferred to the next generation. In case of equality in a rank, crowding distance is determined by calculating the absolute value distance of each solution from its adjacent solutions. Chromosomes with higher crowding distance value will be chosen to reserve diversity of solutions. A flowchart of NSGA-II is shown in Figure 3.2.

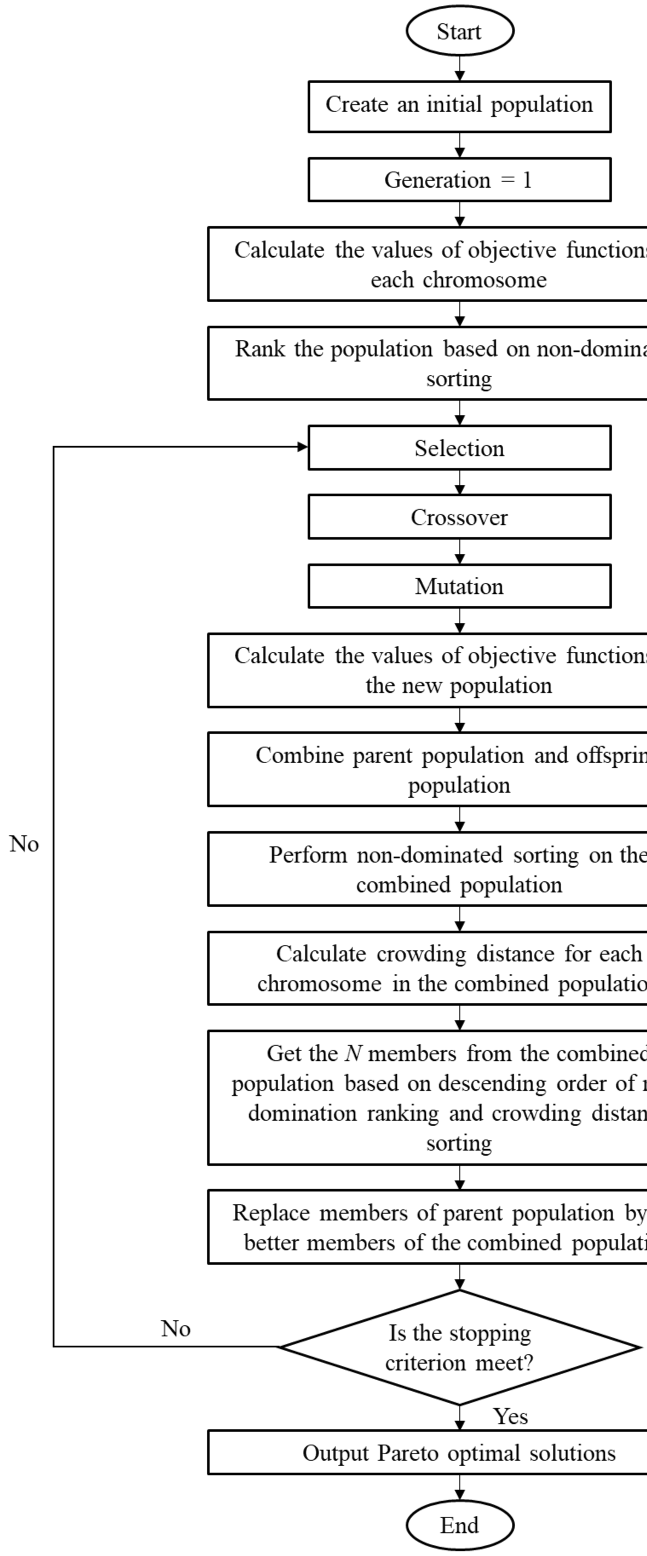

Figure 3.2 A flowchart of NSGA-II

3.3.1.1 Non-dominated sorting

For non-dominated sorting of population, each member of the population is compared with all other members to determine whether it is dominant or non-dominant. Assuming that *S*1 and *S*2 are two solutions, the solution *S*1 dominates solution *S*2, if (a) the solution *S1* is not worse than solution *S*2 for all objectives, and (b) the solution *S*1 is better than solution *S*2 for at least one objective. The solutions that are not dominated by other solutions create the first Pareto front (F_1), i.e. with the ranking 1, and the ones that are dominated by only the first Pareto front create the second Pareto front (F_2), i.e. with the ranking 2, and so on. (Deb et al., 2002)

3.3.1.2 Crowding distance sorting

In case of equality in a rank, crowding distance is applied to maintain the spread of solution, to differentiate and to select solutions to fill the population. The crowding distance of a solution is determined by calculating the distance of this solution from two adjacent solutions. Boundary solutions are assigned with an infinite crowding distance. Solutions with higher crowding distance value, i.e. with lower congestion, will be given higher priority. (Xu et al., 2015)

3.3.1.3 Combination and selection

Members of the parent population (P_t) and offspring population (Q_t) are combined to form a new population ($P_t \cup Q_t$) of population size 2N. As all the best individuals in the parent and offspring populations are included in the combined population, elitism is ensured. Members of the combined population are sorted based on non-dominance. Solutions belongings to the first non-dominated Pareto front F_1 are the best solutions in the combined population. If the size of F_1 is smaller than or equal to the population size N, all solutions in F_1 are selected for the new population (P_{t+1}). The remaining solutions of the new population are filled by subsequent non-dominated Pareto fronts in the descending order of non-domination ranking, i.e. F_2, F_3 and so on. The procedure continues until not all solutions of Pareto front F_i can be accommodated by the new population P_{t+1}. Instead, to maintain population size N in the new population P_{t+1}, solutions of F_i are sorted based on descending crowding distance. Solutions with higher crowding distance value will be chosen. The new population P_{t+1}.will be used for selection, crossover, and mutation to create a new population Q_{t+1}. Figure 3.3 shows a graphical representation of NSGA-II.

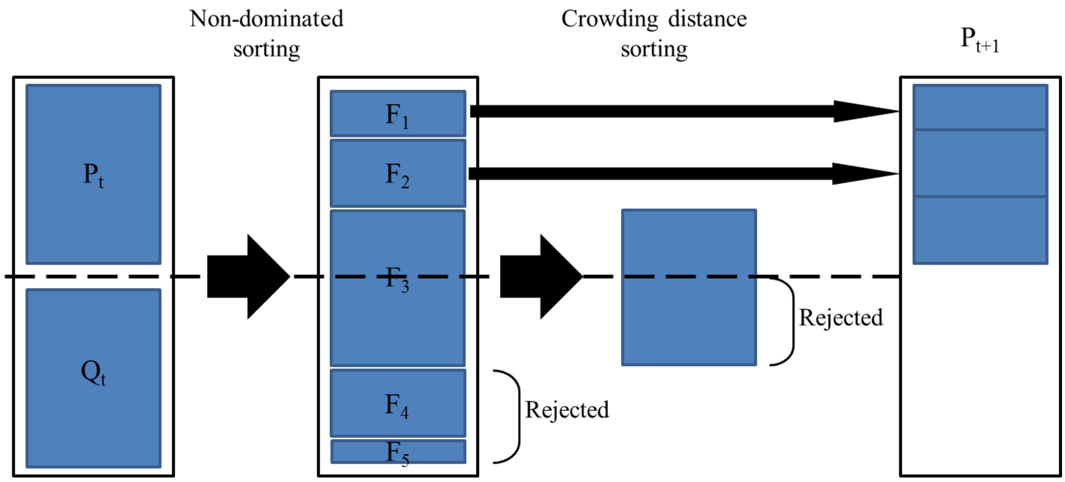

Figure 3.3 Graphical representation of NSGA-II

3.3.1.4 Chromosome representation

The chromosomes are represented as a combination of binary and integer strings. Solutions are represented as an $[I \times (J_I \; + J_I^t + J_I' + J_I'')] \times (M \times L)$ matrix T, where T_{ijlm} and T_{ijlm}^t represents the amount of time (in minutes) that staff *ij* is assigned to task *l* in shift *m*. In this representation, a regular and a temporary nursing staff *ij* is considered to be assigned to task *l* in shift *m* if $T_{ijlm} > 0$ and $T_{ijlm}^t > 0$, respectively. Therefore, the following relationships are established from the values in *T*.

$$X_{ijlm} = \begin{cases} 1 \text{ if } T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijlm}^t = \begin{cases} 1 \text{ if } T_{ijlm}^t > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijm} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijm}^{t} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm}^{t} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ij} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

An example of solution using this representation for a one day (i.e. three shifts) nursing staff level planning problem with six staff is shown in Figure 3.4. In the example, regular nursing staff 1 is assigned to task 2 in shift 1, task 1 in shift 2 and task 3 in shift 3, each task for 480 minutes, while staff 3 of both regular and temporary nursing staff category 1 are not selected in any shift. The values of different variables are determined based on the values in T_{ijlm} and T_{ijlm}^{t}. A sample of the values of deduced binary variables is shown in Tables 3.1 and 3.2.

Nursing staff \ Shifts x Tasks	11	12	13	21	22	23	31	32	33
11	000	480	000	480	000	000	000	000	480
12	240	000	000	000	000	000	000	120	000
13	000	000	000	000	000	000	000	000	000
11^t	000	000	000	000	000	000	000	240	240
12^t	120	000	000	240	000	000	000	000	000
13^t	000	000	000	000	000	000	000	000	000

Regular nursing staff 1 of category 1 is assigned to task 3 in shift 3, for 480 minutes

Regular nursing staff 2 of category 1 is not assigned to task 1 in shift 3

Temporary nursing staff 1 of category 1 is assigned to task 2 & 3 in shift 3, each task for 240 minues

Temporary nursing staff 3 of category 1 is not selected

Figure 3.4 An example of a NSGA-II solution using the representation presented in this study

Table 3.1 Sample of chromosome decoding for regular nursing staff

i	j	m	l	Variables X_{ijlm}	X_{ijm}	X_{ij}	X_{ijq}
1	1	1	1	0	1	1	1
			2	1			
			3	0			
		2	1	1	1		
			2	0			
			3	0			
		3	1	0	1		
			2	0			
			3	1			

Table 3.2 Sample of chromosome decoding for temporary nursing staff

i	j	m	l	Variables X^t_{ijlm}	X^t_{ijm}	X^t_{ijw}
1	1	1	1	0	0	1
			2	0		
			3	0		
		2	1	0	0	
			2	0		
			3	0		
		3	1	0	1	
			2	1		
			3	1		

3.3.1.5 Genetic operation

Crossover is performed to introduce new chromosomes by exchanging genes of current chromosome (i.e. parent chromosome) in the mating pool. In each pair of mating chromosomes $Z1$ and $Z2$, the crossover operator selects, with crossover probability p_c, the time assigned to a particular healthcare task T_{ijlm}^{t} or T_{ijlm}. If the time assignment is selected, then the task assignments, shift assignment, and so as to days off assignment of mating chromosome $Z1$ are exchanged with that of mating chromosome $Z2$. Similar crossover operation is given in Luque and Alba (2011). This crossover operator ensures that the offspring generated after crossover are still feasible in terms of the skill requirement of task, as time assignments are exchanged between identical staff in two different chromosomes.

Figure 3.5 shows an example of crossover operation in which time assignment of regular nursing staff 2 of category 1, and temporary nursing staff 1 of category 1 are selected randomly for crossover. After crossover, regular nursing staff 2 of category 1 in solution $Z1$ has not been assigned any task in shift 3, while regular nursing staff 2 of category 1 and temporary nursing staff 1 of category 1 are now assigned with task in shift 3, i.e. counted in the workforce.

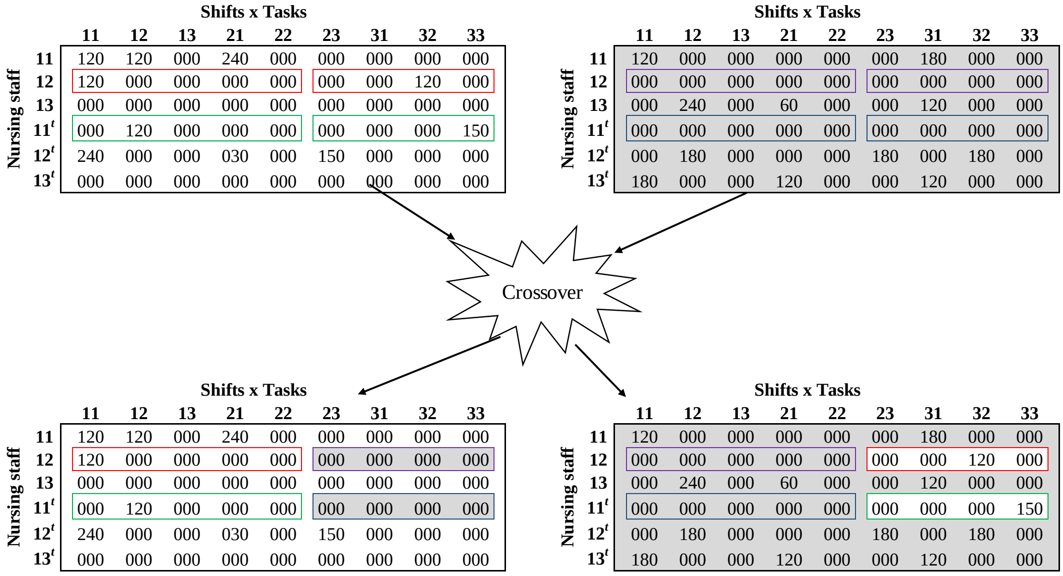

Figure 3.5 An example of crossover operation in NSGA-II using the representation presented in this study

In addition to the crossover operation, mutation is performed to introduce random and sporadic changes to the chromosomes to maintain the diversity of the population in succeeding generations. Mutation operates on a single solution. It is conducted by exchanging the time assignments of two nursing staff, with mutation probability p_m. Figure 3.6 shows an example of mutation operation in which the current time assignment of task 1 in shift 2 are exchanged between regular nursing staff 1 of category 1(light-grey background) and another qualified nursing staff, i.e. regular nursing staff 2 of category 1 in the example (dark-grey background). The mutation operator considers only the list of nursing staff that are qualified to perform the selected task.

Shifts x Tasks (Nursing staff)

	11	12	13	21	22	23	31	32	33
11	120	120	000	240	000	000	000	000	000
12	120	000	000	000	000	000	000	120	000
13	000	000	000	000	000	000	000	000	000
11^t	000	120	000	000	000	000	000	000	150
12^t	240	000	000	030	000	150	000	000	000
13^t	000	000	000	000	000	000	000	000	000

Shifts x Tasks (Nursing staff)

	11	12	13	21	22	23	31	32	33
11	120	120	000	000	000	000	000	000	000
12	120	000	000	240	000	000	000	120	000
13	000	000	000	000	000	000	000	000	000
11^t	000	120	000	000	000	000	000	000	150
12^t	240	000	000	030	000	150	000	000	000
13^t	000	000	000	000	000	000	000	000	000

Figure 3.6 An example of mutation operation in NSGA-II using the representation presented in this study

After mutation, nursing staff 1 of category 1 is assigned 0 minutes for the task, i.e. he/she is not selected for the task. In case the randomly chosen staff is not qualified for the selected task, time assignment will not be exchanged to ensure feasibility of solution.

3.4 Computational Experiments

The purpose of this section is to illustrate the ability of the multi-objective optimisation approach in solving real-world staff level planning problem. The use of heterogeneous workforce perceived in reality is considered. The NSGA-II is coded in MATLAB programming language and run on a PC with an Intel i7-4600U CPU of 2.10 GHz and 8 GB RAM. Data of a subvented nursing home in Hong Kong was collected, revised due to confidentiality issue, and inputted into the models as problem instance.

3.4.1 Description of reference case

At present, there are 4 nursing staff categories: 1 (representing Personal Care Worker, *PCW*), 2 (representing Health Worker, *HW*), 3 (representing Enrolled Nurse, *EN*) and 4 (representing Registered Nurse, *RN*). In shifts 1 and 4, 5 staff from category 1 and 1 staff from either category 3 or 4 are on duty. 2 staff from category 2 may also be required. In shift 2, 5 staff from category 1 and 2 staff from either category 3 or 4 are on duty. 2 staff from category 2 may also be required. In shift 3, 2 staff from category 1 and 1 staff from either category 2, 3 or 4 are on duty. The nurse-to-resident ratio are [1:6.63, 1:8.83] for shifts 1 and 4, [1:5.80, 1:7.57] for shift 2, and 1:17.7 for shift 3. Staff required from each category can be both regular and temporary nursing staff.

Currently, a few temporary nursing staff has been employed and the regular nursing staff sometimes needs to work overtime in order to complete all the healthcare tasks within the shift. It was also reported that (1) monthly salaries of regular nursing staff are based on their staff grade (which refers to ‘nursing staff category’ in the proposed model), subject to a minimum set at the mid-point, which are used when undertaking staff level planning; (2) shifts 1 (daytime shift with monthly healthcare task, also denoted by ‘A*’), 2 (evening shift, also denoted by ‘B’), 3 (overnight shift, also denoted by ‘N’) and 4 (daytime shift, also denoted by ‘A’) are the typical and representative shifts, and (3) currently, the total monthly staffing costs is HK$587,140.

Values of the problem instance are listed in Table 3.3. Service time of healthcare task (in minutes) undertaken by various nursing staff categories (T_{il}) are shown in Table 3.4. The list of healthcare task for each shift (Y_{lm}) is shown in Table 3.5. In Table 3.5, 0 denotes the absence and 1 denotes the presence of healthcare task. For example, nursing staff of category 1 are qualified to perform thirteen tasks, and healthcare task 18 can be performed by nursing staff of categories 3 and 4 but not staff of category 1 or 2.

Table 3.3 Details of problem instance

Notation	Value	Notation	Value
C	{1, 2, 3, 4}	D_1	{1, 2, ... , 16}
D_1^t	{1, 2, 3}	D_2	{1, 2, 3}
D_2^t	{0}	D_3	{1, 2, 3, 4, 5}
D_3^t	{1}	D_4	{1, 2}
D_4^t	{0}	D_1'	{17, 18, 19, … , 32}
D_2'	{4, 5, 6, …, 32}	D_3'	{6, 7, 8, …, 32}
D_4'	{3, 4, 5, …, 32}	D_1''	{4, 5, 6, …, 32}
D_2'', D_4''	{1, 2, 3, …, 32}	D_3''	{2, 3, 4, …, 32}
S	{1, 2, 3, …, 90}	T	{1,2,…26}
P_1	{1, 2, 3, 4, 5, 8, 10, 11, 14, 15, 16, 17, 24}	P_2	{1, 4, 5, 6, 7, 8, 9, 11, 12, 13, 15, 16, 17, 19, 20, 21, 22, 23, 24, 25, 26}
P_3, P_4	{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26}	W'	{1, 2, 3, 4}
Q'	{1}		
$T_1^{w,max}$, $T_2^{w,max}$, $T_3^{w,max}$, $T_3^{w,max}$	18	T_1^{max}, T_2^{max}, T_3^{max}, T_4^{max}	12
C_1^p, C_1^t, R_1^{otp}	64	C_2^p, C_2^t, R_2^{otp}	87
C_3^p, C_3^t, R_3^{otp}	108	C_4^p, C_4^t, R_4^{otp}	138
N	53	N_1	31
N_2	18	N_3	35
N_4	39	N_5	42
N_6	0	N_7	23
N_8	11	N_9	37
N_{10}	18	N_{11}	16
N_{12}	53	N_{13}	25
N_{14}	5	N_{15}	44
N_{16}	53	N_{17}	53

Table 3.3 Details of problem instance (continued)

Notation	**Value**	**Notation**	**Value**
N_{18}	5	N_{19}	5
N_{20}	23	N_{21}	11
N_{22}	2	N_{23}	2
N_{24}	2	N_{25}	42
N_{26}	53	U	8
$S_{1j},\ C_1^h,\ C_1^f$	15,485	$S_{2j},\ C_2^h,\ C_2^f$	21,550
$S_{3j},\ C_3^h,\ C_3^f$	26,785	$S_{4j},\ C_4^h,\ C_4^f$	34,180
$X_1^{w,max},\ X_2^{w,max},$ $X_3^{w,max}, X_4^{w,max},$	6	$O_{1m}^{max},\ O_{2m}^{max},$ $O_{3m}^{max},\ O_{4m}^{max},$	8

Table 3.4 Service time of healthcare tasks (in minutes)

Healthcare Task	Service Time of Healthcare Tasks Undertaken by Nursing Staff Category (In Minutes)			
	1	**2**	**3**	**4**
1	1	0.5	0.5	0.5
2	7	0	7	7
3	7	0	7	7
4	0.5	1	0.5	1
5	2	1	1	1
6	0	4	2	2
7	0	1.5	1	0.5
8	12	24	3	3
9	0	4	2	2
10	2	0	2	2
11	0.5	0.5	0.5	0.5
12	0	1	0.5	0.5
13	0	1	1	0.5
14	2	0	1	1
15	1	1	1	2
16	1	1	0.5	1
17	1	0.3	0.5	1
18	0	0	0.5	0.5
19	0	20	20	20
20	0	103	103	103
21	0	2	0.5	0.5
22	0	0.5	0.5	0.5
23	0	0.5	0.5	0.5
24	1	1	1	1
25	0	0.25	0.5	0.5
26	0	1	1	1

Table 3.5 List of healthcare tasks for each shift

Healthcare Task	Work Shift			
	1	**2, 5, … , 86, 89**	**3, 6, .. , 87, 90**	**4, 7, … , 85, 88**
1	1	1	1	1
2	1	0	0	1
3	0	1	0	0
4	1	1	0	1
5	1	1	1	1
6	1	1	0	1
7	1	1	1	1
8	1	1	0	1
9	1	1	0	1
10	0	1	0	0
11	1	1	0	1
12	1	0	0	1
13	1	0	0	1
14	1	1	1	1
15	1	1	1	1
16	1	1	1	1
17	1	1	1	1
18	1	0	0	0
19	0	0	0	0
20	1	0	0	0
21	1	0	0	1
22	0	0	0	0
23	0	1	0	0
24	1	1	0	1
25	0	0	0	0
26	1	0	0	0

3.4.2 Implementation

NSGA-II is applied to solve the multi-objective staff level planning problem formulated. The quality of solutions obtained depends heavily on the parameters setting of a multi-objective evolutionary algorithm (Sadeghi & Niaki, 2015). There are four parameters in NSGA-II to be calibrated, i.e. the population size (*pop*), the number of iterations to stop the algorithm (*iteration*), the crossover probability (*CR*), and the mutation probability (*MR*).

Many researchers have used the conventional parameter optimization which method relies on experience and trial-and-error. In order to determine the significant factors (here the parameters) affecting a response (here the solution), A Taguchi orthogonal array is used instead of a full factorial experimental design to calibrate the parameters of the developed NSGA-II. Taguchi developed ‘a special type of fractional factorial experiments to reduce a large number of experiments required in a full factorial experiments’ (Sadeghi & Niaki, 2015).

The Taguchi method is designed based on orthogonal arrays, and can be used efficiently as an alternative for the full factorial experimental design to investigate a group of factors. These factors are divided in two groups, namely controllable factors and noise factors. The Taguchi method aims mainly to select the best level of the factors such that the effect of controllable factors is maximised and the effect of noise factors is minimized (Maghsoudlou et al., 2016). There are two suggested ways in the Taguchi method to analyse the results. First, analysis of variance

(ANOVA) that is used for experiments that repeat once, and second, signal-to-noise ratio (S/N) for experiments with multiple runs (Sadeghi & Niaki, 2015). Since NSGA-II have multiple runs to obtain better solutions, S/N is used in this study to analyse the results. The S/N ratio can be calculated in three difference ways, including ‘smaller-the-better’, ‘nominal-the-better’, and ‘greater-the-better’. A larger S/N ratio indicates a better result (Candan & Yazgan, 2015). As the Objective Functions (3.1) and (3.3) are minimisisation while Objective Function (3.2) is maximisation, two equations apply. For the smaller-the-better, the value of S/N can be calculated using Equation (3.18). For the greater-the-better, the value of S/N can be calculated using Equation (3.19).

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \tag{3.18}$$

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{{y_i}^2}\right] \tag{3.19}$$

, where η is the S/N ratio, n is the number of replications, and y_i is the response values.

The Taguchi method was employed to conduct the experiments. Table 3.6 outlines the steps of Taguchi method.

Table 3.6 Steps of Taguchi method

Steps	Activity
1	Selecting and evaluating interactions between factors
2	Determining levels of factors
3	Selecting the appropriate orthogonal array
4	Assign factors and their interactions to each column of the orthogonal array
5	Realisation of the experiments
6	Analysis of the results

In this study, the four parameters were obtained in systematic review of optimization methodology and were selected by simulation method in widely range. Interactions between factors are assumed neglectable. Three levels of the parameters are shown in Table 3.7. The L^9 orthogonal array is applied to reduce the number of experiments from 81 (3^4) to 9. To improve accuracy, experiments were repeated five times. This meant that only 45 (9*5) experiments, instead of 405 experiments, were required to reach a conclusion. Tables 3.8 to 3.10 show the experimental design and response statistics, repeated five times, under NSGA-II for total staffing costs, amount of overtime work and staff level, respectively. The related S/N ratios of total staffing costs, overtime work and staff level of the proposed NSGA-II are shown in Figures 3.7 to 3.8, respectively. The values of S/N ratio of total staffing costs, overtime work and staff level are presented in Tables 3.11, 3.12 and 3.13, respectively. The largest values of S/N ratio depict the optimal condition.

Table 3.7 Parameters (factors) and the levels for staff level planning

	Levels		
Parameter	**Low (1)**	**Medium (2)**	**High (3)**
Population Size (*Pop*)	50	100	150
Number of Iterations to Stop the Algorithm (*Iteration*)	300	500	750
Crossover Rate (*CR*)	0.7	0.8	0.9
Mutation Rate (*MR*)	0.001	0.01	0.1

Table 3.8 Experimental design and response statistics under NSGA-II (total staffing costs)

Number	Control Parameters				Response 1 (HK$)	Response 2 (HK$)	Response 3 (HK$)	Response 4 (HK$)	Response 5 (HK$)
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	247,440	214,980	240,420	247,620	229,620
2	0.7	0.01	100	500	261,960	244,020	247,140	248,580	264,570
3	0.7	0.1	150	750	300,150	247,140	242,100	296,910	243,900
4	0.8	0.001	100	750	296,280	296,280	241,470	237,960	251,250
5	0.8	0.01	150	300	304,050	256,260	241,380	259,830	269,640
6	0.8	0.1	50	500	236,010	301,440	243,690	246,510	239,250
7	0.9	0.001	150	500	241470	245520	235,350	238,350	255,570
8	0.9	0.01	50	750	236010	301440	295,530	246,510	239,250
9	0.9	0.1	100	300	240810	245610	268,620	252,150	294,540

Table 3.9 Experimental design and response statistics under NSGA-II (overtime work)

Number	Control Parameters				Response 1 (hour)	Response 2 (hour)	Response 3 (hour)	Response 4 (hour)	Response 5 (hour)
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	210	360	0	0	120
2	0.7	0.01	100	500	0	0	0	60	0
3	0.7	0.1	150	750	0	0	0	0	0
4	0.8	0.001	100	750	0	0	0	150	0
5	0.8	0.01	150	300	0	0	120	90	150
6	0.8	0.1	50	500	120	0	120	0	120
7	0.9	0.001	150	500	0	60	120	150	0
8	0.9	0.01	50	750	150	0	0	0	150
9	0.9	0.1	100	300	90	0	0	30	0

Table 3.10 Experimental design and response statistics under NSGA-II (staff level)

Number	Control Parameters				Response 1*	Response 2*	Response 3*	Response 4*	Response 5*
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	22	20	21	22	21
2	0.7	0.01	100	500	23	22	22	22	23
3	0.7	0.1	150	750	24	22	22	24	22
4	0.8	0.001	100	750	24	24	22	21	23
5	0.8	0.01	150	300	24	22	21	22	21
6	0.8	0.1	50	500	21	24	21	22	21
7	0.9	0.001	150	500	22	22	21	21	23
8	0.9	0.01	50	750	21	24	23	22	23
9	0.9	0.1	100	300	21	22	23	23	24

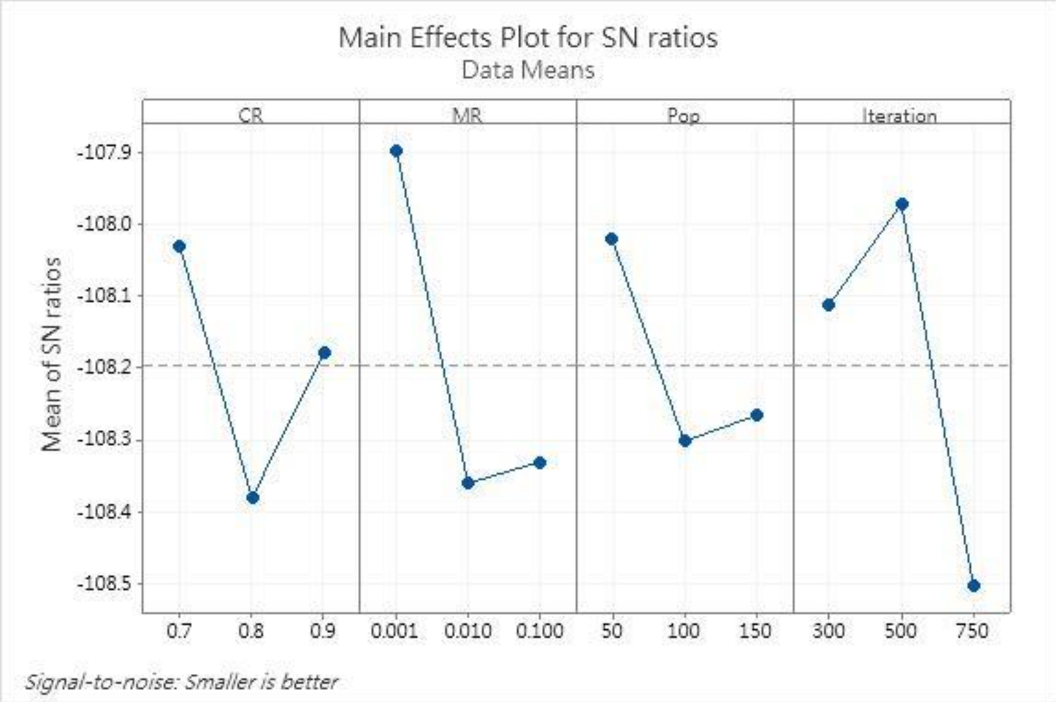

Figure 3.7 S/N ratio plots of total staffing costs for staff level planning

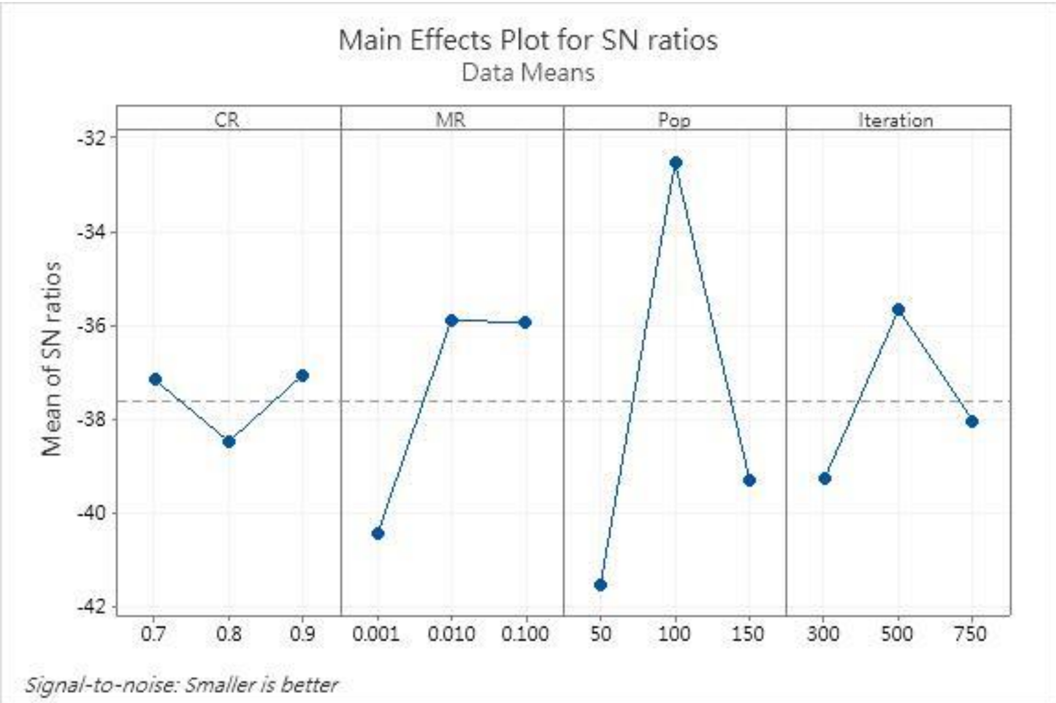

Figure 3.8 S/N ratio plots of overtime work for staff level planning

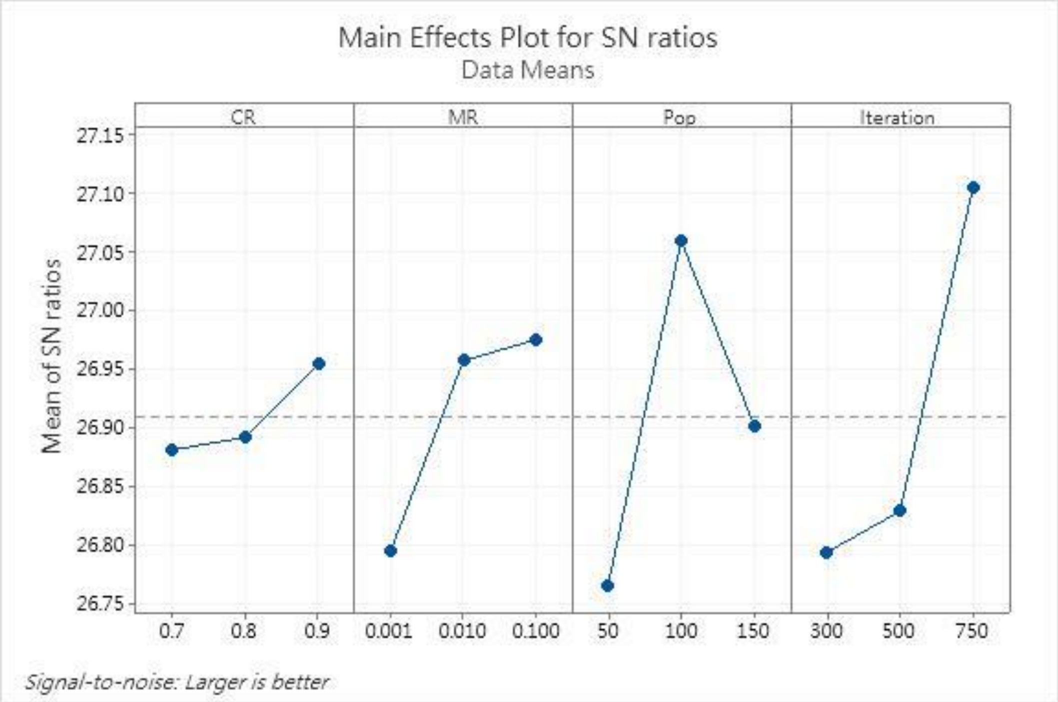

Figure 3.9 S/N ratio plots of staff level for staff level planning

Table 3.11 Response table for S/N ratios (total staffing costs)

Level	CR	MR	Pop	Iteration
1	-108.0	-107.9	-108.0	-108.1
2	-108.4	-108.4	-108.3	-108.0
3	-108.2	-108.3	-108.3	-108.5
Delta	0.4	0.5	0.3	0.5
Rank	3	2	4	1

Table 3.12 Response table for S/N ratios (overtime work)

Level	CR	MR	Pop	Iteration
1	-37.16	-40.46	-41.55	-39.28
2	-38.48	-35.89	-32.55	-35.67
3	-37.06	-35.96	-39.31	-38.04
Delta	1.42	4.57	9.00	3.61
Rank	4	2	1	3

Table 3.13 Response table for S/N ratios (staff level)

Level	CR	MR	Pop	Iteration
1	22.13	21.93	21.87	21.93
2	22.20	22.33	22.60	22.00
3	22.33	22.40	22.20	22.73
Delta	0.20	0.47	0.73	0.80
Rank	4	3	2	1

The Taguchi optimal parameters are the average of that of all responses (Tian et al., 2017), i.e. total staffing costs, that of overtime work, and that of staff level. According to the genetic parameter combinations of highest S/N ratio under different responses in Tables 3.11 to 3.13, the genetic parameter settings obtained from the Taguchi method are *CR* = 0.7, *MR* = 0.001, *pop* = 50, *iteration* = 500 for the total staffing costs optimisation. Similarly, the genetic parameter settings are *CR* = 0.9, *MR* = 0.01, *pop* = 100, *iteration* = 500 for the overtime work optimisation. the genetic parameter settings are *CR* = 0.9, *MR*=0.1, *pop*=100, *iteration* =750 for the staff level optimisation. Therefore, parameters of NSGA-II were set with population size at 84 (*pop* = 84), number of iterations to stop the algorithm at 584 (*iteration* = 584), crossover probability at 0.84 (*CR* = 0.84) and mutation probability at 0.037 (*MR* = 0.037), respectively.

The NSGA-II was coded in MATLAB programming language and ran on a PC with an Intel i7-4600U CPU of 2.10 GHz and 8 GB RAM. The computational time was around 3 minutes.

To illustrate the importance of considering heterogeneous workforce, i.e. a workforce consisting of both regular and temporary nursing staff, as perceived in most countries during nursing staff level planning, models with a homogeneous workforce, i.e. consisting of only regular nursing staff, and model with a heterogeneous workforce are solved. As mentioned, shifts 1 (daytime shift), 2 (evening shift) and 3 (overnight shift) are the typical and representative shifts, the staff level determined from the staff level planning model for the three shifts are summarised in Table 3.14 to Table 3.16. The staff level determined from the staff level planning model for the planning horizon of one month is summarized in Table 3.17. As the staff level planning model generates solution with many different task assignments while having the same staff level, the tables summarise the staff level instead of listing all task assignment to simplify the case. Number(s) within brackets refers to the amount of working hours (in hours) of temporary nursing staff/ overtime work (in hours) of regular nursing staff.

Table 3.14 Staff level of a heterogeneous workforce for daytime shift

Combination	Staff Level							
	PCW		HW		EN		RN	
	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time
1	2(3;1)	0	0	4	0	2	0	1
2	2(3;1)	0	0	5	0	1(2)	0	1
3	2(3;1)	0	0	3	0	2(2;0)	0	1(2)
4	2(4;1)	0	0	3(2;0;0)	0	2(2;0)	0	1(1)
5	1(5)	1(1)	0	3	0	4	1(3)	0

Table 3.15 Staff level of a heterogeneous workforce for evening shift

Combination	Staff Level							
	PCW		HW		EN		RN	
	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time
1	2(4;1)	0	2(3;1)	0	2(3;1)	0	2(3;1)	0
2	2(3;1)	0	2(4;1)	0	2(3;1)	0	2(3;1)	0
3	2(4;1)	0	2(3;1)	0	2(3;1)	0	2(4;1)	0

Table 3.16 Staff level of a heterogeneous workforce for overnight shift

Combination	Staff Level							
	PCW		HW		EN		RN	
	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time
1	2(2;1)	0	1(1)	0	1(1)	0	1(1)	0

Table 3.17 Staff level of a heterogeneous workforce for one month

Combination	Staff Level							
	PCW		HW		EN		RN	
	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time
1	6 (90; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	4	3 (90; 30; 30)	2	3 (90; 30; 30)	1
2	6 (90; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	5	3 (90; 30; 30)	1 (60)	3 (90; 30; 30)	1
3	6 (90; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	3	3 (90; 30; 30)	2 (60; 0)	3 (90; 30; 30)	1 (60)
4	6 (120; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	3 (60; 0; 0)	3 (90; 30; 30)	2 (60; 0)	3 (90; 30; 30)	1 (30)
5	5 (150; 120; 30; 60; 30)	1 (30)	3 (90; 30; 30)	3	3 (90; 30; 30)	4	4 (90; 90; 30; 30)	0
6	6 (90; 30; 90; 30; 60; 30)	0	3 (120; 30; 30)	4	3 (90; 30; 30)	2	3 (90; 30; 30)	1
7	6 (90; 30; 120; 30; 60; 30)	0	3 (120; 30; 30)	5	3 (90; 30; 30)	1 (60)	3 (90; 30; 30)	1
8	6 (90; 30; 120; 30; 60; 30)	0	3 (120; 30; 30)	3	3 (90; 30; 30)	2 (60; 0)	3 (90; 30; 30)	1 (60)
9	6 (120; 30; 120; 30; 60; 30)	0	3 (120; 30; 30)	3 (60; 0; 0)	3 (90; 30; 30)	2 (60; 0)	3 (90; 30; 30)	1 (30)
10	5 (150; 120; 30; 60; 30)	1 (30)	3 (120; 30; 30)	3	3 (90; 30; 30)	4	4 (90; 90; 30; 30)	0
11	6 (90; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	4	3 (90; 30; 30)	2	3 (120; 30; 30)	1
12	6 (90; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	5	3 (90; 30; 30)	1 (60)	3 (120; 30; 30)	1
13	6 (90; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	3	3 (90; 30; 30)	2 (60; 0)	3 (120; 30; 30)	1 (60)
14	6 (120; 30; 120; 30; 60; 30)	0	3 (90; 30; 30)	3 (60; 0; 0)	3 (90; 30; 30)	2 (60; 0)	3 (120; 30; 30)	1 (30)
15	5 (150; 120; 30; 60; 30)	1 (30)	3 (90; 30; 30)	3	3 (90; 30; 30)	4	4 (90; 120; 30; 30)	0

Each optimal solution contains staff level, shift assignment, days off assignment and task assignment of nursing staff in the nursing home. Nursing home manager can choose the optimal solution according to particular interest. For example, if an optimal solution is selected based on the highest staff level with no overtime work, the staff level and the corresponding amount of working hours (in hours) of temporary nursing staff are as shown in Table 3.18.

Table 3.18 Optimised staff level based on NSGA-II

Staff Level							
PCW		**HW**		**EN**		**RN**	
Part-time	**Full-time**	**Part-time**	**Full-time**	**Part-time**	**Full-time**	**Part-time**	**Full-time**
5 (150; 120; 30; 60; 30)	1 (30)	3 (90; 30; 30)	3	3 (90; 30; 30)	4	4 (90; 120; 30; 30)	0

3.5 Summary

Staff level planning is known to be very difficult and critical for increasing nursing home's service capacity and boosting the positive outcomes of both nursing staff and residents. The previous studies of staff level planning mostly consider a single objective/criterion such as staffing cost and staff level. In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff level planning. In this chapter, a multi-objective optimisation approach to staff level planning problem in nursing homes is described. NSGA-II was applied to solve the staff level planning problem and thus staff level for nursing staff in nursing home can be determined. A case study of a subvented nursing home in Hong Kong was conducted to illustrate the approach.

Chapter 4 – A MULTI-OBJECTIVE OPTIMISATION APPROACH TO STAFF SCHEDULING PROBLEM

4.1 Introduction

In this chapter, the formulation of an optimisation model for staff scheduling problem with multi-objectives and criteria are presented in Sections 4.2. The solving of the staff level planning problem using a case study of a subvented nursing home in Hong Kong is illustrated in Section 4.3. A summary is given at the end of the chapter.

Figure 4.1 outlines the methodology. Optimal staff schedule, overtime work hours and work hours are determined based on NSGA-II.

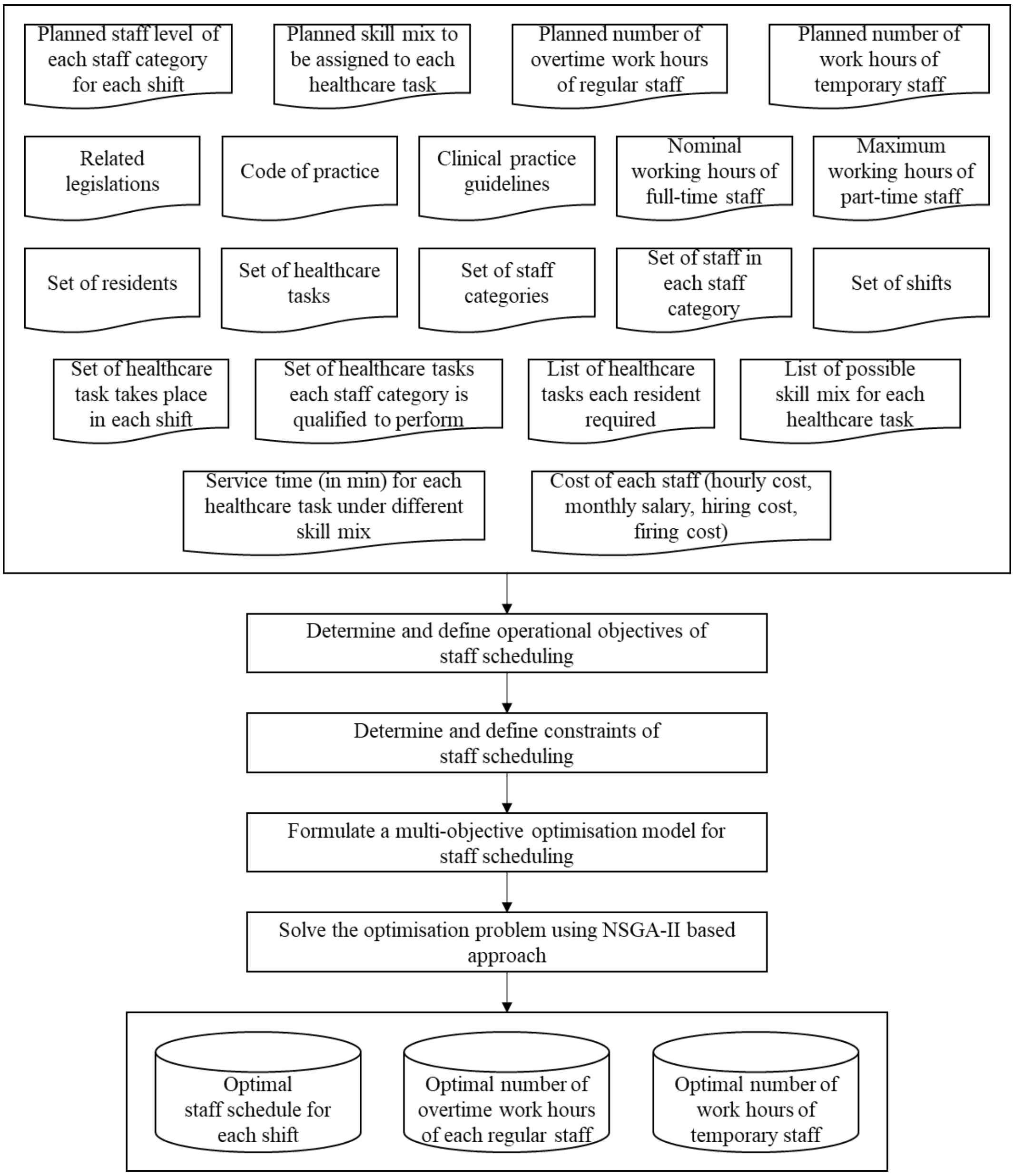

Figure 4.1 Outline of a multi-objective optimisation approach to staff scheduling problem

4.2 Formulation of an Optimisation Model for Staff Scheduling Problem

The importance and research interest of staff scheduling in nursing homes have been extensively reviewed (in Chapter 2). Many different evaluation criteria exist for optimal staff scheduling; however, the previous studies of staff scheduling mostly consider a single objective/criterion. In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff scheduling.

A few recent research solving a multi-objective/multi-criteria staff scheduling problem include Parr and Thompson (2007) and Todorovic and Petrovic (2013). Parr and Thompson treated the objectives and constraints to be dealt with as a weighted cost function, with the weights determined by negotiation with hospital schedulers. Todorovic and Petrovic solved the nurse rostering problem in hospital using bee colony optimisation algorithm, with the objective of minimising the sum of the penalties resulted from soft constraint violation. The soft constraints they considered include 1) forbidden sequence of working shifts, 2) minimum and maximum numbers of working hours/shifts per week/planning period; 3) minimum and maximum numbers of consecutive working days; and 4) minimum and maximum numbers of days.

For the positive outcomes of nursing home manager, nursing staff and residents, this study performs staff scheduling using a multi-objective optimisation approach and makes use of total staffing costs, staff level and overtime work as the evaluation criterion for staff scheduling. In this new multi-objective optimisation approach to staff scheduling, nursing home managers need not carefully adjust the weight of various objectives, which was the case of the weighted-sum method applied by previous studies. Also, various criteria proposed by previous studies can be considered simultaneously as either/both objectives and/or constraints.

Staff Scheduling Problems (SSPs) of nursing staff in nursing home involve a nursing home with a set of work shifts, in which a set of healthcare tasks required by a set of residents are completed by a set of available nursing staff. The nursing home has regulations that impose constraints on the assignment of nursing staff to work shifts and the assignment of work hours and days off to nursing staff over the planning horizon. The objectives are to minimise the total staffing costs and total overtime work (in hours) of all regular nursing staff of all shifts while maximising staff level, given that all operational constraint are satisfied.

There is a set of C= {1, 2, … , I} of available nursing staff categories, a set of D_i = {1, 2…, J_i} regular nursing staff in a particular nursing staff category i, and a set of D_i^t = {1, 2, …, J_i^t} temporary nursing staff in a particular nursing staff category i. For each shift m in set S, a certain number of nursing staff, determined based on the solution of staff level planning in Section 3.2, will be chosen from the set C of i nursing staff, together with an assignment of the work hours and days off, in order to meet operational demands and constraints. For reasons of cost effectiveness and healthcare task fulfilment, temporary nursing staff can be selected and performed a maximum number of hours (T_i^{max}) of work per shift; while $T_i^{w,max}$ hour per week, when the selection of regular nursing staff is unfavourable.

The goal is to find feasible solutions that optimises the total staffing costs of assigning nursing staff *ij*, either temporary or regular nursing staff, to work shift *m*. We refer to this model of the staff scheduling problem as SSP.

The input data, parameters and variables, in addition to Section 3.2, for formulating a staff scheduling model are shown below.

Input Data:

W'	Set of weeks (in the planning horizon of 1 month), *W'* = {1, 2…*W*}
Q'	Set of month (in the planning horizon of 1 month), *Q*'= {1,2…*Q*}

Parameters:

$T_i^{w,max}$	The upper limit of working hours per week for a temporary staff of category *i*
S_{ij}	Monthly salary of regular staff *ij*
R_i^{otp}	Hourly wage of overtime work of a regular nursing staff of category *i*

C_i^h Cost of hiring a regular nursing staff of category *i*

C_i^f Cost of having a regular nursing staff of category *i* left the workforce

$X_i^{w,max}$ The upper limit of shifts a nursing staff of category *i* can undertake in every 7 consecutive days

O_{im}^{max} The upper limit of overtime work (in hours) for a regular nursing staff of category *i* in shift *m*

Variables:

X_{ij} $= \begin{cases} 1 \text{ if regular staff } ij \text{ is counted in the workforce} \\ 0 \text{ otherwise} \end{cases}$

E_{ijw}^t Total working hours of temporary staff *ij* in week *w*

T_{ijm}^t Working hours of the *j*th temporary nursing staff of category *i* in shift *m*

N_i^h Number of additional regular nursing staff of category *i* to be hired

N_i^f Number of existing regular nursing staff of category *i* left the workforce

N_{iw}^t Number of temporary nursing staff of category *i* in week *w*

X_{ijw}^t 1 if the *j*th temporary nursing staff of category *i* is counted in the workforce in week *w*; otherwise 0

X_{ijq} 1 if *j*th nurse of category *i* is counted in workforce for month *q*; otherwise 0

E_{ijw}^t Total working hours of the *j*th temporary nursing staff of category *i* in week *w*

A staff scheduling model is formulated as follows.

$$\mathrm{F}_4 = \text{Minimise} \sum_{i\in C} \sum_{j\in D_i \cup D'_i} \left(X_{ij} S_{ij} + R_i^{otp} \sum_{m\in S} T_{ijm}^{ot} \right) + \sum_{i\epsilon C} \left(C_i^h N_i^h + C_i^f N_i^f + C_i^t T_i^t \right) \tag{4.1}$$

$$\mathrm{F}_5 = \text{Maximise} \left(\sum_{i\in C} \sum_{j\in D_i \cup D'_i} \sum_{m\in S} X_{ijm} + \sum_{i\in C} \sum_{j\in D_i^t \cup D''_i} \sum_{m\in S} X_{ijm}^t \right) \tag{4.2}$$

$$\mathrm{F}_6 = \text{Minimise} \sum_{i\in C} \sum_{j\in D_i \cup D'_i} \sum_{m\in S} T_{ijm}^{ot} \tag{4.3}$$

, where

$$X_{ij} = \begin{cases} 1 \text{ if } \sum_{m=1}^{90} X_{ijm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D'_i \tag{4.4}$$

$$T_{ijm}^{ot} = \max \left[\left(\sum_{\forall l \in P_i} T_{ijlm} - U \right), 0 \right] \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D'_i \quad ,\forall m \in S \tag{4.5}$$

$$N_i^h = \sum_{j\epsilon D_i \cup D'_i} \sum_{q\in Q'} \{X_{ijq} - X_{ij(q-1)}\}, \qquad ,\forall i \in C \tag{4.6}$$

$if\ X_{ijq} = 1$

$$N_i^f = \sum_{j\epsilon D_i \cup D'_i} \sum_{q\in Q'} \{X_{ij(q-1)} - X_{ijq}\}, \qquad ,\forall i \in C \tag{4.7}$$

$if\ X_{ijq} = 0$

$$X_{ijq} = \begin{cases} 1 \text{ if } \sum_{m=1}^{90} X_{ijm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall q \in Q' \tag{4.8}$$

$$T_i^t = \sum_{j \in D_i^t \cup D_i''} \sum_{m \epsilon S} \sum_{l \in P_i} T_{ijlm}^t \qquad ,\forall i \in C \tag{4.9}$$

Subject to

$$\sum_{l \in P_i} \sum_{i \in C} T_{il} \cdot N_l \cdot Y_{lm} \leq \sum_{i \in C} \sum_{j \in D_i \cup D'_i} (U + T_{ijm}^{\text{ot}}) + \sum_{i \in C} \sum_{j \in D_i^t} T_{ijm}^t \qquad ,\forall m \in S \tag{4.10}$$

$$\sum_{m=\{1,22,43,64\}}^{m+20} X_{ijm} \leq X_i^{w,max} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \tag{4.11}$$

$$X_{ijm} + X_{ij(m+1)} \leq 1 \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall m \in S \tag{4.12}$$

$$X_{ijm}^t + X_{ij(m+1)}^t \leq 1 \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \quad ,\forall m \in S \tag{4.13}$$

$$\sum_{m=\{1,4,\ldots 85,88\}}^{m+2} X_{ijm} \leq 1 \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \tag{4.14}$$

$$\sum_{m=\{1,4,\ldots 85,88\}}^{m+2} X_{ijm}^t \leq 1 \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \tag{4.15}$$

$$0 \le T_{ijm}^{\text{ot}} \le O_{im}^{max} \cdot X_{ijm} \qquad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \; ,\forall m \in S \qquad (4.16)$$

$$0 \le T_{ijm}^{\text{t}} \le T_{ijm}^{\text{t}} \cdot X_{ijm}^{t} \le T_i^{w,max} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall m \in S \qquad (4.17)$$

$$E_{ijw}^{t} = \sum_{m \in \{1,22,43,\dots\}}^{m+20} T_{ijm}^{t} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall w \in W' \qquad (4.18)$$

$$0 \le \; E_{ijw}^{t} \le T_i^{w,max} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall w \in W' \qquad (4.19)$$

$$X_{ijw}^{t} = \begin{cases} 1 \text{ if } E_{ijw}^{t} \ge 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall w \in W' \qquad (4.20)$$

$$X_{ij} \in \{0, 1\} \qquad ,\forall i \in C, \; ,\forall j \in D_i \cup D_i', \qquad (4.21)$$

$$X_{ijw}^{t} \in \{0, 1\} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall w \in W' \qquad (4.22)$$

$$X_{ijq} \in \{0, 1\} \qquad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \; ,\forall q \in Q' \qquad (4.23)$$

$$X_{ijm} \in \{0, 1\} \qquad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \; ,\forall m \in S \qquad (4.24)$$

$$X_{ijm}^{t} \in \{0, 1\} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall m \in S \qquad (4.25)$$

In the model, the objective function (4.1) minimises the total staffing cost of all shifts, taking into account the costs yielding from hiring new and firing existing nursing staff as well. Objective function (4.2) maximises the staff level of all shifts. Objective function (4.3) minimises the total overtime work of regular nursing staff of all shifts. Equations (4.4) to (4.9) define X_{ij}, T^{ot}_{ijm}, N^{h}_{i}, N^{f}_{i}, X_{ijq}, and T^{t}_{i}. For example, a regular nursing staff is considered being counted in the workforce (i.e. X_{ij}=1) only if he/she is assigned to at least one work shift in the particular month within the planning horizon.

Similar to Constraint (3.7) in the staff level planning model, Constraint (4.10) imposes the task requirements as specified by the amount of time required to complete all healthcare tasks within each shift by regular and temporary nursing staff. Constraint (4.11) limits the number of shifts each selected regular nursing staff can undertake in seven consecutive days, i.e. 21 (3x7) shifts. In other words, this constraint ensures at least one day of day off is assigned to each selected regular nursing staff. Constraints (4.12) and (4.13) prohibit the model from assigning consecutive shifts to each selected regular and temporary nursing staff, respectively. Constraint (4.14) and (4.15) prohibit the model from assigning more than one shift per day to each selected regular and temporary nursing staff, respectively. In other words, the model ensures no split shifts is allowed. Constraint (4.16) limits the number of hours of overtime work for each selected regular nursing staff. If the regular nursing staff is not selected, this constraint prohibits the model from assigning overtime work to this regular nursing staff. Similarly, Constraint (4.17) limits the number of working hours that a selected temporary nursing staff is allowed to work and prohibits the model from assigning working hours to this temporary nursing staff if he/she is not selected for the shift. Constraints (4.18) and (4.19) define and limits the total weekly working hours for each selected temporary nursing staff. Constraint (4.20) define the relationship between X_{ijw}^{t} and E_{ijw}^{t}. Constraint (4.21) to (4.25) define X_{ij}, X_{ijw}^{t}, X_{ijq}, X_{ijm} and X_{ijm}^{t} are binary variables.

A NSGA-II approach, similar to the one described in Section 3.3, is applied to solve the multi-objective staff scheduling problem.

4.3 Computational Experiments

The purpose of this section is to illustrate the ability of the multi-objective optimisation approach in solving real-world staff scheduling problem. The use of heterogeneous workforce perceived in reality is considered. The NSGA-II is coded in MATLAB programming language and run on a PC with an Intel i7-4600U CPU of 2.10 GHz and 8 GB RAM. Data of a subvented nursing home in Hong Kong was collected, revised due to confidentiality issue, and inputted into the models as problem instance. For the details of the reference case, please refer to Section 3.4.1.

NSGA-II is applied to solve the multi-objective staff scheduling problem formulated. The staff level required for each shift is determined by the staff level planning optimisation model, then the staff scheduling optimisation model assigns staff to shift based on the staff level determined by the staff level planning model. Surplus staff might be eliminated during genetic operations. For illustration purpose, in this section, the staff level as shown in Table 4.1 are input into the scheduling problem for subsequent scheduling.

Table 4.1 Staff level as input for staff scheduling

Staff Level							
PCW		HW		EN		RN	
Part-time	Full-time	Part-time	Full-time	Part-time	Full-time	Part-time	Full-time
12	0	8	2	6	8	6	6

Again, as the quality of solutions obtained depends heavily on the parameters setting of a multi-objective evolutionary algorithm (Sadeghi & Niaki, 2015), four parameters in NSGA-II will be calibrated, i.e. the population size (*pop*), the number of iterations to stop the algorithm (*iteration*), the crossover probability (*CR*), and the mutation probability (*MR*). As the Objective Functions (4.1) and (4.3) are minimisisation while Objective Function (4.2) is maximisation, two equations apply. For the smaller-the-better, the value of S/N can be calculated using Equation (4.26). For the greater-the-better, the value of S/N can be calculated using Equation (4.27).

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \tag{4.26}$$

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{{y_i}^2}\right] \tag{4.27}$$

, where η is the S/N ratio, n is the number of replications, and y_i is the response values.

In this study, the four parameters were obtained in systematic review of optimization methodology and were selected by simulation method in widely range. Interactions between factors are assumed neglectable. Three levels of the parameters are shown in Table 4.2. The L^9 orthogonal array is applied to reduce the number of experiments from 81 (3^4) to 9. To improve accuracy, experiments were repeated five times. This meant that only 45 (9*5) experiments, instead of 405 experiments, were required to reach a conclusion.

Table 4.2 Parameters (factors) and the levels for staff scheduling

	Levels		
Parameter	**Low (1)**	**Medium (2)**	**High (3)**
Population Size (Pop)	50	100	150
Number of Iterations to Stop the Algorithm (Iteration)	300	500	750
Crossover Rate (CR)	0.7	0.8	0.9
Mutation Rate (MR)	0.001	0.01	0.1

Tables 4.3 to 4.5 show the experimental design and response statistics, repeated five times, under NSGA-II for total staffing costs, amount of overtime work and staff level, respectively. The related S/N ratios of total staffing costs, overtime work and staff level of the proposed NSGA-II are shown in Figures 4.2 to 4.4, respectively. The values of S/N ratio of total staffing costs, overtime work and staff level are presented in Tables 4.6, 4.7 and 4.8, respectively. The largest values of S/N ratio depict the optimal condition.

Table 4.3 Experimental design and response statistics under NSGA-II (total staffing costs)

Number	Control Parameters				Response 1 (HK$)	Response 2 (HK$)	Response 3 (HK$)	Response 4 (HK$)	Response 5 (HK$)
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	774264	668108	668108	922990	774264
2	0.7	0.01	100	500	907441	804989	907441	804989	804989
3	0.7	0.1	150	750	831547	1003497	804679	1050284	698966
4	0.8	0.001	100	750	832177	918599	746565	832177	918599
5	0.8	0.01	150	300	782747	808077	835845	904861	836891
6	0.8	0.1	50	500	833716	837314	921435	921435	833745
7	0.9	0.001	150	500	783544	831714	780706	780706	696992
8	0.9	0.01	50	750	747295	832946	886846	1051791	1051791
9	0.9	0.1	100	300	1022552	833395	833395	1022552	886099

Table 4.4 Experimental design and response statistics under NSGA-II (overtime work)

Number	Control Parameters				Response 1 (hour)	Response 2 (hour)	Response 3 (hour)	Response 4 (hour)	Response 5 (hour)
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	0	8	8	0	0
2	0.7	0.01	100	500	0	0	0	0	0
3	0.7	0.1	150	750	0	0	0	0	5
4	0.8	0.001	100	750	0	0	5	0	0
5	0.8	0.01	150	300	5	2	0	0	0
6	0.8	0.1	50	500	2	0	0	0	1
7	0.9	0.001	150	500	2	0	2	2	4
8	0.9	0.01	50	750	5	0	0	0	0
9	0.9	0.1	100	300	0	0	0	0	0

Table 4.5 Experimental design and response statistics under NSGA-II (staff level)

Number	Control Parameters				Response 1*	Response 2*	Response 3*	Response 4*	Response 5*
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	51	49	49	52	51
2	0.7	0.01	100	500	54	52	54	52	52
3	0.7	0.1	150	750	52	53	47	55	46
4	0.8	0.001	100	750	52	54	50	52	54
5	0.8	0.01	150	300	47	50	48	57	49
6	0.8	0.1	50	500	49	48	53	53	50
7	0.9	0.001	150	500	48	52	47	47	44
8	0.9	0.01	50	750	50	52	54	55	55
9	0.9	0.1	100	300	55	52	52	55	53

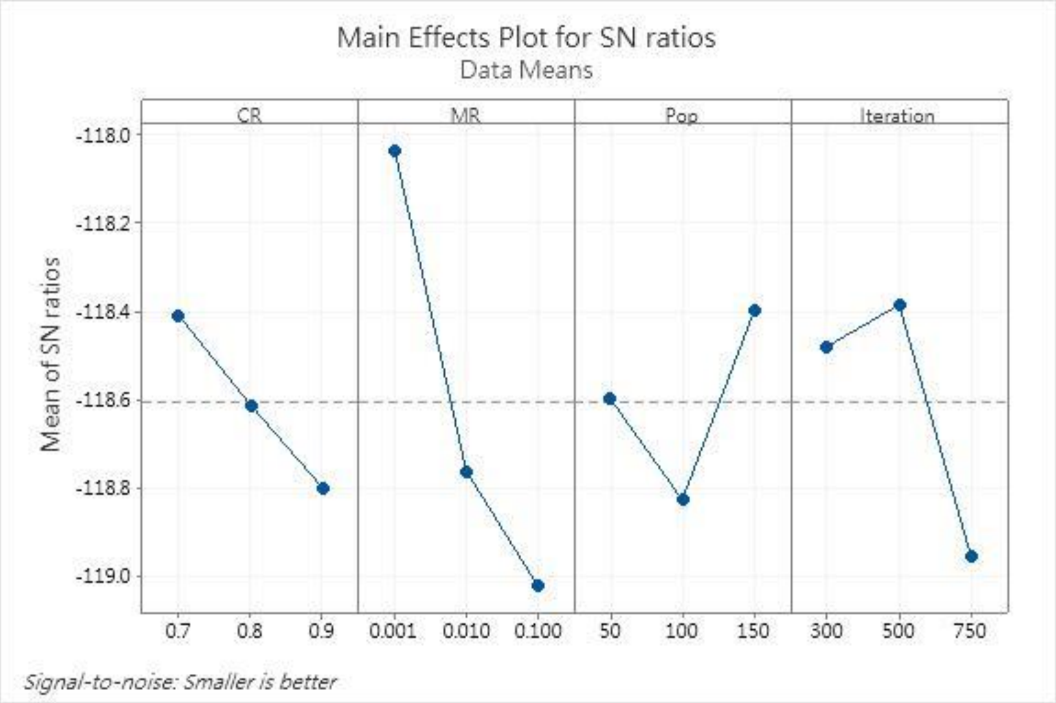

Figure 4.2 S/N ratio plots of total staffing costs for staff scheduling

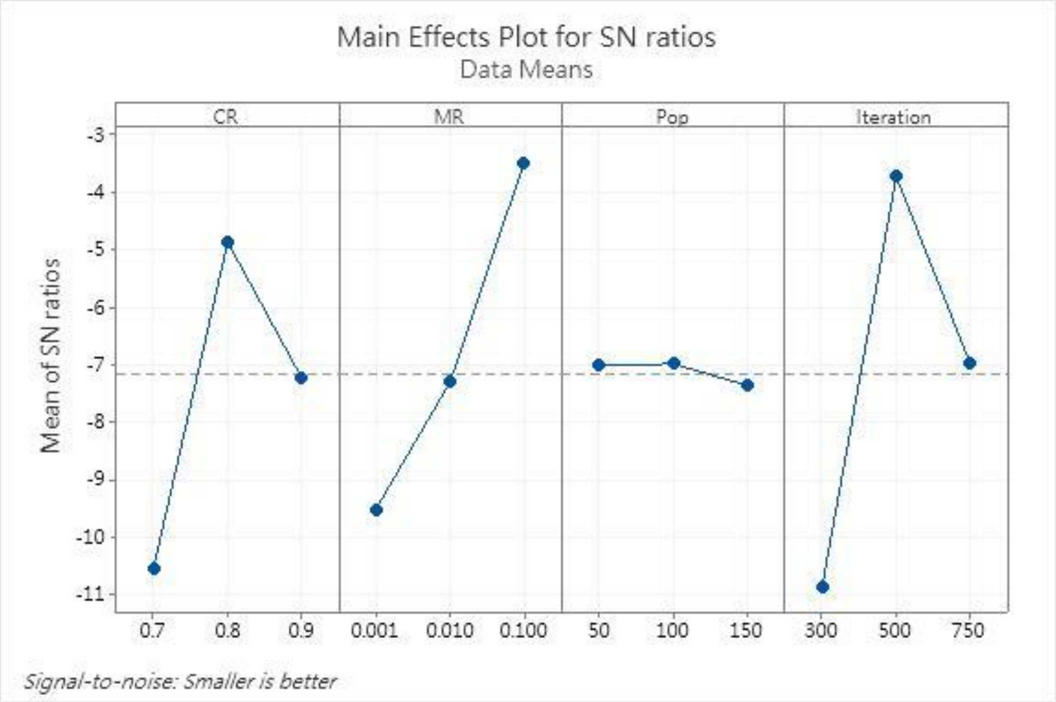

Figure 4.3 S/N ratio plots of overtime work for staff scheduling

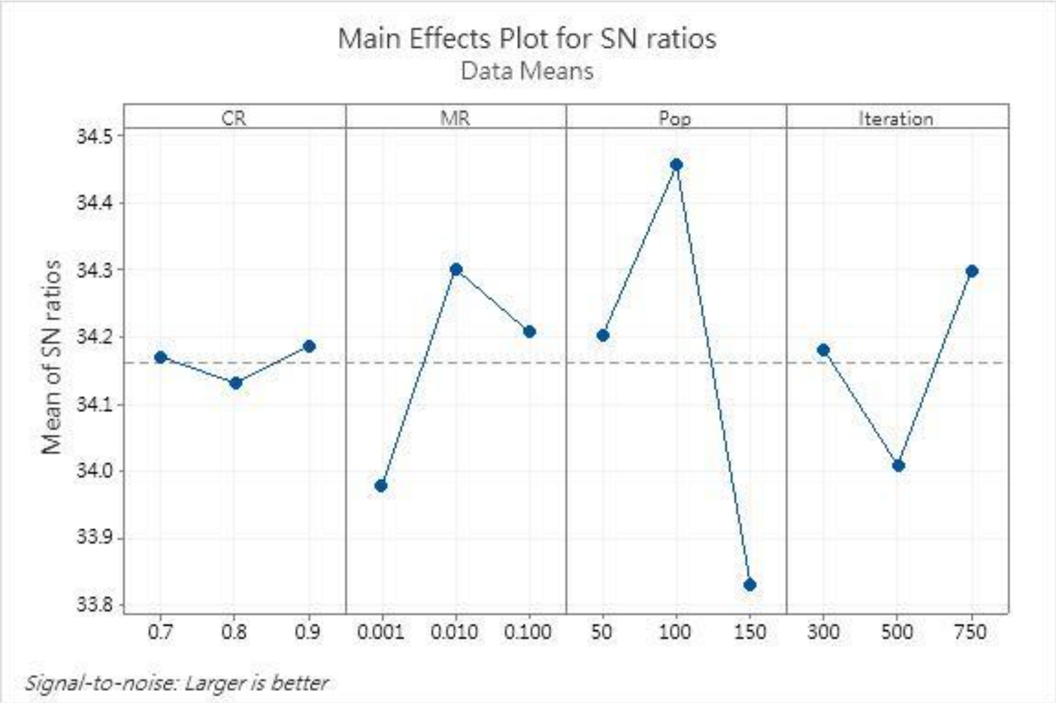

Figure 4.4 S/N ratio plots of staff level for staff scheduling

Table 4.6 Response table for S/N ratios (total staffing costs)

Level	**CR**	**MR**	**Pop**	**Iteration**
1	-118.4	-118.0	-118.6	-118.5
2	-118.6	-118.8	-118.8	-118.4
3	-118.8	-119.0	-118.4	-119.0
Delta	0.4	1.0	0.4	0.6
Rank	4	1	3	2

Table 4.7 Response table for S/N ratios (overtime work)

Level	**CR**	**MR**	**Pop**	**Iteration**
1	-10.536	-9.518	-7.024	-10.858
2	-4.875	-7.312	-6.990	-3.741
3	-7.236	-3.495	-7.369	-6.990
Delta	5.661	6.023	0.379	7.117
Rank	3	2	4	1

Table 4.8 Response table for S/N ratios (staff level)

Level	CR	MR	Pop	Iteration
1	34.17	33.98	34.20	34.18
2	34.13	34.30	34.46	34.01
3	34.19	34.21	33.83	34.30
Delta	0.05	0.32	0.63	0.29
Rank	4	2	1	3

The Taguchi optimal parameters are the average of that of all responses (Tian et al., 2017), i.e. total staffing costs, that of overtime work, and that of staff level. According to the genetic parameter combinations of highest S/N ratio under different responses in Tables 4.6 to 4.8, the genetic parameter settings obtained from the Taguchi method are *CR* = 0.7, *MR* = 0.001, *pop* = 150, *iteration* = 500 for the total staffing costs optimisation. Similarly, the genetic parameter settings are *CR* = 0.8, *MR* = 0.1, *pop* = 100, *iteration* = 500 for the overtime work optimisation. the genetic parameter settings are *CR* = 0.9, *MR*=0.01, *pop*=100, *iteration* =750 for the staff level optimisation. Therefore, parameters of NSGA-II were set with population size at 117 (*pop* = 117), number of iterations to stop the algorithm at 584 (*iteration* = 584), crossover probability at 0.8 (*CR* = 0.8) and mutation probability at 0.037 (*MR* = 0.037), respectively.

The NSGA-II was coded in MATLAB programming language and ran on a PC with an Intel i7-4600U CPU of 2.10 GHz and 8 GB RAM. The computational time was around 20 minutes. Figure 4.5 shows the Pareto optimal solutions of the staff scheduling problem solved by NSGA-II.

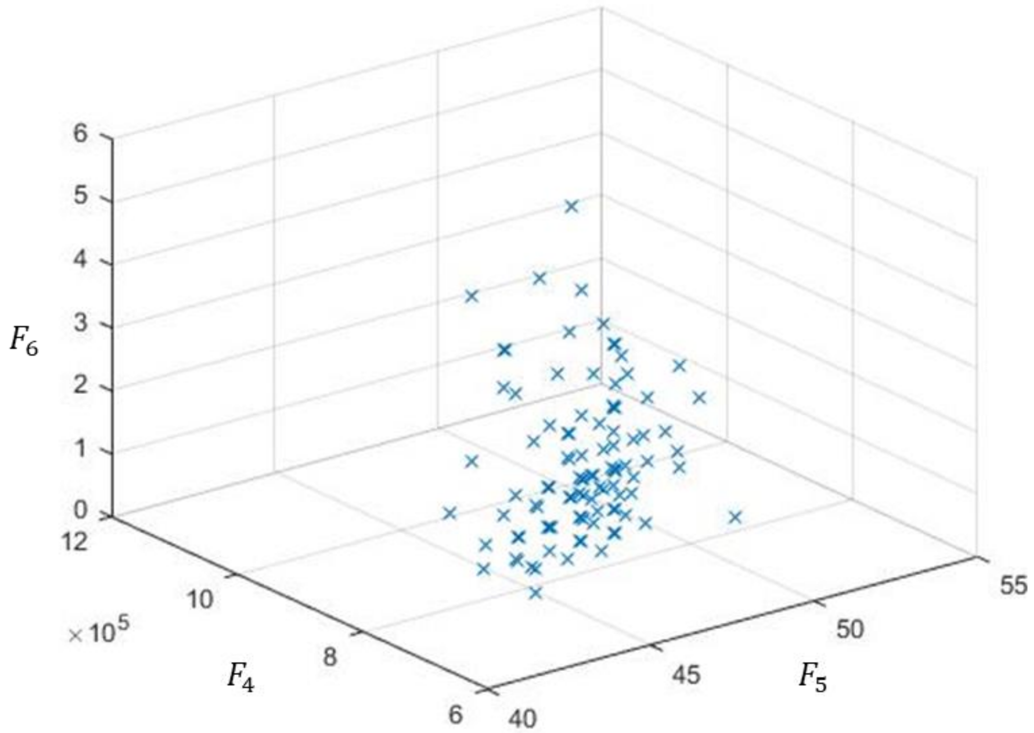

Figure 4.5 Pareto solutions based on NSGA-II (staff scheduling)

Each optimal solution contains staff level, shift assignment, days off assignment and task assignment of nursing staff in the nursing home. Nursing home manager can choose the optimal solution according to particular interest. For example, if an optimal solution is selected primarily based on the highest staff level and with the lease overtime work, an extract of the staff schedule obtained from the staff scheduling model for temporary nursing staff and regular nursing staff are shown in Table 4.9 and 4.10, respectively

In Tables 4.9 and 4.10, ‘A*’ denotes the assignment to daytime shift with monthly healthcare task, ‘A’ denotes the assignment to daytime shift, ‘P’ denotes the assignment to evening shift, ‘N’ denotes the assignment to overnight shift, while ‘0’ denotes the assignment of day off. In Table 4.9, the number(s) within brackets refers to the amount of working hours (in hours) of temporary nursing staff. In Table 4.10, the number(s) within brackets refers to the amount of overtime work (in hours) of regular nursing staff.

Table 4.9 An extract of optimised staff schedule for temporary nursing staff based on NSGA-II

Category	Nature	ID	Day									
			1	2	3	4	5	6	7	8	9	10
PT	PCW	1	A*(2)	A(1)	P(1)	N(2)	P(2)	A(2)	0	0	N(1)	0
PT	PCW	2	N(2)	N(2)	N(2)	P(1)	A(4)	N(2)	0	N(2)	0	A(2)
PT	PCW	3	P(1)	P(2)	A(1)	A(1)	A(1)	P(4)	0	P(2)	A(2)	0
PT	PCW	4	N(1)	N(1)	N(1)	N(1)	N(2)	N(1)	0	0	0	0
PT	PCW	5	0	0	0	0	N(1)	P(1)	A(4)	A(1)	0	0
PT	PCW	6	0	0	0	0	0	0	A(1)	0	0	N(2)
PT	PCW	7	0	0	0	0	0	0	P(1)	A(4)	P(2)	P(2)
PT	PCW	8	0	0	0	0	0	0	N(2)	0	N(2)	N(1)
PT	PCW	9	0	0	0	0	0	0	N(1)	N(1)	0	0
PT	EN	1	P(1)	A(2)	P(3)	P(4)	P(4)	N(1)	0	A(3)	A(3)	P(1)
PT	EN	2	0	N(1)	P(1)	P(1)	P(1)	0	A(3)	0	0	0
PT	EN	3	P(3)	P(1)	N(1)	N(1)	N(1)	P(1)	0	P(1)	P(3)	0
PT	EN	4	N(1)	P(3)	A(3)	A(2)	A(3)	A(3)	0	0	0	A(2)
PT	EN	5	0	0	0	0	0	0	P(3)	P(3)	0	0
PT	EN	6	0	0	0	0	0	0	P(1)	0	N(1)	N(1)

Table 4.10 An extract of optimised staff schedule for regular nursing staff based on NSGA-II

Category	Nature	ID	Day									
			1	2	3	4	5	6	7	8	9	10
FT	PCW	1	A*(0)	A(0)	P(0)	A(0)	0	A(0)	P(0)	0	P(0)	P(0)
FT	PCW	2	P(0)	P(0)	A(0)	P(0)	P(0)	0	0	P(0)	A(0)	A(0)
FT	PCW	3	0	0	0	0	0	0	0	0	0	0
FT	EN	1	A*(0)	0	0	0	0	P(0)	0	0	0	0
FT	EN	2	A*(0)	0	0	0	0	0	0	0	0	0
FT	EN	3	0	0	0	0	0	0	0	0	0	0
FT	EN	4	0	0	0	0	0	0	0	0	0	0
FT	EN	5	A*(0)	0	0	0	0	0	0	0	0	P(0)
FT	EN	6	0	0	0	0	0	0	0	0	0	0
FT	RN	1	0	0	0	0	0	0	0	0	0	0
FT	RN	2	A*(0)	0	0	0	0	0	0	0	0	0
FT	RN	3	A*(0)	0	0	0	0	0	0	0	0	0
FT	RN	4	0	0	0	0	0	0	0	0	0	0
FT	RN	5	P*(0)	P(0)	0	0	0	0	0	0	0	0
FT	RN	6	A*(0)	0	0	0	0	0	0	0	P(0)	0

4.4 Summary

Staff scheduling problem and different variation of the problem have eeb proved by researchers for the NP-hardness. The previous studies of staff scheduling mostly consider a single objective/criterion such as staffing cost and staff level. In reality, several objectives/criteria have to be considered simultaneously in order to obtain good quality or even optimal solutions for the staff level planning. Even for the few previous studies that consider multiple objectives/criteria, they mainly applied the weighted sum method which is difficult to adjust the weight for obtaining quality solution. In this chapter, a multi-objective otimisation approach to staff scheduling problem in nursing homes is described. NSGA-II was applied to solve the staff scheduling problem. A case study of a subvented nursing home in Hong Kong was conducted to illustrate the approach.

Chapter 5 – DEVELOPMENT OF A METHODOLOGY FOR INTEGRATED STAFF LEVEL PLANNING AND SCHEDULING

5.1 Introduction

In reality, staff level planning and staff scheduling are sometimes conducted separately to meet the needs of users. For example, staff level planning not only serve as a foundation for annual salary budget, or equipping nurse managers' with the ability to manage salary costs or control position, but also 'providing a consistent framework for developing staff schedules and an automatic calculation of actual productivity to targeted benchmark, as well as department-specific vacancy rates', according to Ponti, Germain and Moulton (2010, pp.36). However; staff level planning and scheduling are highly interrelated and separate consideration of them would result in strategic and operational conflicts. For instance, when the staff level was determined without considering the operational requirements, such as forbidden sequence of working shifts and maximum number of consecutive working days, this may usually under-estimate the staff level required and result in constraints violation. The summary of constraints violation when using the staff level determined in Section 3.4.2 for scheduling in Section 4.3 is shown in Table 5.1. The three values refer to the number of constraints violation regarding assignment of consecutive shifts (Constraint (4.12) and Constraint (4.13)), assignment of more than one shift per day (Constraint (4.14) and Constraint (4.15)), and assignment of no day off (Constraint (4.11)), respectively.

Table 5.1 Summary of constraint violations

Constraint Violation	Number of Violations
Assignment of consecutive shifts	326
Assignment of more than one shift per day	199
Assignment of no day off	191

In this chapter, a methodology for integrated staff level planning and scheduling is developed for nursing staff of nursing home is presented. After reviewing the related studies, it was noted that no previous studies on nursing homes' quantitatively study the integrated staff level planning and scheduling problem. Also, the previous studies of staff level planning and scheduling in nursing homes do not consider skill mix, skill substitution, and consequence of skill in their model. Therefore, in this chapter, a methodology for performing the integrated staff level planning and scheduling problem with the consideration of skill mix, skill substitution and consequence of skill is developed for nursing staff of nursing home. Multi-skilled workforce, staff task flexibility and the legal requirements of labour skills for job substitution (skill substitution) without creating a homogeneous workforce, are also considered. Unlike the prior research, the proposed model also addresses concerns on the work shift described in Section 2.7.1 by considering equal distribution of the work burden among available staff in every shift, and various critical factors, such as resident case-mix and nurse-to-resident ratio. This can maintain the nursing home manager's power and ability to advocate for evidence-based practices for best resident outcomes.

As discussed by Bowblis and Lucas (2012, p. 60), resident case-mix specifies the 'intensity of care required, can impact the care practices a facility employs'. Resident case-mix can be measured using various mental health and physical acuity measures, such as the proportion of residents with dementia and the proportion of residents that are chair bound (Bowblis & Lucas, 2012). In this study, resident case-mix measures the level of functional dependence by considering the number of residents receiving each treatment (i.e. healthcare task).

Nursing staff level planning incorporating skills can be categorised into managerial and technical aspects. From the managerial point of view, defining different types of skills and analysing the impact of different skill types are important. In line with the managerial point of view of skills, the skill determinant, i.e. nursing staff grade (De Bruecker et al., 2015), is defined in this study for the integrated staff level planning and scheduling model formulation. The proposed model also considers different consequences of skills, including the labour costs (Majozi & Zhu, 2005), the speed of work, and the tasks that the nursing staff can perform (Smet et al., 2014). In this study, higher skilled staff induce higher labour costs for both regular nursing staff and temporary nursing staff. Unlike previous studies that assuming higher skilled persons can increase the speed of the produced work (De Bruecker et al., 2015), this study considers the speed of work of staff based on time study conducted at the reference case. Task restrictions resulting from the skills of a staff are formulated as constraints in the optimisation model to be proposed.

The rest of this chapter is divided into the following sections. Section 5.2 describes the problem and Section 5.3 describes the formulation of the optimisation model. The NSGA-II based approach for solving the optimisation model is described in Section 5.4. The solving of the optimisation model using a case study of a subvented nursing home in Hong Kong is presented in Section 5.5. A summary is given at the end of the chapter.

5.2 A Methodology for Integrated Staff Level Planning and Scheduling

The methodology for integrated staff level planning and scheduling mainly involves defining objectives and constraints of staff level planning and scheduling, the formulation of a multi-objective optimisation model for integrated staff level planning and scheduling, and solving the model formulated using the proposed Two Level Non-dominated Sorting Genetic Algorithm-II (TLNSGA-II). Figure 5.1 outlines the methodology.

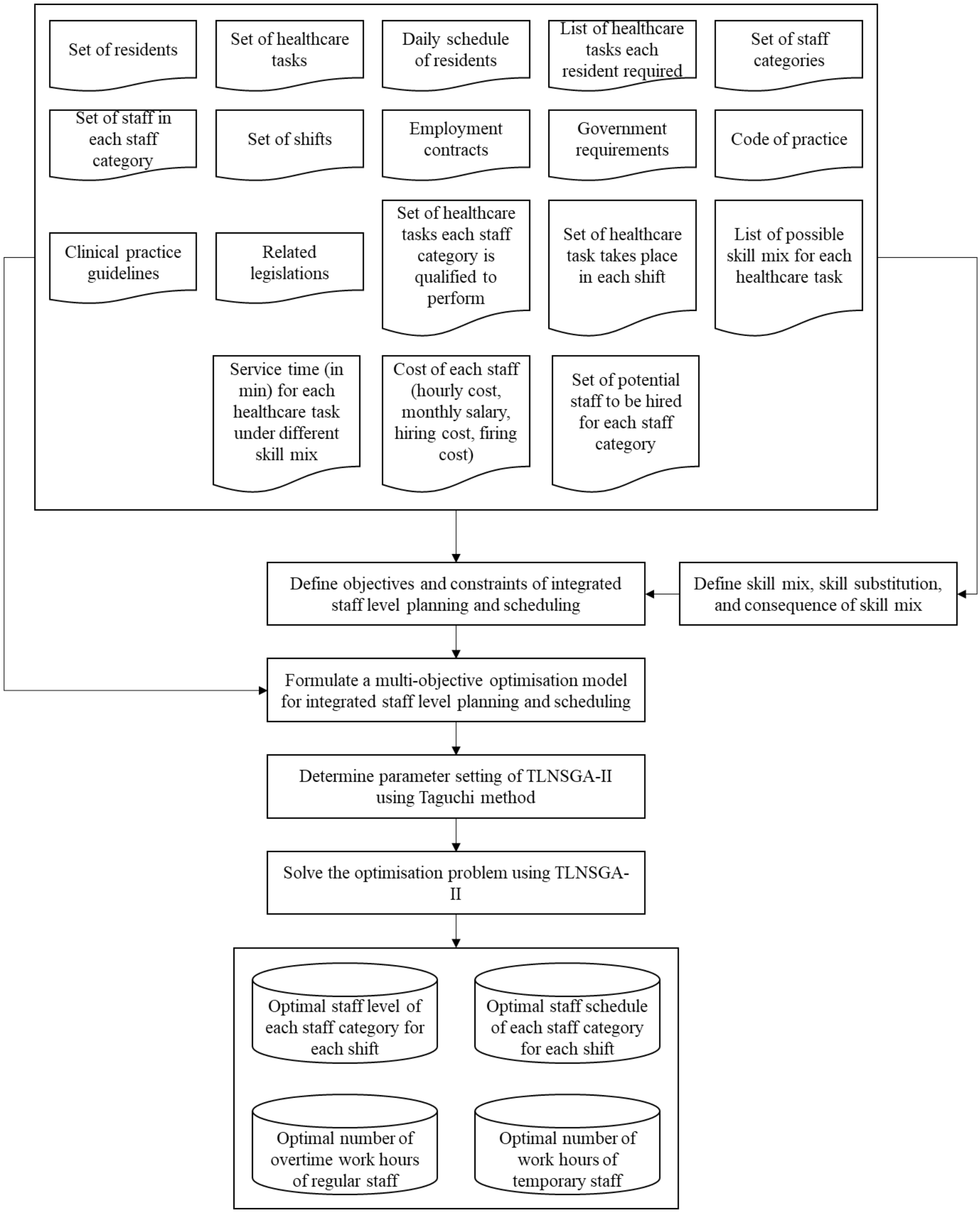

Figure 5.1 Outline of methodology for integrated staff level planning and scheduling

5.3 Description of the Integrated Staff Level Planning and Scheduling Problem

Integrated Staff Level Planning and Scheduling Problems (ISLPSPs) of nursing staff in nursing homes involve a nursing home with a set of healthcare services (or tasks) required by a set of residents that must be completed by either a set of available nursing staff or a set of nursing staff to be hired. Each nursing staff belongs to a specific category and has his/her own qualifications, skill sets, set of healthcare services qualified to perform, and constraints. Each resident has his/her own healthcare needs (i.e. healthcare tasks to be fulfilled by the nursing staff). The ISLPSPs being consider in this study are based on the concept of planning the staff level required and schedule of individual nursing staff such that sufficient nursing staff are assigned to shifts with fixed start and end times. The nursing home has regulations that impose constraints on the scheduling/assignment of nursing staff to shift work, as well as constraints on the assignment of nursing staff to healthcare tasks. The goal is to find an optimal staff level and schedule in shifts with fixed start and end times, such that all the constraints are satisfied while the total staffing costs and overtime work of regular nursing staff are minimised, while staff level is maximised.

There is a set of C= {1, 2, … , I} of available nursing staff categories, a set of D_i = {1, 2…, J_i} nursing staff in a particular nursing staff category i, and a set of D_i^t = {1, 2, …, J_i^t} temporary nursing staff in a particular nursing staff category i,.a set of resident types, R = {1, 2…K}, a set of work shifts (in the planning horizon of 1 month) S = {1, 2… M}, and a set of healthcare task, T = {1, 2, … , L}. Nursing staff have different skills, so P_i is the set of healthcare tasks that nursing staff of category *i* is qualified to perform. Each healthcare task *l* for each resident requires T_{il} minutes during the shift when it is provided by either regular or temporary nursing staff of category *i*. Sometimes, a healthcare task may jointly require nursing staff from various categories.

It is necessary to find two 4-dimensional integer matrices $T_{i\times j\times l\times m}$ and $T^t_{i\times j\times l\times m}$, such that $X_{ijlm} = 1$ and X_{ijm} if the *j*th regular nursing staff of category *i* is assigned to any task *l* in shift *m*, and $X^t_{ijlm} = 1$ and $X^t_{ijm} = 1$ if the *j*th temporary nursing staff of category *i* is assigned to task *l* in shift *m*. Thus, a general ISLPSP on the finite sets (*C*, $D_i \cup D'_i \cup D^t_i \cup D''_i$, *T*, *S*) is defined as a mapping :

$$C\times D_i \cup D'_i \cup D^t_i \cup D''_i \rightarrow T\times S\ .$$

Prior to the beginning of the planning horizon, the nursing home manager collects the service requirement of residents and the particulars of the nursing staff, such as nursing staff category, monthly salary and availability, for the staff level planning and scheduling. Residents can be nursed by various types of nursing staff, given that the nursing staff fulfils the healthcare task's legal requirement of labour skills (skill substitution) and is available. The skill substitution without creating a homogeneous workforce reflects staff task flexibility and practical requirements in reality. Consequently, a nursing home manager will assign nursing staff to shifts that contains at least a healthcare task the nursing staff is able to perform. Further, there are two main types of resident care, namely direct care and indirect care, provided by nursing staff throughout the shift. Direct care refers to the amount of time nursing staff spend with residents, while indirect care is the time spent on other tasks for residents, such as documentation of a resident's vital sign and meetings for formulating resident's individual care plan (ICP). In the proposed model, the amount of direct and indirect care that the residents require in each shift are given as parameters to the model. Consequently, the following basic assumptions are used in this study:

Assumption 1: A nursing home manager needs not determine the assignment of nurse to residents before optimising the staffing level.

Assumption 2: A nursing home manager assigns nursing staff to tasks and shifts based on the healthcare task requirements and staff availability.

Assumption 3: Each nursing staff can serve up to one resident at any time, despite the staff's identity, healthcare task or resident type.

Assumption 4: Quality of care remains constant and independent of the nursing staff performing the healthcare task.

Assumption 5: Direct and indirect care can be performed in any time period within the shift.

ISLPSPs have a number of constraints that need to be satisfied in order to have a feasible staff level and scheduling plan, and they are the result of legislation, clinical protocols, operational guidelines and contracts with the nursing staff. The constraints, particularly work limits, are not the same for all nursing staff. In the proposed model, the following constraints are considered:

(i) Restrictions on service requirements from legislation and service agreements.

The legislation and service agreement on service requirements and staffing requirements have to be met.

(ii) Restrictions on working hours and rest periods from the legislation and employment contracts.

The legislation and contracts concern the maximum length of continuous work within a day, maximum number of continuous days worked, minimum length of continuous rest between shifts and other limits that have to be met.

(iii) Day off request.

Day offs are considered to be a constraint to ensure that no nursing staff is assigned to a shift while on a day off.

(iv) Limits on split shifts.

Split shifts are defined as two separate shifts within the same day, where the time between the shifts is less than the minimum resting period between shifts. In our setting, this needs to be a constraint so split shifts are not allowed.

(v) Maximum amount of overtime work.

The legislation and contracts on the maximum length of overtime work within a day is given. However, since the overtime work creates pressure on frontline nursing staff and contributes to their turnover rate, less overtime work for each nursing staff is desirable. This encourages nursing home managers to create an integrated staff level and scheduling plan with the least overtime work possible, making the plan more favourable to the nursing staff.

5.4 Optimisation Model for Integrated Staff Level Planning and Scheduling

The objectives are to minimise the total staffing costs, and the amount of overtime work while maximising the staff level (i.e. nurse-to-resident ratio), as shown in Objective functions (5.1) – (5.3). The notations used in the optimisation model are shown in the following:

Input Data:

C Set of nursing staff categories, $C = \{1, 2, \ldots, I\}$

D_i Set of nursing staff in a particular nursing staff category i, $D_i = \{1, 2\ldots, J_i\}$ where J_i is the given initial number of regular nursing staff of category i

D_i^t Set of temporary nursing staff in a particular staff category *i*, D_i^t = {1, 2, …, J_i^t} where J_i^t is the given initial number of temporary nursing staff of category *i*

D_i' Set of potential regular nursing staff in a particular staff category *i* to be hired, $D_i' = \{J_i + 1, J_i + 2, \ldots, J_i + J_i'\}$ where J_i' is the given maximum allowable regular nursing staff of category *i* to be hired

D_i'' Set of potential temporary nursing staff in a particular staff category *i* to be hired, D_i''= $\{J_i^t + 1, J_i^t + 2, \ldots, J_i^t + J_i''\}$ where J_i'' is the given maximum allowable temporary nursing staff of category *i* to be hired

R Set of resident types, *R* = {1, 2…*K*}

S Set of shifts (in the planning horizon of 1 month), *S* = {1, 2… *M*}

T Set of healthcare tasks, *T* = {1, 2…*L*}

P_i Set of healthcare tasks that nursing staff of category *i* is qualified to perform, P_i = {1, 2, …, L_i }

W' Set of weeks (in the planning horizon of 1 month), *W'* = {1, 2…*W*}

Q' Set of month (in the planning horizon of 1 month), *Q*'= {1,2…*Q*}

Parameters:

T_i^{max} The upper limit of working hours per shift for a temporary staff of category *i*

$T_i^{w,max}$ The upper limit of working hours per week for a temporary nursing staff of category *i*

S_{ij} Monthly salary of the j^{th} regular nursing staff of category *i*

R_{ij}^{otp} Hourly wage of overtime work for the j^{th} regular nursing staff of category *i*

C_i^h Cost of hiring a regular nursing staff of category *i*

C_i^f Cost of having a regular nursing staff of category *i* left the workforce

C_i^t Hourly wage of a temporary nursing staff of category *i*

N_{kl} Number of type *k* residents requiring the l^{th} healthcare task

M_{il} Skill mix level (i.e. number of nursing staff) for nursing staff of category *i* required for the l^{th} healthcare task

T_{ikl} Service time (in minutes) of the l^{th} healthcare task for each resident of type *k* per shift if it is provided by nursing staff, either regular or temporary, of category *i*

Y_{klm} 1 if the l^{th} healthcare task is needed for type *k* resident in shift *m*; otherwise 0

$X_i^{w,max}$ The upper limit of shifts a nursing staff of category *i* can undertake in every 7 consecutive days

O_{im}^{max} The upper limit of overtime work for a regular nursing staff of category *i* in shift *m*

U Standard working hour for all regular nursing staff per shift

Variables:

N_i^h Number of additional regular nursing staff of category *i* to be hired

N_i^f Number of existing regular nursing staff of category *i* left the workforce

N_{iw}^{t} Number of temporary nursing staff of category *i* in week *w*

X_{ij} 1 if the *j*th regular nursing staff of category *i* is counted in the workforce; otherwise 0

X_{ijw}^{t} 1 if the *j*th temporary nursing staff of category *i* is counted in the workforce in week *w*; otherwise 0

X_{ijq} 1 if *j*th nurse of category *i* is counted in workforce for month *q*; otherwise 0

T_{i}^{t} Total working hours of temporary nursing staff of category *i*

E_{ijw}^{t} Total working hours of the *j*th temporary nursing staff of category *i* in week *w*

T_{ijm}^{ot} Overtime work (in hours) for the *j*th regular nursing staff of category *i* in shift *m*

T_{ijm}^{t} Working hours of the *j*th temporary nursing staff of category *i* in shift *m*

$$X_{ijlm} = \begin{cases} 1 \text{ if regular staff } ij \text{ is assigned to task } l \text{ in shift } m \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijlm}^{t} = \begin{cases} 1 \text{ if temporary staff } ij \text{ is assigned to task } l \text{ in shift } m \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijm} = \begin{cases} 1 \text{ if regular staff } ij \text{ is selected in shift } m \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijm}^{t} = \begin{cases} 1 \text{ if temporary staff } ij \text{ is selected in shift } m \\ 0 \text{ otherwise} \end{cases}$$

Decision Variables:

T_{ijlm}	Amount of time (in minutes) that regular staff *ij* is assigned to perform task *l* in shift *m*
T^{t}_{ijlm}	Amount of time (in minutes) that temporary staff *ij* is assigned to perform task *l* in shift *m*

The following shows the formulated optimisation model for the ISLPSPs of nursing staff in nursing homes.

Objectives:

$$\mathrm{F}_7 = \text{Minimise} \sum_{i\in C} \sum_{j\in D_i \cup D'_i} \left(X_{ij} S_{ij} + R^{otp}_{ij} \sum_{m\in S} T^{ot}_{ijm} \right) + \sum_{i\epsilon C} \left(C^h_i N^h_i + C^f_i N^f_i + C^t_i T^t_i \right) \tag{5.1}$$

$$\mathrm{F}_8 = \text{Minimise} \sum_{i\in C} \sum_{j\in D_i \cup D'_i} \sum_{m\in S} T^{ot}_{ijm} \tag{5.2}$$

$$\mathrm{F}_9 = \text{Maximise} \sum_{i\in C} \sum_{j\in D_i \cup D''_i} \sum_{m\in S} X_{ijm} + \sum_{i\in C} \sum_{j\in D^t_i \cup D''_i} \sum_{m\in S} X^t_{ijm} \quad ,\forall m \in S \tag{5.3}$$

, where

$$X_{ij} = \begin{cases} 1 \text{ if } \sum_{m\in S} X_{ijm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \quad ,\forall i \in C, \; ,\forall j \in D_i \cup D'_i \tag{5.4}$$

$$T_{ijm}^{ot} = \max\left[\left(\sum_{l\in P_i} T_{ijlm} - U\right), 0\right] \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall m \in S \tag{5.5}$$

$$X_{ijq} = \begin{cases} 1 \text{ if } \sum_{m\in S} X_{ijm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall q \in Q' \tag{5.6}$$

$$X_{ijm} = \begin{cases} 1 \text{ if } \sum_{l\in P_i} X_{ijlm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall m \in S \tag{5.7}$$

$$X_{ijm}^{t} = \begin{cases} 1 \text{ if } \sum_{l\in P_i} X_{ijlm}^{t} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall m \in S \tag{5.8}$$

$$N_i^h = \sum_{j\in D_i \cup D_i'} \sum_{q\in Q'} \left\{X_{ijq} - X_{ij(q-1)}\right\},\ if\ X_{ijq} = 1 \qquad ,\forall i \in C \tag{5.9}$$

$$N_i^f = \sum_{j\epsilon D_i \cup D_i'} \sum_{q\in Q'} \left\{X_{ij(q-1)} - X_{ijq}\right\}, if\ X_{ijq} = 0 \qquad ,\forall i \in C \tag{5.10}$$

$$T_i^t = \sum_{j\in D_i^t \cup D_i''} \sum_{m\epsilon S} \sum_{l\in P_i} T_{ijlm}^{t} \qquad ,\forall i \in C \tag{5.11}$$

Constraints:

$$\sum_{i\in C} \sum_{j\in D_i \cup D_i'} X_{ijm} \cdot T_{ijlm} + \sum_{i\in C} \sum_{j\in D_i^t \cup D_i''} X_{ijm}^{t} \cdot T_{ijlm}^{t} \geq \sum_{i\in C} \sum_{k\in R} \sum_{l\in T} N_{kl} T_{ikl} Y_{klm} M_{il} \qquad , \forall m \in S \tag{5.12}$$

$$\sum_{l \in P_i} T_{ijlm} \leq \left(U + T_{ijm}^{ot}\right) \cdot X_{ijm} \qquad ,\forall i \in C, \; ,\forall j \in D_i \cup D_i' \; ,\forall m \in S \tag{5.13}$$

$$\sum_{l \in P_i} T_{ijlm}^{t} \leq T_i^{max} \cdot X_{ijm}^{t} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall m \in S \tag{5.14}$$

$$T_{ijlm} \leq \left(U + T_{ijm}^{ot}\right) \cdot X_{ijlm} \qquad ,\forall i \in C \; ,\forall j \in D_i \cup D_i', \; ,\forall l \in P_i, \forall m \in S \tag{5.15}$$

$$T_{ijlm}^{t} \leq T_i^{max} \cdot X_{ijlm}^{t} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall l \in P_i, \forall m \in S \tag{5.16}$$

$$X_{ijlm} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C, \; \forall j \in D_i, \; \forall m \in S \tag{5.17}$$

$$X_{ijlm}^{t} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm}^{t} \geq 1 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall m \in S \tag{5.18}$$

$$\sum_{m=\{1,22,43,64\}}^{m+20} X_{ijm} \leq X_i^{w,max} \qquad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \tag{5.19}$$

$$X_{ijm} + X_{ij(m+1)} \leq 1 \qquad ,\forall i \in C, \; ,\forall j \in D_i \cup D_i', \; ,\forall m \in S \tag{5.20}$$

$$X_{ijm}^{t} + X_{ij(m+1)}^{t} \leq 1 \qquad ,\forall i \in C, \; ,\forall j \in D_i \cup D_i', \; ,\forall m \in S \tag{5.21}$$

$$\sum_{m=\{1,4,\ldots 85,88\}}^{m+2} X_{ijm} \leq 1 \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \tag{5.22}$$

$$\sum_{m=\{1,4,\ldots 85,88\}}^{m+2} X_{ijm}^{t} \leq 1 \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i'' \tag{5.23}$$

$$0 \leq T_{ijm}^{ot} \leq O_{im}^{max} \cdot X_{ijm} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall m \in S \tag{5.24}$$

$$0 \leq T_{ijm}^{\mathrm{t}} \leq T_{ijm}^{\mathrm{t}} \cdot X_{ijm}^{t} \leq T_{i}^{w,max} \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \quad ,\forall m \in S \tag{5.25}$$

$$T_{ijm}^{t} = \sum_{l \in P_i} T_{ijlm}^{t} \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \quad ,\forall m \in S \tag{5.26}$$

$$E_{ijw}^{t} = \sum_{m \in \{1,22,43,\ldots\}}^{m+20} T_{ijm}^{t} \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \quad ,\forall w \in W \tag{5.27}$$

$$0 \leq E_{ijw}^{t} \leq T_{i}^{w,max} \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \quad ,\forall w \in W \tag{5.28}$$

$$X_{ijw}^{t} = \begin{cases} 1 \text{ if } E_{ijw}^{t} > 0 \\ 0 \text{ otherwise} \end{cases} \qquad ,\forall i \in C \quad ,\forall j \in D_i^t \cup D_i'' \quad ,\forall w \in W \tag{5.29}$$

$$N_{iw}^{t} = \sum_{j \in D_i^t \cup D_i''} X_{ijw}^{t} \qquad ,\forall i \in C \quad ,\forall w \in W' \tag{5.30}$$

$$X_{ijlm} \in \{0, 1\} \qquad ,\forall i \in C \quad ,\forall j \in D_i \cup D_i' \quad ,\forall l \in P_i ,\forall m \in S \tag{5.31}$$

$$X_{ijlm}^{t} \in \{0,1\} \quad ,\forall i \in C, \; ,\forall j \in D_i^t \cup D_i'' \; ,\forall l \in P_i, \forall m \in S \tag{5.32}$$

$$X_{ijm} \in \{0,1\} \quad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \; ,\forall m \in S \tag{5.33}$$

$$X_{ijm}^{t} \in \{0,1\} \quad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'', \; ,\forall m \in S \tag{5.34}$$

$$X_{ijw}^{t} \in \{0,1\} \quad ,\forall i \in C \; ,\forall j \in D_i^t \; ,\forall w \in W \tag{5.35}$$

$$X_{ij} \in \{0,1\} \quad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \tag{5.36}$$

$$X_{ijq} \in \{0,1\} \quad ,\forall i \in C \; ,\forall j \in D_i \cup D_i' \; ,\forall q \in Q' \tag{5.37}$$

$$T_{ijlm} \geq 0 \quad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i', \; ,\forall l \in P_i, \forall m \in S \tag{5.38}$$

$$T_{ijlm}^{t} \geq 0 \quad ,\forall i \in C \; ,\forall j \in D_i^t \cup D_i'', \; ,\forall l \in P_i, \forall m \in S \tag{5.39}$$

The model is a multi-objective optimisation model. Objective function (5.1) minimises total staffing costs of regular and temporary nursing staff, taking into account cost resulting from hiring additional or firing existing regular nursing staff. In a nursing home, all incomplete healthcare tasks cannot be stocked and thus there is a possibility that regular nursing staff needs to work overtime in order to complete all healthcare tasks within a shift. Objective unction (5.2) thus minimises the overtime work (in hours) of all regular nursing staff. Objective function (5.3) maximises the staff level. Equations (5.4) to (5.9) define X_{ij}, T_{ijm}^{ot}, X_{ijq}, X_{ijm}, X_{ijm}^{t} and T_{i}^{t}, respectively. Equations (5.10) and (5.11) refer to the situation of a newly hired staff and the situation an existing staff left the workforce, respectively.

In a nursing home, both direct and indirect care demands of all residents (in staff hours) have to be satisfied within each shift (i.e. daytime, evening and overnight shifts), by either regular and/or temporary nursing staff, and all unserved staff hours cannot be stocked. Constraint (5.12) is a nursing staff demand constraint which specifies the amount of time required to complete all healthcare tasks within a shift. Sometimes, a healthcare task requires the cooperation of nursing staff from various nursing staff categories. Skill mix, denoted by M_{il} in the model, reflects a certain degree of staff task flexibility and practical requirements in reality. The minimum estimated demand for resident care (in staff hours) in shift *m*, forecasted based on historical data and seasonal characteristics, are considered during demand forecasting. Constraint (5.13) limits the number of working hours for each selected regular nursing staff. If the regular nursing staff is not selected for the shift *m*, this constraint prohibits the model from assigning healthcare tasks or hours to this regular nursing staff in shift *m*. Similarly, Constraint (5.14) limits the number of working hours for each selected temporary nursing staff. If the temporary nursing staff is not selected for the shift *m*, this constraint prohibits the model from assigning healthcare tasks or hours to this temporary nursing staff in shift *m*. In addition, Constraints (5.15) and (5.16) prohibit the model from assigning hours to a nursing staff that has not been selected to perform a given healthcare task *l* in a given shift *m*. Constraints (5.17) and (5.18) define X_{ijlm} and X_{ijlm}^{t}.

Constraint (5.19) assures that every regular nursing staff can undertake at most $X_i^{w,max}$ shifts in a week. This constraint also ensures at least one day of day off is assigned to each selected regular nursing staff. Constraints (5.20) and (5.21) ensures regular and temporary nursing staff cannot undertake consecutive shift, respectively. Constraint (5.22) and (5.23) prohibit the model from assigning more than one shift per day to each selected regular and temporary nursing staff, respectively. In other words, Constraints (5.22) and (5.23) ensure there shall be no split shift scheduled. Constraint (5.24) expresses the limitation posed on regular nursing staff concerning the maximum number of overtime work (in hours) a regular nursing staff can work per shift. Temporary nursing staff can be hired when the residents' service demand level (in staff hours) cannot be satisfied by existing regular nursing staff within each shift, and when the hiring of additional regular nursing staff is unfavorable. Constraint (5.25) limits the maximum number of working hours a temporary nursing staff can work per week. In addition, Constraints (5.24) and (5.25) also prohibit the model from assigning overtime work or working hour to the regular and temporary nursing staff if he/she is not selected for the shift. Constraints (5.26) and (5.27) define the relationship between T_{ijm}^{t}, T_{ijlm}^{t} and E_{ijw}^{t}, while Constraint

(5.28) specifies the range of E_{ijw}^{t}. Constraints (5.29) and (5.30) define X_{ijw}^{t} and N_{iw}^{t}. Constraints (5.31) to (5.37) define X_{ijlm}, X_{ijlm}^{t}, X_{ijm}, X_{ijm}^{t}, X_{ijw}^{t}, X_{ij} and X_{ijq} are binary variables. Finally, Constraints (5.38) and (5.39) represents the non-negativity restrictions on the decision variables T_{ijlm} and T_{ijlm}^{t}.

The proposed multi-objective optimisation model thus aims at finding a reasonable level and mix of nursing staff with the lowest total staffing costs, the least amount of overtime work and the highest staff level. Various important considerations informed by existing literature and expertise in the field are also taken into consideration.

5.5 Two Level NSGA-II Approach

A Two Level Non-dominated Sorting Genetic Algorithm – II (TLNSGA-II) is designed to decompose this integrated problem into staff level planning and scheduling problems, and to solve them in an iterative approach.

5.5.1 Description of TLNSGA-II

The TLNSGA-II algorithm consists of two layers. The inner layer determines the skill mix assigned to each healthcare task within a shift by a NSGA-II. It is the master problem since it directly confines the number and mix of nursing staff required for each shift. The chromosome will store the information of the skill mix-task assignments. The outer layer determines the staff assigned to skill mix for all shifts (staff scheduling) and the solution determined will feedback into the master problem for generating individuals of outer layer for next generation. The procedures of the TLNSGA-II algorithm are outlined as follows:

Step 1: To start with, a pool of initial solutions for assigning qualified skill mix (in minutes) to each task within a shift will be formed. Chromosomes will be generated randomly and using Constructive Heuristics according to a pre-defined population size. Subsequently, Steps 1a – 1g will be carried out iteratively until the stopping condition is reached, i.e. a pre-defined number of iterations is reached in this study.

- Step 3a: Calculate objective function values for each individual, and perform non-dominated sorting
- Step 3b: Perform tournament selection
- Step 3c: Perform crossover and mutation in inner layer
- Step 3d: Assign fitness to individuals of inner layer
- Step 3e: Combine parent and offspring population, perform non-dominated sorting for the combined population
- Step 3f: Calculate crowding distance and assign rank to chromosome
- Step 3g: Generate population for next generation based on rank, crowding distance and elitist strategy

Step 2: The best individuals of the inner layer will be selected, act as input data and passed to staff scheduling (i.e. outer layer).

Step 3: In the staff scheduling outer layer, chromosomes will be initialised using the inputs from skill mix-task assignment (i.e. inner layer). Subsequently, Steps 3a – 3g will be carried out iteratively until the stopping condition is reached, i.e. a pre-defined number of iterations is reached in this study.

Step 3a: Calculate objective function values for each chromosome, and perform non-dominated sorting

Step 3b: Perform tournament selection

Step 3c: Perform crossover and mutation

Step 3d: Generate offspring population

Step 3e: Combine parent and offspring population, perform non-dominated sorting for the combined population

Step 3f: Calculate crowding distance and assign rank to chromosome

Step 3g: Generate population for next generation based on rank, crowding distance and elitist strategy

Step 4: Mismatch of decisions between the two layers might occur – the initial solution given by the skill mix-task assignment problem (i.e. inner layer) does not comply with the staff scheduling problem (i.e. outer layer). In other words, the number and mix of nursing staff given by the master problem cannot meet all scheduling constraints. The number and mix of nursing staff decision has to be adjusted to align with the scheduling constraints.

Step 5: Check if stopping condition is reached. If not, repeat Steps 2 – 4. Otherwise, record the Pareto optimal solutions.

Figure 5.2 describes our proposed TLNSGA-II. The general descriptions of steps involved in NSGA-II are outlined in Sections 3.3.1.1 to 3.3.1.5.

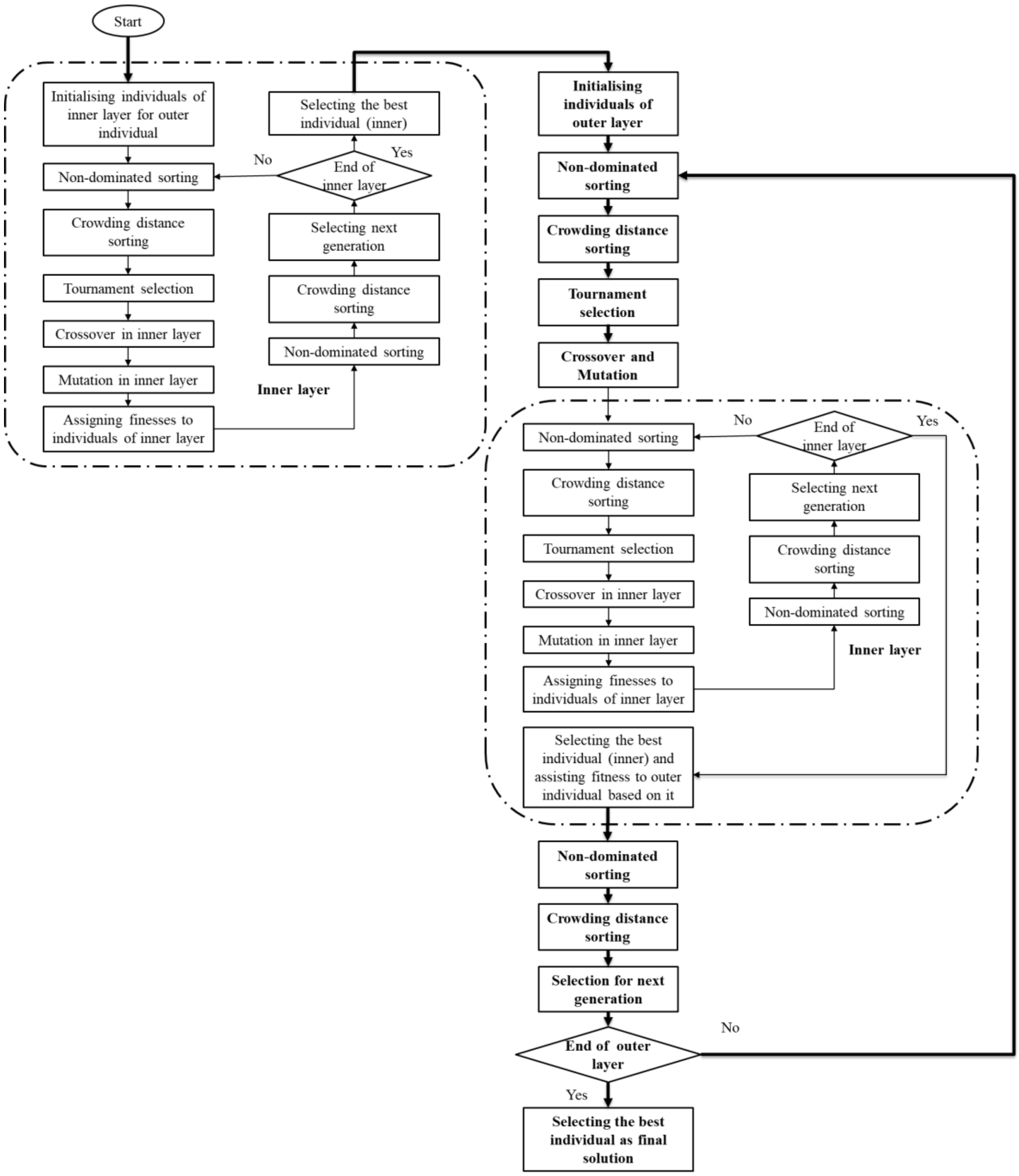

Figure 5.2 Flowchart of TLNSGA-II

5.5.1.1 Chromosome representation

In both the skill mix-task assignment problem and scheduling problem, each solution is defined by a chromosome with the number of genes depending on the number of nursing staff categories (*I*), the number of nursing staff in a category (J_i, J_i^t, J_i' and J_i''), the number of shifts (*M*), and the number of healthcare task (*L*).

The chromosomes are represented as mixed-integer strings. Solutions are represented as an $[I \times (J_I + J_I^t + J_I' + J_I'')] \times (M \times L)$ matrix *T*, where T_{ijlm} and T_{ijlm}^t represents the amount of time (in minutes) that staff *ij* is assigned to task *l* in shift *m*. In this representation, a regular and a temporary nursing staff *j* of category *i* is considered to be assigned to task *l* in shift *m* if $T_{ijlm} > 0$ and $T_{ijlm}^t > 0$, respectively.

Therefore, the following relationships are established from the values in T_{ijlm} and T_{ijlm}^t.

$$X_{ijlm} = \begin{cases} 1 \text{ if } T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijlm}^t = \begin{cases} 1 \text{ if } T_{ijlm}^t > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijm} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijm}^t = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm}^t > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijw}^{t} = \begin{cases} 1 \text{ if } \sum_{m \in \{1,22,43,\dots\}}^{m+20} T_{ijm}^{t} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ij} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$X_{ijq} = \begin{cases} 1 \text{ if } \sum_{l \in P_i} T_{ijlm} > 0 \\ 0 \text{ otherwise} \end{cases}$$

Solution using this representation is shown in Figure 5.3. In the example, regular nursing staff 1 of category 1 is assigned to task 3 in shift 2 for 240 minutes, regular nursing staff 2 of category 1 is not assigned to task 2 in shift 3, temporary nursing staff 1 of category 1 is assigned to tasks 1, 2 and 3 in shift 3, while temporary nursing staff 3 of category 1 is not assigned to any task in any shift. The values of various variables are determined based on the values in T_{ijlm} and T_{ijlm}^{t}. Sample of the values of binary variables deduced is shown in Tables 5.1 and 5.2.

Nursing staff \ Shifts x Tasks	11	12	13	21	22	23	31	32	33
11	000	480	000	480	240	240	000	000	000
12	240	000	000	000	000	000	120	000	000
13	000	000	000	000	000	000	000	000	000
11^t	000	000	000	000	000	000	120	120	120
12^t	120	000	000	240	000	000	000	000	000
13^t	000	000	000	000	000	000	000	000	000

Regular nursing staff 1 of category 1 is assigned to task 3 in shift 2, for 240 minutes

Regular nursing staff 2 of category 1 is not assigned to task 2 in shift 3

Temporary nursing staff 1 of category 1 is assigned to tasks 1, 2 & 3 in shift 3, each task for 120 minues

Temporary nursing staff 3 of category 1 is not selected

Figure 5. 3 An example of a TLNSGA-II solution using the representation presented in this study

Table 5.2 Sample of chromosome decoding for regular nursing staff

				Variables			
i	***j***	***m***	***l***	X_{ijlm}	X_{ijm}	X_{ij}	X_{ijq}
1	**1**	**1**	**1**	0	1	1	1
			2	1			
			3	0			
		2	**1**	1	1		
			2	1			
			3	1			
		3	**1**	0	0		
			2	0			
			3	0			

Table 5.3 Sample of chromosome decoding for temporary nursing staff

				Variables		
i	***j***	***m***	***l***	X^t_{ijlm}	X^t_{ijm}	X^t_{ijw}
1	**1**	**1**	**1**	0	0	1
			2	0		
			3	0		
		2	**1**	0	0	
			2	0		
			3	0		
		3	**1**	1	1	
			2	1		
			3	1		

5.6 Determination of Parameter Setting of TLNSGA-II using Taguchi Method

The proposed TLNSGA-II was coded in MATLAB programming language. The quality of solutions obtained depends heavily on the parameters setting of a multi-objective evolutionary algorithm (Sadeghi & Niaki, 2015). There are four parameters in TLNSGA-II to be calibrated, i.e. the population size (*pop*), the number of iterations to stop the algorithm (*iteration*), the crossover probability (*CR*), and the mutation probability (*MR*).

Many researchers have used the conventional parameter optimization which method relies on experience and trial-and-error. In order to determine the significant factors (here the parameters) affecting a response (here the solution), A Taguchi orthogonal array is used instead of a full factorial experimental design to calibrate the parameters of the developed TLNSGA-II. Taguchi developed 'a special type of fractional factorial experiments to reduce a large number of experiments required in a full factorial experiments' (Sadeghi & Niaki, 2015).

The Taguchi method is designed based on orthogonal arrays, and can be used efficiently as an alternative for the full factorial experimental design to investigate a group of factors. These factors are divided in two groups, namely controllable factors and noise factors. The Taguchi method aims mainly to select the best level of the factors such that the effect of controllable factors is maximised and the effect of noise factors is minimized (Maghsoudlou et al., 2016). There are two suggested ways in the Taguchi method to analyse the results. First, analysis of variance (ANOVA) that is used for experiments that repeat once, and second, signal-to-noise ratio (S/N) for experiments with multiple runs (Sadeghi & Niaki, 2015). Since TLNSGA-II have multiple runs to obtain better solutions, S/N is used in this study to analyse the results. The S/N ratio can be calculated in three difference ways, including 'smaller-the-better', 'nominal-the-better', and 'greater-the-better'. A larger S/N ratio indicates a better result (Candan & Yazgan, 2015). As the Objective Functions (5.1) and (5.2) are minimisisation while Objective Function (5.3) is maximization, two equations apply. For the smaller-the-better, the value of S/N can be calculated using Equation (5.40). For the greater-the-better, the value of S/N can be calculated using Equation (5.41).

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \tag{5.40}$$

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{{y_i}^2}\right] \tag{5.41}$$

, where η is the S/N ratio, n is the number of replications, and y_i is the response values.

In this study, the four parameters were obtained in systematic review of optimization methodology and were selected by simulation method in widely range. Interactions between factors are assumed neglectable. Three levels of the parameters are shown in Table 5.4. The L^9 orthogonal array is applied to reduce the number of experiments from 81 (3^4) to 9. To improve accuracy, experiments were repeated five times. This meant that only 45 (9*5) experiments, instead of 405 experiments, were required to reach a conclusion.

Table 5.4 Parameters (factors) and the levels for integrated staff level planning and scheduling

	Levels		
Parameter	**Low (1)**	**Medium (2)**	**High (3)**
Population Size (Pop)	50	100	150
Number of Iterations to Stop the Algorithm (Iteration)	300	500	750
Crossover Rate (CR)	0.7	0.8	0.9
Mutation Rate (MR)	0.001	0.01	0.1

5.7 Summary

Staff level planning and scheduling of nursing staff is known to be very difficult and critical to nursing home's service capacity and outcomes of both nursing staff and residents. In the literature, researchers treat the problem in two consecutive phases and always ignore critical factors. No model with the consideration of multi-skilled workforce, heterogeneous workforce, skill substitution and skill mix has been formulated for staff level planning and scheduling in nursing home, to the best of our knowledge. In this chapter, the ISLPSP was examined and a methodology for ISLPSP was developed. The ISLPSP model for nursing staff in nursing homes was formulated, with multi-skilled workforce, heterogeneous workforce, staff task flexibility, resident case-mix, skill mix and skill substitution considerations explained.

To tackle the multi-objective and integrated optimisation problem, a NSGA-II based approach namely TLNSGA-II was proposed. In the proposed approach, the integrated problem is decomposed into the skill mix-task assignment master problem and the staff scheduling sub-problem. A case study of a subvented nursing home in Hong Kong will be conducted in the next chapter to evaluate the proposed model and approach. The optimal settings of genetic parameters will be determined based on Taguchi method.

Chapter 6 – CASE STUDY

6.1 Introduction

The proposed integrated optimisation model and the TLNSGA-II are verified and their effectiveness in solving a real-world ISLPSP are illustrated using a case study. In this study, a single case research design is used. According to Yin (2013), choosing a unique and representative case in the problem domain is important when adopting the single case research design. Although Yin (2013) also argues that the multiple case research design is preferred over the single case design in terms of result robustness, it is appropriate to adopt a single case design in this study. As this study aims to address the nursing home staff level planning and scheduling problem for nursing homes, the selected registered subvented nursing home in Hong Kong, i.e. Pok Oi Hospital Tuen Mun Nursing Home, has various categories of nursing staff, such as Enrolled Nurses (ENs) and Registered Nurses (RNs), and various types of residents with various healthcare needs. Thus, it is suitable for use as a representative reference case. Therefore, the adoption of a single case research design is appropriate in this study, and it is a time- and cost-effective method.

The description of the subvented nursing home selected is presented in Section 6.2. Implementation and the parameters setting are included in Section 6.3. A detail analysis is given in Section 6.4 to illustrate the capability of the developed approach in solving the proposed model.

6.2 Description of Reference Case

A subvented nursing home in Hong Kong has been selected as the reference case for demonstrating the effectiveness of the model formulated in solving the ISLPSP in real world. Nursing home manager of the subvented nursing home was consulted, and the main points in the consultation are summarised as follows:

(i) Currently, staff level required for each shift is estimated by nursing home manager manually based on perceived experience;

(ii) Staff scheduling is designed by nursing home manager manually based on schedule of previous month and perceived experience;

(iii) Problems highlighted frequently include balancing staff load and fulfilling legal requirements; and

(iv) A computerized solution is desirable.

Data sets were obtained as shown in Table 6.1. At present, there are 4 nursing staff categories: 1 (representing Personal Care Worker, PCW), 2 (representing Health Worker, HW), 3 (representing Enrolled Nurse, EN) and 4 (representing Registered Nurse, RN). In shifts 1 and 4, 5 staff from category 1 and 1 staff from either category 3 or 4 are on duty. 2 staff from category 2 may also be required. In shift 2, 5 staff from category 1 and 2 staff from either category 3 or 4 are on duty. 2 staff from category 2 may also be required. In shift 3, 2 staff from category 1 and 1 staff from either category 2, 3 or 4 are on duty. The nurse-to-resident ratio are [1:6.63, 1:8.83] for shifts 1 and 4, [1:5.80, 1:7.57] for shift 2, and 1:17.7 for shift 3. Staff required from each category can be both regular and temporary nursing staff

Currently, a few temporary nursing staff has been employed and regular nursing staff sometimes need to work overtime in order to complete all the healthcare tasks within a shift. It was also reported that (1) monthly salaries of regular nursing staff are based on their staff grade (which refers to 'nursing staff category' in the proposed model), subject to a minimum set at the mid-point, which are used when undertaking staff level planning; (2) shifts 1 (daytime shift with monthly/weekly healthcare task requirement, also denoted by 'A*'), 2 (evening shift, also denoted by 'B'), 3 (overnight shift, also denoted by 'N') and 4 (daytime shift, also denoted by 'A') are the typical and representative shifts, and (3) currently, the total monthly staffing costs is HK$587,140.

Values of the problem instance are listed in Table 6.1. The list of healthcare task for each shift is shown in Table 6.2, where 0 denotes the absence and 1 denotes the presence. The list of healthcare task each nursing staff category is eligible to perform is listed in Table 6.3. In the table, 0 denotes ineligible and 1 denotes eligible. The service time (in minutes) of individual healthcare task depends on the number and the type of nursing staff assigned (i.e. skill mix assignment), and the number of residents requiring the service. Table 6.4 shows the possible skill mix and service time (in minutes) of healthcare tasks.

For example, there are 6 possible and qualified skill mix for healthcare task 1. Healthcare task 1 of one resident can be completed by 1 PCW in 1 minute, or it can be completed by 1 PCW and 1 HW together consuming each of them 0.5 minutes, and so on. The concepts of skill substitution and skill consequence (in terms of the amount of time required for each healthcare task) are implemented to reflect practice in reality and staff task flexibility.

Table 6.1 Details of the Hong Kong subvented nursing home

Notation	**Value**	**Notation**	**Value**
C	{1, 2, 3, 4}	D_1	{1, 2, ... , 16}
D_1^t	{1, 2, 3}	D_2	{1, 2, 3}
D_2^t	{0}	D_3	{1, 2, 3, 4, 5}
D_3^t	{1}	D_4	{1, 2}
D_4^t	{0}	D_1'	{17, 18, 19, … , 32}
D_2'	{4, 5, 6, …, 32}	D_3'	{6, 7, 8, …, 32}
D_4'	{3, 4, 5, …, 32}	D_1''	{4, 5, 6, …, 32}
D_2'', D_4''	{1, 2, 3, …, 32}	D_3''	{2, 3, 4, …, 32}
S	{1, 2, 3, …, 90}	T	{1,2,…26}
P_1	{1, 2, 3, 4, 5, 8, 10, 11, 14, 15, 16, 17, 24}	P_2	{1, 4, 5, 6, 7, 8, 9, 11, 12, 13, 15, 16, 17, 19, 20, 21, 22, 23, 24, 25, 26}
P_3, P_4	{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26}	W'	{1, 2, 3, 4}
Q'	{1}	R	{1}
$T_1^{w,max}$, $T_2^{w,max}$, $T_3^{w,max}$, $T_3^{w,max}$	18	T_1^{max}, T_2^{max}, $T_3^{,max}$, $T_4^{,max}$	12
C_1^t, R_1^{otp}	64	C_2^t, R_2^{otp}	87
C_3^t, R_3^{otp}	108	C_4^t, R_4^{otp}	138
N	53	$N_{1,1}$	31
$N_{1,2}$	18	$N_{1,3}$	35
$N_{1,4}$	39	$N_{1,5}$	42
$N_{1,6}$	0	$N_{1,7}$	23
$N_{1,8}$	11	$N_{1,9}$	37
$N_{1,10}$	18	$N_{1,11}$	16
$N_{1,12}$	53	$N_{1,13}$	25
$N_{1,14}$	5	$N_{1,15}$	44
$N_{1,16}$	53	$N_{1,17}$	53

Notation	Value	Notation	Value
$N_{1,18}$	5	$N_{1,19}$	5
$N_{1,20}$	23	$N_{1,21}$	11
$N_{1,22}$	2	$N_{1,23}$	2
$N_{1,24}$	2	$N_{1,25}$	42
$N_{1,26}$	53	U	8
$S_{1j},\ C_1^h,\ C_1^f$	15,485	$S_{2j},\ C_2^h,\ C_2^f$	21,550
$S_{3j},\ C_3^h,\ C_3^f$	26,785	$S_{4j},\ C_4^h,\ C_4^f$	34,180
$X_1^{w,max},\ X_2^{w,max},$ $X_3^{w,max}, X_4^{w,max},$	6	$O_{1m}^{max},\ O_{2m}^{max},$ $O_{3m}^{max},\ O_{4m}^{max},$	8

Table 6.2 List of healthcare task for each shift

		Healthcare Task																									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Shift	**1**	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	0	1	0	1
	2	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	3	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	4	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	5	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	6	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	7	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	8	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	9	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	10	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	11	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	12	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	13	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	14	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	15	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	16	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	17	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0

		Healthcare Task																									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	18	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	19	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	20	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	21	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	22	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	23	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	24	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	25	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	26	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
Shift	**27**	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	28	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	29	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	30	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	31	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	32	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	33	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	34	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	35	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	36	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0

		Healthcare Task																									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	37	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	38	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	39	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	40	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	41	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	42	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	43	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	44	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	45	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
Shift	**46**	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	47	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	48	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	49	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	50	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	51	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	52	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	53	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	54	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	55	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0

		Healthcare Task																									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Shift	**56**	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	57	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	58	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	59	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	60	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	61	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	62	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	63	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	64	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	65	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	66	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	67	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	68	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	69	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	70	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	71	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	72	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	73	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	74	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0

		Healthcare Task																									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Shift	**75**	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	76	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	77	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	78	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	79	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	80	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	81	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	82	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	83	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	84	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	85	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	86	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	87	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
	88	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	0	0	1	0	0
	89	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0
	90	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0

Table 6.3 List of healthcare tasks each nursing staff category is eligible to perform

		Staff Category			
		PCW	**HW**	**EN**	**RN**
Healthcare Task	**1**	1	1	1	1
	2	1	0	1	1
	3	1	0	1	1
	4	1	1	1	1
	5	1	1	1	1
	6	0	1	1	1
	7	0	1	1	1
	8	1	1	1	1
	9	0	1	1	1
	10	1	0	1	1
	11	1	1	1	1
	12	0	1	1	1
	13	0	1	1	1
	14	1	0	1	1
	15	1	1	1	1
	16	1	1	1	1
	17	1	1	1	1
	18	0	0	1	1
	19	0	1	1	1
	20	0	1	1	1
	21	0	1	1	1
	22	0	1	1	1
	23	0	1	1	1
	24	1	1	1	1
	25	0	1	1	1
	26	0	1	1	1

Table 6.4 Skill mix and service time (in minutes) of healthcare tasks

		Healthcare Task								
		1	2	3	4	5	6	7	8	9
Skill Mix	1	1xPCW;1	1xPCW;7	1xPCW;7	1xPCW;0.5	2xPCW;1	1xEN;2	1xEN;1	1xPCW;12	1xEN;2
	2	2xPCW;0.5	1xEN;7	1xEN;7	1xHW;1	1xEN;1	1xRN;2	1xRN;0.5	1xHW;24	1xRN;2
	3	1xPCW&1xHW; 0.5&0.5	1xRN;7	1xRN;7	1xEN;0.5	1xRN;1	2xHW;2	1xHW;1.5	1xEN;3	2xHW;2
	4	1xHW;0.5	-	-	1xRN;1	1xPCW;1	-	-	1xRN;3	
	5	1xEN;0.5	-	-	2xPCW;0.5	1xHW;1	-	-	2xPCW;12	
	6	1xRN;0.5	-	-	-	1xHW&1xPCW; 1&1	-	-	-	
	7	-	-	-	-	1xEN&1xPCW; 1&1	-	-	-	
	8	-	-	-	-	1xRN&1xPCW; 1&1	-	-	-	

		Healthcare Task								
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Skill Mix	**1**	2xPCW;1	1xEN;0.5	1xHW;1	1xHW;1	2xPCW;1	1xPCW;1	1xPCW;1	2xPCW;0.3	1xRN;0.5
	2	2xEN;1	1xRN;0.5	1xEN;0.5	1xEN;1	1xEN;1	1xHW;1	1xHW;1	1xEN;0.5	1xEN;0.5
	3	2xRN;1	1xPCW;0.5	1xRN;0.5	1xRN;0.5	1xRN;1	1xEN;1	1xRN;1	1xRN;1	-
	4	-	1xHW;0.5	1xPCW&1xHW; 1&1	1xHW;1	-	1xRN;2	1xEN;0.5	1xPCW;1	-
	5	-	-	-	-	-	2xPCW;0.5	1xPCW&1xHW; 0.25&0.25	1xHW;0.3	-
	6	-	-	-	-	-	-	2xPCW;1	1xHW&1xPCW; 0.2&0.2	-
	7	-	-	-	-	-	-	-	1xEN&1xPCW; 0.5&0.5	-
	8	-	-	-	-	-	-	-	1xRN&1xPCW; 1&1	-

		Healthcare Task							
		19	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Skill Mix	**1**	1xEN;20	1xHW;103	1xHW;2	1xHW;0.5	1xHW;0.5	1xPCW;1	1xHW;0.25	1xHW;1
	2	1xRN;20	1xEN;103	1xEN;0.5	1xEN;0.5	1xEN;0.5	1xHW;1	1xEN;0.5	1xEN;1
	3	1xHW;20	1xRN;103	1xRN;0.5	1xRN;0.5	1xRN;0.5	1xEN;1	1xRN;0.5	1xRN;1
	4	-	-	-	-	-	1xRN;1	-	-

6.3 Parameter Settings

Tables 6.7 to 6.9 show the experimental design and response statistics, repeated five times, under TLNSGA-II for total staffing costs, amount of overtime work and staff level, respectively. The related S/N ratios of total staffing costs, overtime work and staff level of the proposed TLNSGA-II are shown in Figures 6.1 to 6.3, respectively. The values of S/N ratio of total staffing costs, overtime work and staff level are presented in Tables 6.5, 6.6 and 6.7, respectively. The largest values of S/N ratio depict the optimal condition.

Table 6.5 Experimental design and response statistics under TLNSGA-II (total staffing costs)

Number	Control Parameters				Response 1 (HK$)	Response 2 (HK$)	Response 3 (HK$)	Response 4 (HK$)	Response 5 (HK$)
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	661350	614399	576446	539145	559956
2	0.7	0.01	100	500	1454795	1680065	1907803	1576487	1471629
3	0.7	0.1	150	750	1492135	1692649	1489065	1487931	1730191
4	0.8	0.001	100	750	1285645	1972070	1580425	1492135	1341895
5	0.8	0.01	150	300	530077	579555	596895	640248	520455
6	0.8	0.1	50	500	1720583	1939407	1482395	1760115	1640218
7	0.9	0.001	150	500	2501255	1384995	1524765	1588805	2244295
8	0.9	0.01	50	750	1492135	1482535	1341895	1439435	1706313
9	0.9	0.1	100	300	520455	645216	645098	581430	549619

Table 6.6 Experimental design and response statistics under TLNSGA-II (overtime work)

Number	Control Parameters				Response 1 (hour)	Response 2 (hour)	Response 3 (hour)	Response 4 (hour)	Response 5 (hour)
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	37	38	264	18	0
2	0.7	0.01	100	500	0	37	34	0	0
3	0.7	0.1	150	750	0	90	20	78	110
4	0.8	0.001	100	750	450	51	0	0	0
5	0.8	0.01	150	300	7	0	0	11	0
6	0.8	0.1	50	500	0	16	90	18	62
7	0.9	0.001	150	500	31	0	0	0	11
8	0.9	0.01	50	750	0	0	0	0	42
9	0.9	0.1	100	300	0	21	58	0	140

Table 6.7 Experimental design and response statistics under TLNSGA-II (staff level)

Number	Control Parameters				Response 1	Response 2	Response 3	Response 4	Response 5
	CR	*MR*	*Pop*	*Iteration*					
1	0.7	0.001	50	300	15	14	14	12	13
2	0.7	0.01	100	500	41	54	56	51	49
3	0.7	0.1	150	750	44	52	43	47	53
4	0.8	0.001	100	750	336	62	47	44	40
5	0.8	0.01	150	300	14	13	15	16	11
6	0.8	0.1	50	500	53	59	38	52	49
7	0.9	0.001	150	500	70	42	46	47	66
8	0.9	0.01	50	750	45	44	39	43	51
9	0.9	0.1	100	300	11	16	16	14	14

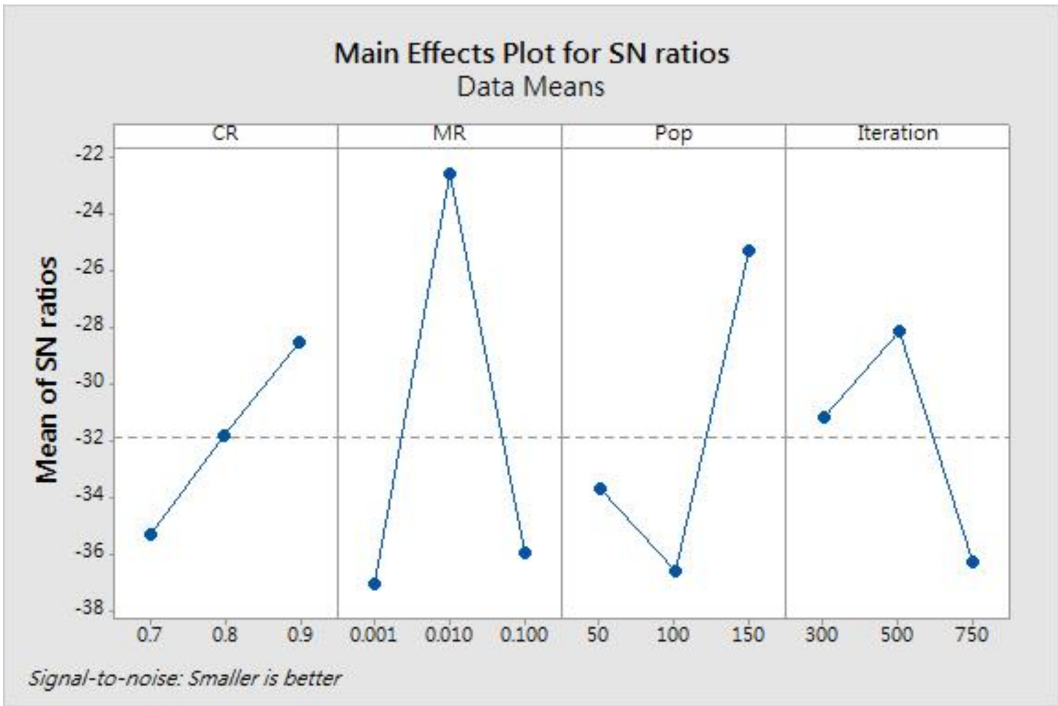

Figure 6.1 S/N ratio plots of total staffing costs for the poposed TLNSGA-II

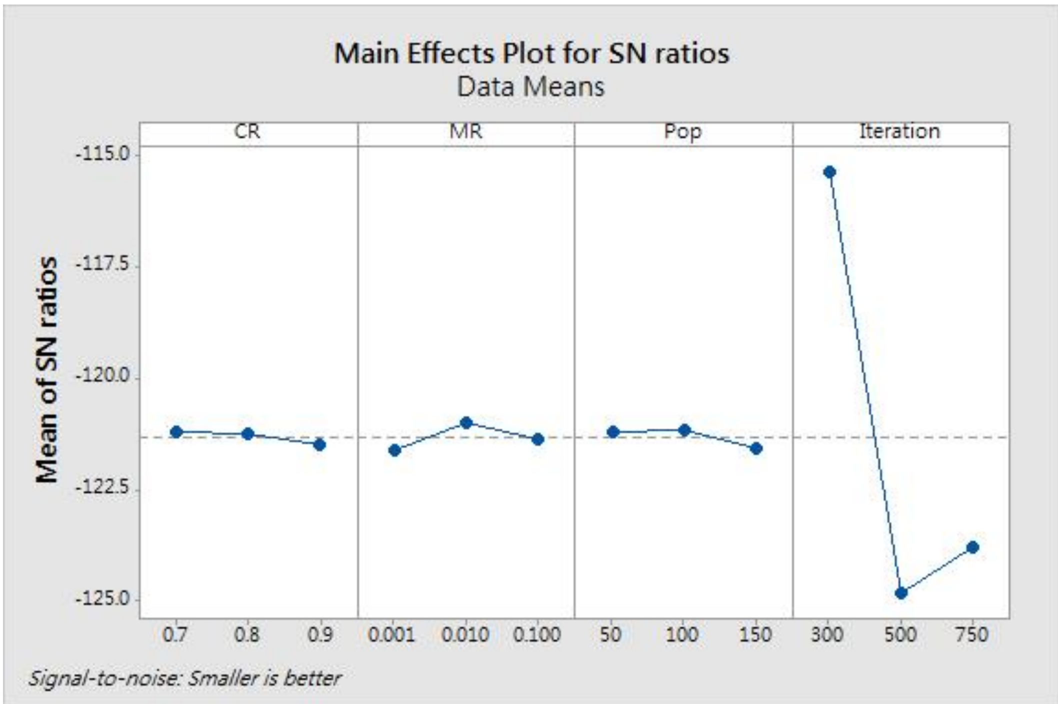

Figure 6.2 S/N ratio plots of overtime work for the proposed TLNSGA-II

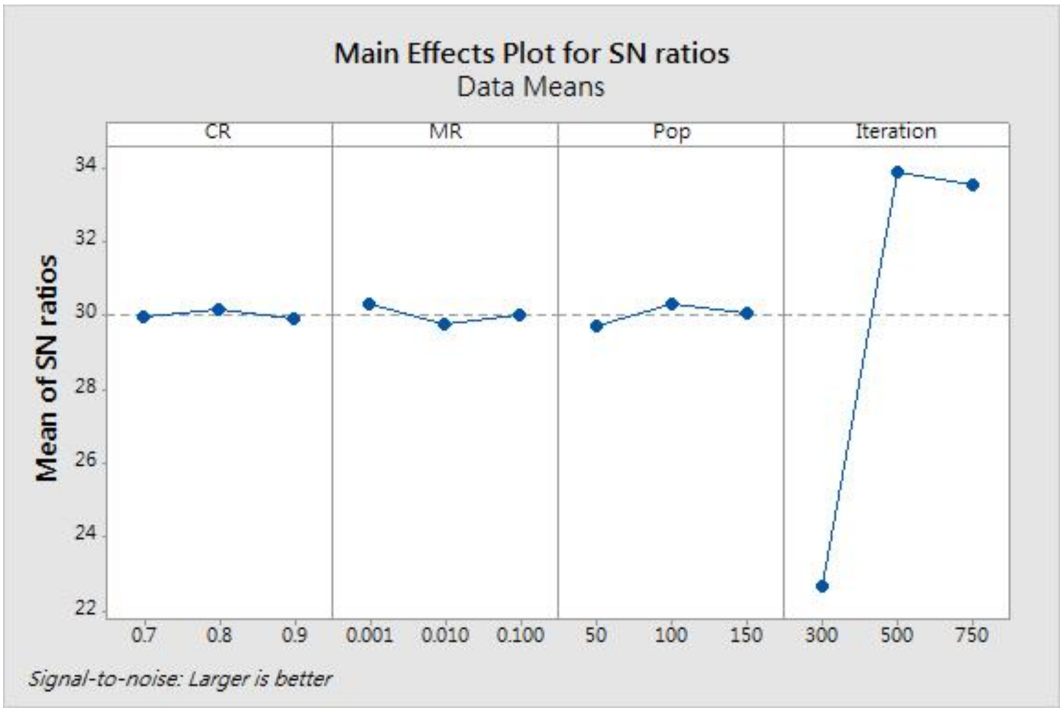

Figure 6.3 S/N ratio plots of staff level for the proposed TLNSGA-II

Table 6.8 Response table for S/N ratios (total staffing costs)

Level	CR	MR	Pop	Iteration
1	-121.2	-121.6	-121.2	-115.4
2	-121.2	-121.0	-121.2	-124.8
3	-121.5	-121.4	-121.6	-123.8
Delta	0.3	0.6	0.4	9.5
Rank	4	2	3	1

Table 6.9 Response table for S/N ratios (overtime work)

Level	CR	MR	Pop	Iteration
1	-35.31	-37.04	-33.70	-31.22
2	-31.81	-22.61	-36.62	-28.12
3	-28.51	-35.99	-25.31	-36.29
Delta	6.80	14.43	11.31	8.17
Rank	4	1	2	3

Table 6.10 Response table for S/N ratios (staff level)

Level	CR	MR	Pop	Iteration
1	29.98	30.34	29.72	22.65
2	30.19	29.76	30.31	33.91
3	29.93	30.00	30.07	33.54
Delta	0.27	0.58	0.59	11.25
Rank	4	3	2	1

The Taguchi optimal parameters are the average of that of all responses (Tian et al., 2017), i.e. total staffing costs, that of overtime work, and that of staff level. According to the genetic parameter combinations of highest S/N ratio under different responses in Tables 6.8 to 6.10, the genetic parameter settings obtained from the Taguchi method are *CR* = 0.9, *MR* = 0.01, *pop* = 150, *iteration* = 500 for the total staffing costs optimisation. Similarly, the genetic parameter settings are *CR* = 0.7, *MR* = 0.01, *pop* = 100, *iteration* = 300 for the overtime work optimisation. the genetic parameter settings are *CR* = 0.8, *MR*=0.001, *pop*=100, *iteration* =500 for the staff level optimisation. Therefore, parameters of TLNSGA-II were set with population size at 117 (*pop* = 117), number of iterations to stop the algorithm at 434 (*iteration* = 434), crossover probability at 0.8 (*CR* = 0.8) and mutation probability at 0.007 (*MR* = 0.007), respectively.

6.4 Implementation

The TLNSGA-II with constructive heuristic is set as follows: the population size of 117, the number of iterations to stop the algorithm is 434, the crossover probability is 0.8 and the mutation probability is 0.007, which are mentioned and explained in Section 6.3. The proposed TLNSGA-II was coded in MATLAB programming language and ran on a PC with an Intel i7-4600U CPU of 2.10 GHz and 8 GB RAM. The computational time was around 75 minutes.

Figure 6.4 shows the Pareto optimal solutions of the multi-objective, integrated optimisation problem solved by the TLNSGA-II approach.

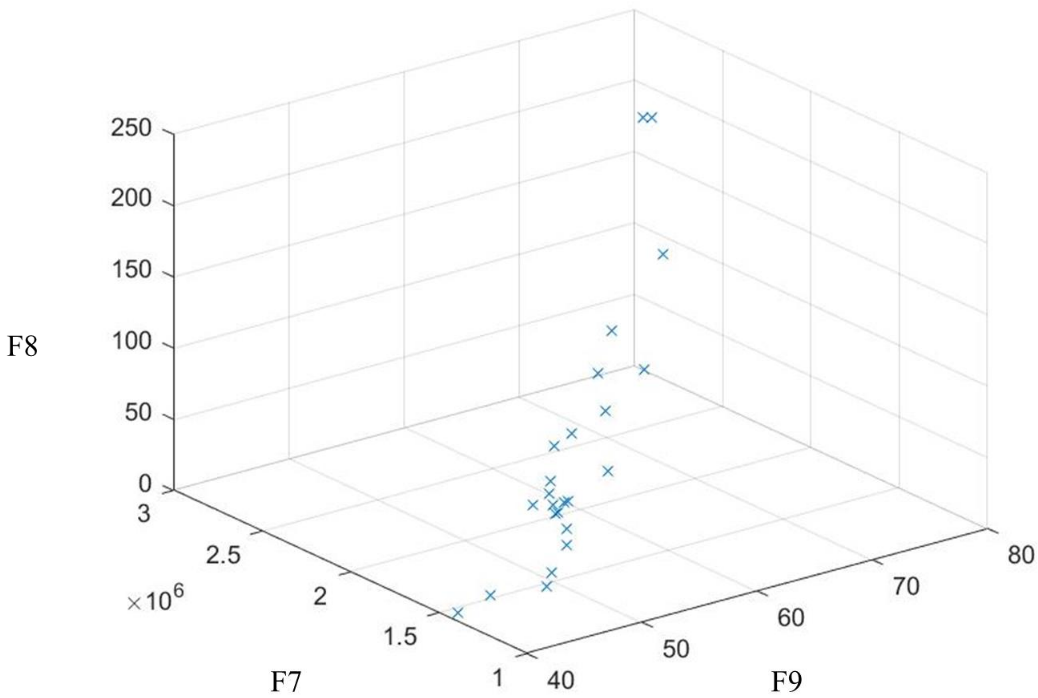

Figure 6.4 Pareto solutions based on TLNSGA-II

Each optimal solution contains staff level, shift assignment, days off assignment and task assignment of nursing staff in the nursing home. Nursing home manager can choose the optimal solution according to particular interest. For example, if an optimal solution is selected based on the lowest total staffing cost with no overtime work, the staff level and the staff schedule are as shown in Tables 6.11 and 6.12, respectively. Number(s) within brackets refers to the amount of working hours (in hours) of temporary nursing staff/ overtime work (in hours) of regular nursing staff.

Table 6.11 Optimised staff level based on TLNSGA-II

Staff Level							
PCW		**HW**		**EN**		**RN**	
Part-time	**Full-time**	**Part-time**	**Full-time**	**Part-time**	**Full-time**	**Part-time**	**Full-time**
8	0	0	16	0	9	0	4

Table 6.12 Optimised staff schedule based on TLNSGA-II

Category	Nature	ID	Day									
			1	2	3	4	5	6	7	8	9	10
PT	**PCW**	**1**	0	P(1)	N(4)	P(4)	P(1)	A(4)	P(4)	0	N(4)	0
PT	**PCW**	**2**	N(1)	N(4)	P(1)	A(4)	N(1)	0	A(1)	0	0	N(4)
PT	**PCW**	**3**	A*(1)	P(4)	A(4)	N(1)	P(4)	N(1)	0	P(4)	A(1)	A(1)
PT	**PCW**	**4**	P(1)	A(4)	P(4)	P(1)	A(4)	P(4)	0	A(1)	P(4)	N(1)
PT	**PCW**	**5**	N(4)	0	A(1)	N(4)	0	P(1)	A(4)	A(4)	P(1)	0
PT	**PCW**	**6**	A*(4)	N(1)	0	A(1)	A(1)	A(1)	P(1)	N(1)	0	A(4)
PT	**PCW**	**7**	P(4)	A(1)	N(1)	0	N(4)	N(4)	N(4)	N(4)	N(1)	P(4)
PT	**PCW**	**8**	0	0	0	0	0	0	N(1)	P(1)	A(4)	P(1)
FT	**EN**	**1**	N(0)	N(0)	N(0)	0	N(0)	P(0)	P(0)	A(0)	A(0)	N(0)
FT	**EN**	**2**	P(0)	P(0)	N(0)	P(0)	N(0)	P(0)	0	0	0	0
FT	**EN**	**3**	A*(0)	0	A(0)	A(0)	0	N(0)	P(0)	A(0)	0	0
FT	**EN**	**4**	P(0)	N(0)	0	A(0)	A(0)	0	A(0)	N(0)	P(0)	A(0)
FT	**EN**	**5**	0	A(0)	P(0)	N(0)	P(0)	A(0)	A(0)	0	0	P(0)
FT	**EN**	**6**	A*(0)	A(0)	P(0)	P(0)	A(0)	N(0)	0	N(0)	P(0)	0
FT	**EN**	**7**	N(0)	P(0)	A(0)	N(0)	P(0)	A(0)	0	0	A(0)	A(0)

Category	Nature	ID	Day									
			1	2	3	4	5	6	7	8	9	10
FT	**EN**	**8**	0	0	0	0	0	0	N(0)	P(0)	N(0)	P(0)
FT	**EN**	**9**	0	0	0	0	0	0	N(0)	P(0)	N(0)	N(0)
FT	**RN**	**1**	A*(0)	A(0)	0	N(0)	P(0)	P(0)	N(0)	P(0)	P(0)	0
FT	**RN**	**2**	N(0)	N(0)	N(0)	P(0)	A(0)	A(0)	0	0	A(0)	P(0)
FT	**RN**	**3**	P(0)	P(0)	P(0)	0	N(0)	N(0)	P(0)	N(0)	0	A(0)
FT	**RN**	**4**	0	0	A(0)	A(0)	0	0	A(0)	A(0)	N(0)	N(0)
FT	**HW**	**1**	A*(0)	A(0)	P(0)	P(0)	0	A(0)	A(0)	P(0)	A(0)	A(0)
FT	**HW**	**2**	A*(0)	A(0)	P(0)	A(0)	P(0)	P(0)	0	P(0)	A(0)	N(0)
FT	**HW**	**3**	0	N(0)	P(0)	A(0)	A(0)	N(0)	N(0)	0	N(0)	0
FT	**HW**	**4**	N(0)	N(0)	N(0)	0	P(0)	A(0)	A(0)	A(0)	P(0)	P(0)
FT	**HW**	**5**	N(0)	0	A(0)	N(0)	P(0)	A(0)	N(0)	0	P(0)	0
FT	**HW**	**6**	P(0)	A(0)	N(0)	P(0)	N(0)	N(0)	0	P(0)	N(0)	P(0)
FT	**HW**	**7**	P(0)	0	A(0)	N(0)	0	N(0)	P(0)	0	P(0)	N(0)
FT	**HW**	**8**	A*(0)	N(0)	N(0)	P(0)	N(0)	P(0)	0	N(0)	0	0

Category	Nature	ID	Day									
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
FT	**HW**	**9**	P(0)	N(0)	0	P(0)	A(0)	N(0)	P(0)	A(0)	N(0)	0
FT	**HW**	**10**	A*(0)	A(0)	N(0)	0	A(0)	A(0)	P(0)	A(0)	P(0)	P(0)
FT	**HW**	**11**	N(0)	P(0)	A(0)	N(0)	N(0)	P(0)	0	P(0)	A(0)	N(0)
FT	**HW**	**12**	0	P(0)	A(0)	A(0)	A(0)	P(0)	A(0)	0	A(0)	A(0)
FT	**HW**	**13**	P(0)	P(0)	P(0)	A(0)	P(0)	0	P(0)	N(0)	0	A(0)
FT	**HW**	**14**	N(0)	P(0)	0	N(0)	N(0)	0	A(0)	A(0)	0	A(0)
FT	**HW**	**15**	0	0	0	0	0	0	N(0)	N(0)	N(0)	P(0)
FT	**HW**	**16**	0	0	0	0	0	0	N(0)	N(0)	0	N(0)

Category	Nature	ID	Day									
			11	12	13	14	15	16	17	18	19	20
PT	PCW	1	A(1)	P(1)	0	N(4)	N(1)	0	N(4)	0	P(4)	A(4)
PT	PCW	2	P(1)	0	N(1)	P(4)	0	A(4)	P(1)	A(4)	A(4)	N(4)
PT	PCW	3	A(4)	0	N(4)	N(1)	N(4)	N(1)	0	P(1)	0	P(4)
PT	PCW	4	N(4)	N(1)	P(1)	0	P(4)	A(1)	A(1)	A(1)	0	0
PT	PCW	5	0	A(4)	A(4)	P(1)	P(1)	P(4)	A(4)	0	A(1)	A(1)
PT	PCW	6	P(4)	P(4)	A(1)	A(4)	A(1)	0	N(1)	N(1)	P(1)	0
PT	PCW	7	0	A(1)	P(4)	0	0	N(4)	P(4)	P(4)	N(4)	N(1)
PT	PCW	8	N(1)	N(4)	0	A(1)	A(4)	P(1)	0	N(4)	N(1)	P(1)
FT	EN	1	0	N(0)	N(0)	P(0)	P(0)	N(0)	0	P(0)	0	A(0)
FT	EN	2	N(0)	P(0)	P(0)	0	N(0)	0	0	N(0)	0	P(0)
FT	EN	3	N(0)	P(0)	0	N(0)	N(0)	P(0)	P(0)	0	N(0)	P(0)
FT	EN	4	A(0)	0	N(0)	P(0)	0	0	P(0)	A(0)	0	N(0)
FT	EN	5	0	N(0)	0	0	A(0)	N(0)	N(0)	P(0)	A(0)	0
FT	EN	6	P(0)	A(0)	A(0)	0	0	0	0	0	P(0)	N(0)
FT	EN	7	A(0)	A(0)	A(0)	A(0)	0	A(0)	A(0)	N(0)	P(0)	A(0)

Category	**Nature**	**ID**	**Day**									
			11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
FT	**EN**	**8**	0	0	P(0)	A(0)	A(0)	A(0)	N(0)	0	N(0)	0
FT	**EN**	**9**	P(0)	0	0	N(0)	P(0)	P(0)	A(0)	A(0)	A(0)	0
FT	**RN**	**1**	0	N(0)	0	P(0)	N(0)	N(0)	0	P(0)	N(0)	P(0)
FT	**RN**	**2**	N(0)	P(0)	P(0)	A(0)	0	A(0)	A(0)	A(0)	P(0)	0
FT	**RN**	**3**	A(0)	A(0)	N(0)	N(0)	P(0)	0	P(0)	N(0)	0	N(0)
FT	**RN**	**4**	P(0)	0	A(0)	0	A(0)	P(0)	N(0)	0	A(0)	A(0)
FT	**HW**	**1**	0	0	N(0)	N(0)	P(0)	0	N(0)	N(0)	0	0
FT	**HW**	**2**	N(0)	0	P(0)	N(0)	N(0)	N(0)	N(0)	N(0)	0	0
FT	**HW**	**3**	P(0)	N(0)	N(0)	P(0)	A(0)	N(0)	0	P(0)	P(0)	A(0)
FT	**HW**	**4**	0	A(0)	A(0)	P(0)	A(0)	P(0)	N(0)	0	P(0)	0
FT	**HW**	**5**	N(0)	P(0)	A(0)	N(0)	N(0)	0	P(0)	A(0)	0	A(0)
FT	**HW**	**6**	A(0)	A(0)	A(0)	0	A(0)	A(0)	P(0)	A(0)	A(0)	A(0)
FT	**HW**	**7**	N(0)	P(0)	0	0	N(0)	N(0)	P(0)	N(0)	N(0)	P(0)
FT	**HW**	**8**	A(0)	P(0)	P(0)	A(0)	P(0)	A(0)	0	N(0)	P(0)	P(0)

Category	Nature	ID	Day									
			11	12	13	14	15	16	17	18	19	20
FT	**HW**	**9**	A(0)	P(0)	A(0)	N(0)	P(0)	N(0)	0	A(0)	A(0)	N(0)
FT	**HW**	**10**	0	A(0)	P(0)	A(0)	0	P(0)	A(0)	P(0)	P(0)	0
FT	**HW**	**11**	P(0)	N(0)	P(0)	0	N(0)	0	P(0)	0	0	A(0)
FT	**HW**	**12**	P(0)	0	0	A(0)	0	0	A(0)	P(0)	A(0)	P(0)
FT	**HW**	**13**	A(0)	0	N(0)	0	0	A(0)	A(0)	P(0)	N(0)	P(0)
FT	**HW**	**14**	P(0)	N(0)	0	P(0)	A(0)	P(0)	A(0)	0	N(0)	N(0)
FT	**HW**	**15**	N(0)	N(0)	0	A(0)	0	A(0)	N(0)	0	A(0)	N(0)
FT	**HW**	**16**	0	A(0)	N(0)	P(0)	P(0)	P(0)	0	A(0)	N(0)	N(0)

Category	Nature	ID	Day									
			21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
PT	**PCW**	**1**	0	A(1)	N(4)	N(4)	P(1)	P(4)	0	P(1)	P(1)	0
PT	**PCW**	**2**	P(4)	0	A(4)	A(4)	0	A(4)	A(4)	N(4)	P(4)	A(1)
PT	**PCW**	**3**	A(1)	A(4)	P(1)	0	A(4)	N(4)	0	A(1)	0	A(4)
PT	**PCW**	**4**	A(4)	N(4)	P(4)	P(1)	P(4)	0	A(1)	P(4)	A(4)	N(1)
PT	**PCW**	**5**	N(4)	P(4)	A(1)	P(4)	0	P(1)	P(4)	0	N(4)	N(4)
PT	**PCW**	**6**	N(1)	N(1)	N(1)	N(1)	N(4)	0	N(4)	0	A(1)	P(1)
PT	**PCW**	**7**	P(1)	0	0	A(1)	N(1)	N(1)	N(1)	N(1)	N(1)	0
PT	**PCW**	**8**	0	P(1)	0	0	A(1)	A(1)	P(1)	A(4)	0	P(4)
FT	**EN**	**1**	N(0)	0	0	P(0)	P(0)	P(0)	0	A(0)	0	N(0)
FT	**EN**	**2**	A(0)	N(0)	N(0)	N(0)	N(0)	0	P(0)	P(0)	A(0)	0
FT	**EN**	**3**	0	P(0)	A(0)	A(0)	A(0)	0	A(0)	N(0)	0	A(0)
FT	**EN**	**4**	0	A(0)	A(0)	N(0)	0	P(0)	A(0)	N(0)	P(0)	A(0)
FT	**EN**	**5**	P(0)	P(0)	0	0	N(0)	N(0)	0	0	A(0)	P(0)
FT	**EN**	**6**	N(0)	N(0)	P(0)	P(0)	0	0	N(0)	P(0)	N(0)	N(0)
FT	**EN**	**7**	A(0)	0	P(0)	0	0	A(0)	P(0)	A(0)	0	0

Category	Nature	ID	Day									
			21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
FT	**EN**	**8**	0	A(0)	0	A(0)	P(0)	A(0)	N(0)	0	P(0)	P(0)
FT	**EN**	**9**	P(0)	0	N(0)	0	A(0)	N(0)	0	0	N(0)	0
FT	**RN**	**1**	N(0)	0	0	0	A(0)	P(0)	P(0)	0	0	A(0)
FT	**RN**	**2**	0	P(0)	N(0)	N(0)	N(0)	N(0)	0	P(0)	N(0)	N(0)
FT	**RN**	**3**	P(0)	N(0)	P(0)	A(0)	P(0)	0	A(0)	A(0)	A(0)	0
FT	**RN**	**4**	A(0)	A(0)	A(0)	P(0)	0	A(0)	N(0)	N(0)	P(0)	P(0)
FT	**HW**	**1**	N(0)	N(0)	P(0)	A(0)	P(0)	A(0)	0	P(0)	A(0)	N(0)
FT	**HW**	**2**	A(0)	0	P(0)	N(0)	0	P(0)	P(0)	A(0)	0	0
FT	**HW**	**3**	A(0)	N(0)	P(0)	0	A(0)	N(0)	P(0)	A(0)	A(0)	A(0)
FT	**HW**	**4**	0	0	0	N(0)	N(0)	N(0)	P(0)	A(0)	A(0)	0
FT	**HW**	**5**	P(0)	P(0)	N(0)	P(0)	P(0)	0	A(0)	0	A(0)	P(0)
FT	**HW**	**6**	0	A(0)	0	A(0)	0	N(0)	0	0	0	A(0)
FT	**HW**	**7**	0	0	A(0)	N(0)	N(0)	P(0)	N(0)	N(0)	0	N(0)
FT	**HW**	**8**	P(0)	P(0)	A(0)	0	A(0)	A(0)	N(0)	0	P(0)	P(0)

Category	Nature	ID	Day									
			21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
FT	**HW**	**9**	N(0)	N(0)	0	A(0)	A(0)	A(0)	P(0)	N(0)	P(0)	0
FT	**HW**	**10**	A(0)	0	N(0)	P(0)	N(0)	P(0)	A(0)	A(0)	0	A(0)
FT	**HW**	**11**	P(0)	A(0)	P(0)	0	N(0)	0	N(0)	0	N(0)	P(0)
FT	**HW**	**12**	A(0)	A(0)	0	A(0)	P(0)	0	N(0)	P(0)	P(0)	A(0)
FT	**HW**	**13**	0	N(0)	N(0)	P(0)	P(0)	0	0	N(0)	N(0)	0
FT	**HW**	**14**	P(0)	A(0)	A(0)	P(0)	0	N(0)	0	P(0)	N(0)	N(0)
FT	**HW**	**15**	N(0)	P(0)	N(0)	N(0)	0	A(0)	A(0)	N(0)	P(0)	P(0)
FT	**HW**	**16**	N(0)	P(0)	A(0)	0	A(0)	P(0)	A(0)	P(0)	N(0)	N(0)

6.5 Analysis of Computational Results

For the integrated staff level planning and scheduling model, all healthcare tasks of residents are completed with the use of a heterogeneous workforce. In addition, since the staff level planning and scheduling decisions are now handled in an iterative approach, the integrated model yields only feasible plans that are strategically and operationally aligned with one another.

In this section, the Pareto optimal solutions obtained are analysed and compared against the one used currently, i.e. determined manually based on perceive experience and plans of previous months.

To illustrate the cost effectiveness of the proposed integrated staff level planning and scheduling model and TLNSGA-II, the total monthly staffing costs, the monthly staffing costs without considering the cost associated with hiring and firing regular nursing staff, and the nurse-to-resident ratio of the Pareto optimal solutions are compared with that of the current manual one.

The comparison of solution quality in terms of total monthly staffing costs obtained from the proposed model and the current manual one is shown in Figure 6.5. The comparison of solution quality in terms of monthly staffing costs, excluding costs associated with hiring additional and hiring existing regular nursing staff, is shown in Figure 6.6. In other words, Figure 6.5 shows the one-time cost that nursing home need to suffer when switching from the current practice to the use of the proposed model and TLNSGA-II, while Figure 6,6 shows that actual staffing costs that nursing home need to pay its staff in the longer term, given that the demand of residents are relatively constant.

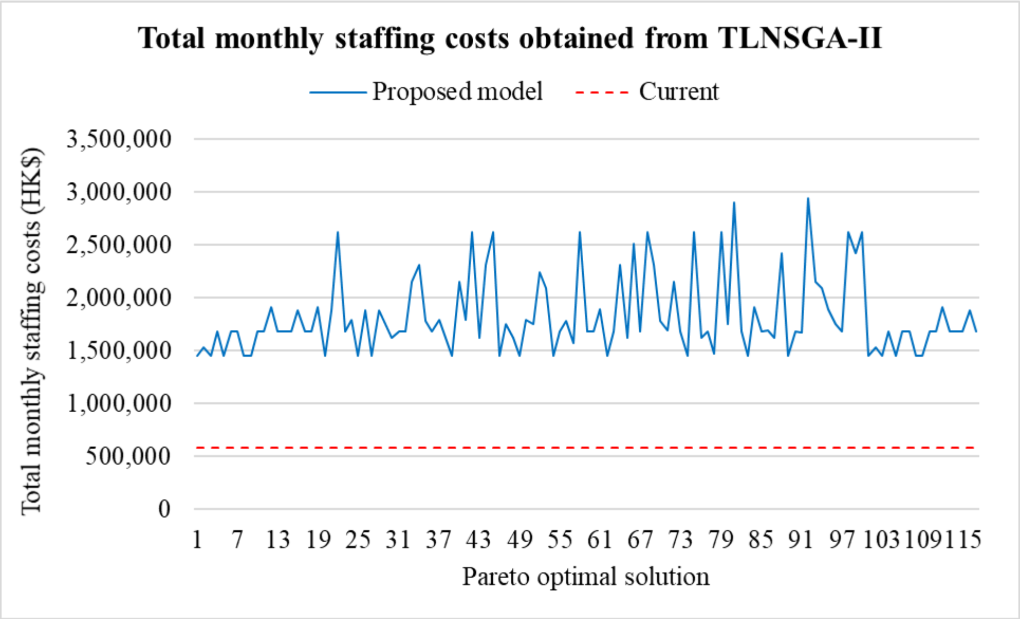

Figure 6.5 Total monthly staffing costs obtained from TLNSGA-II

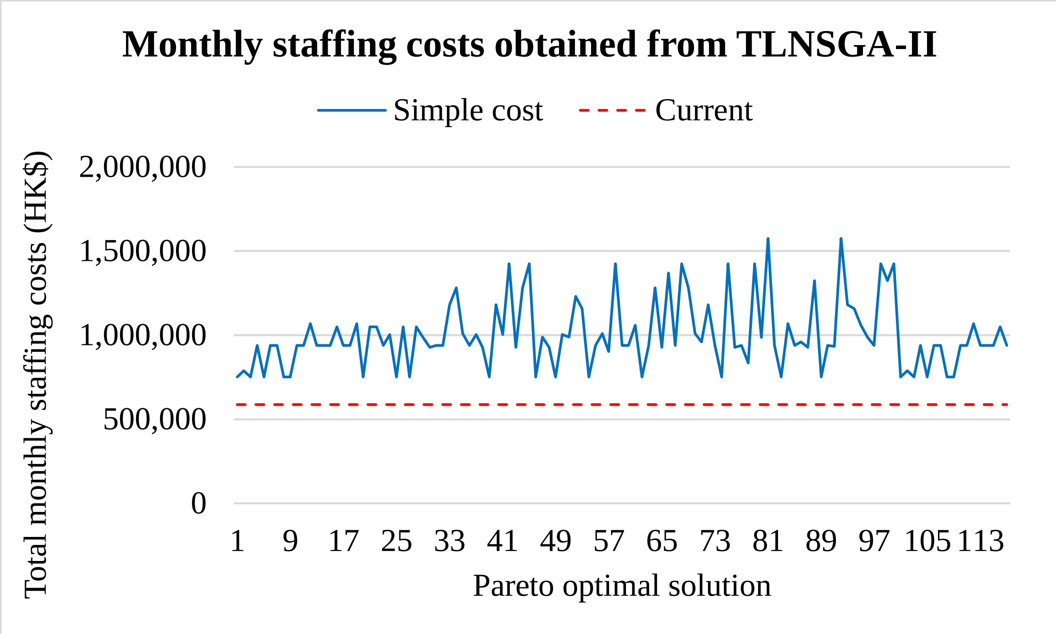

Figure 6.6 Monthly staffing costs obtained from TLNSGA-II

The comparison of solution quality in terms of total staff level is shown in Figure 6.7.

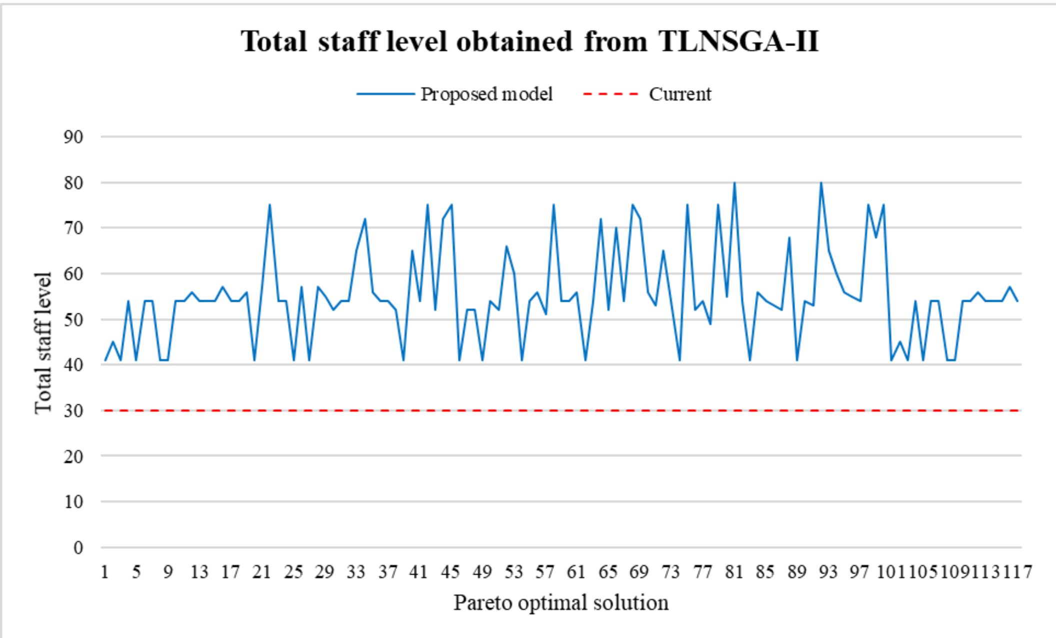

Figure 6.7 Total staff level obtained from TLNSGA-II

As far as the objectives are concerned, the value of nurse-to-resident ratios of 1:5.3 and 1:5.9 (for all shifts) are obtained from the proposed model and TLNSGA-II, whereas the value of nurse-to-resident ratios of 1:6.63 and 1:8.83 (for shifts 1 and 4), 1:5.8 and 1:7.57 (for shift 2), and 1:17.7 (for shift 3) are yielded in current practice. In other words, the proposed model solved by TLNSGA-II shows a significant advantage in nurse-to-resident ratio for all shifts. Although the same nurse-to-resident ratios can sometimes be obtained for shift 2, the proposed model being solved by TLNSGA-II can always yield Pareto-optimal solutions no worse than actual practice.

The advantages of the proposed model are contributed by the consideration of heterogeneous workforce, skill mix and skill substitution, which allow existing workforce to perform any task they are qualified to. In other words, these enhance the flexibility of assigning eligible nursing staff to a task so as the flexibility and cost effectiveness of assigning nursing staff to shift.

Another interesting findings of the case study is the staff level change of various staff categories. From Tables 6.1 and 6.11, one can note the significant staff level change was occurred for staff category '*PCW*' and '*HW*'. For '*PCW*', the staff level reduced from 19 to 8 and all half of them changed from full-time to part-time. On the contrary, for 'HW', the staff level significantly increased from 3 to 16. These changes were due to the fact that, though '*PCW*' has a relatively lower monthly salary (i.e. 28% less than that of '*HW*'), they are qualified to perform only half of healthcare tasks. Instead, 'PCW' has a moderate monthly salary (39% more than that of '*PCW*', but 24% less than that of '*EN*' and 59% less than that of '*RN*') and is qualified to perform 81% of the healthcare tasks. The changes in the staff level, once again, illustrate the cost effectiveness and positive staff and resident outcomes of incorporating skill related concepts, such as multi-skilled workforce, heterogeneous workforce, skill mix, and skill substitution, in nursing staff level planning and scheduling.

6.6 Summary

Staff level planning and staff scheduling are known to be a NP-complete and NP-hard problems, and are critical to the strategic and operation management of nursing homes. In this chapter, a TLNSGA-II with constructive heuristic approach is applied to solve the ISLPSP of a nursing home in Hong Kong. The parameters used in the TLNSGA-II calibrated using the Taguchi method. The performance of the model formulated and algorithm proposed have been verified and evaluated by conducting simulation experiments and comparing the results with the current manual scheduling. The results demonstrated that although the total monthly cost increase, it was mainly due to the cost associated with hiring additional and firing existing staff. The staffing costs, excluding hiring additional and firing existing staff, when analysed together with the nurse-to-resident ratio, indicate that the proposed model can significantly increase the nurse-to-resident ratio without heavily increase the staffing costs in the longer-term. Also, the proposed integrated model and TLNSGA-II show an improvement in the nurse-to-resident ratio that the staff level determined from the skill mix-task assignment master problem will be updated by the input from the scheduling sub problem. The proposed integrated model effectively balances between total staffing costs, overtime work and staff level.

Nursing home manager can choose the Pareto optimal solution based on his/her ultimate needs or according to particular scenarios.

Chapter 7 –CONCLUSION AND FUTURE WORK

7.1 Conclusions

Almost all developed regions are facing the demographical changes and problems associated with ageing population. Owing to the needs for increasing the provision of residential care services for the elderly, enhancing nursing homes' capacity and improving the working environment, staff level planning and scheduling of nursing staff are gaining increasing importance in today's nursing homes.

Existing staff level planning and scheduling approach rely on human experience, and often lead to ineffective and inefficient planning, and various critical factors are commonly ignored. After reviewing the previous studies of staff level planning and scheduling, some deficiencies of the existing studies were noted. First, the previous studies of staff level planning and scheduling mostly consider a single objective/criterion. In reality, several objectives/criterion have to be simultaneously in order to obtain god quality or even optimal solutions for the staff level planning and scheduling. Second, the previous studies of staff level planning and scheduling did not consider skill mix, skill substitution and consequence of skill quantitatively in their planning models. Finally, in the previous studies, staff level planning and scheduling are often addressed in two consecutive phases. However, staff level planning and scheduling are highly interrelated and separate consideration of them would result in strategic and operational conflicts.

To address the above deficiencies, in this research, a multi-objective optimisation approach to study staff level planning and scheduling, and a methodology for performing the integrated staff level planning and scheduling with consideration of skill mix, skill substitution and consequence of skill are proposed. The algorithm starts with staff level planning problem because it directly confines the number and mix of nursing staff required for each shift, and thus affect the total staffing levels and total staffing costs. Solution of staff scheduling will provide feedback for the master problem for further process. This study can be treated as the first of its kind to deal with the multi-skilled ISLPSP with skill mix and skill substitution that uses tuned TLNSGA-II to find Pareto front solutions.

The complicated idea of skills substitution and consequence of skill are incorporated in the model formulated for ISLPSP to increase the flexibility of workforce and better respond to an irregular fluctuating demand of nursing homes. The significance of the research can fill the research gap of modelling a ISLPSP for nursing staff in nursing homes with the consideration of various critical factors, and to transform the existing hierarchical and distinctive staff level planning and scheduling processes into an integrated and iterated planning decision.

The contribution of this study is twofold. First, the staff level planning and scheduling problem are studied from a multi-objective optimisation perspectives. Second, a methodology for performing the integrated staff level planning and scheduling with the consideration of skill mix, skill substitution and consequence of skill is proposed. The work presented in this study is the first to perform implicit task assignment in an integrated model and incorporates skill related concept in task assignment, shift assignment and staff level planning. A number of earlier research exist that integrate task assignment with shift assignment. However, to the best of our knowledge, this study is unique through the combination of an integrated staff level planning and scheduling formulation with implicit task assignment.

In this study, due to the limited data available for conducting numerical experiments, only a single case study of a subvented nursing home in Hong Kong is considered. Though the chosen case is a representative one, the limited data available limits the testing of performance of the proposed model and TLNSGA-II. Testing of the model and algorithm with larger data set and more data sets are suggested, if data is available.

7.2 Future Work

Future work related to this study are suggested as follows:

(i) In the development of the proposed model, it is assumed that all existing staff are available on any shift and thus can be assigned to any shift on any day. In reality, staff may have preference for day off, such as consecutive days off. Future work could consider staff preference for day off, such that their unavailability can be input into the model in advance.

(ii) In the TLNSGA-II, genetic parameters are calibrated using Taguchi method. Although Taguchi method is considered a robust experimental design which can significantly reduce the number of experiments, the method does not consider interactions between genetic parameters. In the future, the Taguchi method can be used with ANOVA for identifying significant parameters and determining initial optimal parameters combination, and followed by other calibration method.

(iii) The proposed multi-objective model, considers the total staffing costs and staff level as one of the objectives and may result in bias towards the use of temporary nursing staff which may cause job dissatisfaction of existing regular nursing staff. In the future, one may consider the inclusion of level change of regular nursing staff as one of the objectives, so as to balance the concerns of both existing nursing staff and nursing home manager.

(iv) The proposed model and TLNSGA-II can be employed for a wide range of applications with respect to staffing and scheduling of multi-skilled and heterogeneous workforce with skill substitution, such as staff planning in elderly home and physician planning in care centers.

REFERENCES

AbuAlRub, R. F., Omari, F. H., & Al-Zaru, I. M. (2009). Support, satisfaction and retention among Jordanian nurses in private and public hospitals. *International Nursing Review*, 56, 326-332.

Aiken, L. H., Clarke, S. P., Sloane, D. M., Lake, E. T., & Cheney, T. (2008). Effects of hospital care environment on patient mortality and nurse outcomes. *Journal of Nursing Administration*, 38(5), 223-229.

Aiken, L., Clark, S., & Sloane, D. (2002). Hospital staffing, organization, and quality of care: Cross-national findings. *Nursing Outlook*, *50*(5), 187-194.

Aksin, O. Z., Armony, M., & Mehrotra, V. (2007). The modern call-center: A multidisciplinary perspective on operations management research. *Production and Operations Management*, *16*(6), 665-688.

American Nurses Association. (2010a). *Safe staffing saves lives*. Retrieved from http://www.safe.staffing.saveslives.org/WhatisANADoing/FederalLegistation.aspx

American Nurses Association. (2010b). *Safe staffing saves lives*. Retrieved from http://www.safestaffingsaveslives.org/WhatisSafeStaffing/SafeStaffingPrinciples.aspx

Ansefine, K. E., Muzakki, Sanudin, Anggadjaja, E., & Santoso, H. (2017). Smart and wearable technology approach for elderly monitoring in nursing home. In: *2017 IEEE 3rd International Conference on Engineering Technologies and Social Sciences (ICETSS),* Bangkok, pp. 1-6.

Asgeirsson, E. I., & Siguroardottir, G. L. (2016). Near-optimal MIP solutions for preference based self-scheduling. *Annals of Operations Research*, 239(1), 273-293.

Association of Hong Kong Nursing Staff. (2012). *NGO nurse human resources survey 2012*. Retrieved from http://www.nurse.org.hk/media/contentbuilder/upload/c04041209.pdf

Association of Hong Kong Nursing Staff. (2013). *Nurse human resources survey 2013*. Retrieved from http://www.nurse.org.hk/media/contentbuilder/upload/c04041308.pdf

Association of Hong Kong Nursing Staff. (2014). *HA nursing staff human resources questionnaire 2014*. Retrieved from: http://www.nurse.org.hk/media/contentbuilder/upload/c04041408.pdf. (in Chinese).

Au, Y. (2009). *A study on the problem of Hong Kong's nursing shortage: How and why policy makers have failed to tackle it*. (Thesis). University of Hong Kong, Hong Kong SAR. Retrieved from: http://dx.doi.org/10.5353/th_b4675536.

Ayre, T. C., Gerdtz, M. F., Parker, J., & Nelson, S. (2007). Nursing skill mix and outcomes: A Singapore perspective. *International Nursing Review*, *54*(1), 56-62.

Bakirli, G., Birant, D., & Kut, Alp. (2011). An incremental genetic algorithm for classification and sensitivity analysis of its parameters. *Expert Systems with Applications*, *38*(3), 2609-2620.

Bard, J. F., & Purnomo, H. W. (2005). A column generation-based approach to solve the preference scheduling problem for nurses with downgrading. *Socio-Economic Planning Sciences*, *39*(3), 193-213.

Bartholdi, J. J. (1981). A guaranteed-accuracy round-off algorithm for cyclic scheduling and set covering. *Operations Research*, *29*(3), 501–510.

Baumann, S. L. (2006). Nursing issues in Hong Kong. *Nursing Science Quarterly*, 19(2), 157.

Beddoe, G., Petrovic, S., & Li, J. (2009). A hybrid metaheuristic case-based reasoning system for nurse rostering. *Journal of Scheduling*, *12*(2), 99-119.

Bekker, R., Moeke, D., & Schmidt, B. (2019). Keeping pace with the ebbs and flows in daily scheduling nursing home operations. *Health Care Management Science*, 22, 350-363.

Benavides, A. J., Ritt, M., & Miralles, C. (2014). Flow shop scheduling with heterogeneous workers. *European Journal of Operational Research*, *237*(2), 713-720.

Bourque, M. (1980). Patient scheduling in a therapeutic clinic. *Proceedings of the Annual Symposium on Computer Application in Medical Care*, *2*, 781-785.

Bowblis, J. R., & Lucas, J. A. (2012). The impact of state regulations on nursing home care practices. *Journal of Regulatory Economics*, *42*(1), 52-72.

Braekers, K., Hartl, R.F., Parragh, S.N., & Tricoire, F. (2016). A bi-objective home cares scheduling problem: Analyzing the trade-off between costs and client inconvenience. *European Journal of Operational Research*, 248, 428-443.

Brunner, J. O., & Edenharter, G. (2011). Long term staff scheduling of physicians with different experience levels in hospitals using column generation. *Health Care Management Science*, *14*(2), 189-202.

Brusco, M. J., Johns, T. R., & Reed, J. H. (1998). Cross-utilization of a two-skilled workforce. *International Journal of Operations & Production Management*, *18*(6), 555-564.

Buchan, J. (2004). What difference does ('good') HRM make? *Human Resources for Health*, 2(1), 6.

Buchan, J. (2006). Evidence of nursing shortages or a shortage of evidence? *Journal of Advanced Nursing*, 56(5), 457-458.

Buchan, J., & Aiken, L. (2008). Solving nursing shortages: A common priority. *Journal of Clinical Nursing*, 17(24), 3262-3268.

Buchan, J., & Calman, L. (2006). The global shortage of registered nurses: An overview of issues and actions. Proceedings from: *The Global Nursing Shortage: Priority Areas for Intervention*. Geneva, Switzerland: International Council of Nurses.

Burdett, R.L. & Kozan, E. (2018). An integrated approach for scheduling health care activities in a hospital. *European Journal of Operational Research*, 264, 756-773.

Burgio, L. D., Fisher, S. E., Fairchild, J. K., Scilley, K., & Hardin, J. M. (2004). Quality of care in the nursing home: Effects of staff assignment and work shift. *The Gerontologist*, *44*(3), 368-377.

Burke, E. K., Li, J., & Qu, R. (2010). A hybrid model of integer programming and variable neighbourhood search for highly-constrained nurse rostering problems. *European Journal of Operational Research*, *203*(2), 484-493.

Burke, E., & Petrovic, S. (Eds.). (2004). *European journal of operational research*, *Special issue on timetabling and rostering*. Amsterdam: Elsevier.

Busetti, F. (2003). *Simulated annealing overview*. Retrieved from http://www.aiinfinance.com/saweb.pdf

Butchers, E. R., Day, P. R., Goldie, A. P., Miller, S., Meyer, J. A., Ryan, D. M., Scott, A. C., & Wallace, C. A. (2001). Optimized crew scheduling at Air New Zealand. *Interfaces*, *31*(1) 30-56.

Butler, M., Collins, R., Drennan, J., Halligan, P., O'Mathuna, D. P., Schultz, T. J., Sheridan, A., & Vilis, E. (2011). Hospital nurse staffing models and patient and staff-related outcomes. *Cochrane Database of Systematic Reviews*, *7*. DOI: 10.1002/14651858.CD007019.pub2.

Cai, C., & Zhou, Z. (2009). Structural empowerment, job satisfaction, and turnover intention of Chinese clinical nurses. *Nursing Health Sciences*, 11, 397-403.

Cai, X., & Li, K. N. (2000). A genetic algorithm for scheduling staff of mixed skills under multi-criteria. *European Journal of Operational Research*, *12*5(2), 359-369.

Candan, G., & Yazgan, H. R. (2015). Genetic algorithm parameter optimisation using Taguchi method for a flexible manufacturing system scheduling problem. *International Journal of Production Research*, 53(3), 897-915.

Cappanera, P., & Scutella, M. G. (2013). Home care optimization: Impact of pattern generation policies on scheduling and routing decisions. *Electronic Notes in Discrete Mathematics*, 41, 53-60.

Carlos, S., Sanchez, A., & Martorell, S. (2011). Model to study the effect of workforce on a safety equipment and its optimization. *Mathematical and Computer Modelling*, 54(7–8), 1808-1812.

Census and Statistics Department. (2014). *Hong Kong population projections 2012-2041*. Retrieved from: http://www.censtatd.gov.hk/press_release/pressReleaseDetail.jsp?charsetID=1&pressRID=2990.

Chan, Z. C. Y., Tam, W. S., Lung, M. K. Y., Wong, W. Y., & Chau, C. W. (2013). On nurses moving from public to private hospitals in Hong Kong. *Journal of Clinical Nursing*, 22(9-10), 1382-1390.

Chapman, S. S. (2009). How have mandated nurse staffing ratios affected hospitals? Perspectives from California hospital leaders. *Journal of Healthcare Management*, *54*(5), 321-335.

Chen, D., Zeng, B., Sun, Z., Zhao, L., Huang, Z., & Wang, M. (2016). An off-bed detection and bathroom accident monitor system for nursing home. In: *2016 International Conference on Advanced Robotics and Mechatronics (ICARM)*, Macau, pp. 53-58.

Chen, H. C., Chu, C. I., Wang, Y. H., & Lin, L. C. (2008). Turnover factors revisited: A longitudinal study of Taiwan-based staff nurses. *International Journal of Nursing Studies*, 45(2), 277-285.

Chen, X., Thomas, B. W., & Hewitt, M. (2016). The technician routing problem with experience-based service times. *Omega*, 61, 49-61.

Chen, X., Thomas, B. W., & Hewitt, M. (2017). Multi-period technician scheduling with experience-based service times and stochastic customers. *Computers and Operations Research*, 82, 1-14.

Chikanda, A. (2005). Nurse migration from Zimbabwe: Analysis of recent trends and impacts. *Nursing Inquiry*, 12(3), 162-174.

Chou, K. L., & Chi, I. (2004). Factors associated with the use of publicly funded services by Hong Kong Chinese older adults. *Social Sciences & Medicine*, 58(6), 1025-1035.

Corominas, A., Lusa, A. & Olivella, J. (2012). A detailed workforce planning model including non-linear dependence of capacity on the size of the staff and cash management. *European Journal of Operational Research*, 216(2), 445-458.

Currall, S. C., Towler, A. J., Judge, T. A., & Kohn, L. (2005). Pay satisfaction and organizational outcomes. *Personnel Psychology*, 58(3), 613-640.

Currie, V., Harvey, G., West, E., McKenna, H., & Keeney, S. (2005). Relationship between quality of care, staffing levels, skill mix and nurse autonomy: Literature review. *Journal of Advanced Nursing*, *51*(1), 73-82.

Dall, T., Chen, Y. J., Seifert, R., Maddox, P., & Hogan, P. (2009). The economic value of professional nursing. *Medical Care*, *47*(1), 97-104.

De Bruecker, P., Van den Bergh, J., Belien, J., & Demeulemeester, E. (2015). Workforce planning incorporating skills: State of the art. *European Journal of Operational Research*, *243*(1), 1-16.

De Bruecker, P., Van den Bergh, J., Beliën, J., & Demeulemeester, E. (2014). *Workforce planning incorporating skills: State of the art*. Retrieved from http://ssrn.com/abstract=2437372

De Gieter, S., Hofmans, J., Pepermans, R. (2011). Revisiting the impact of job satisfaction and organizational commitment on nurse turnover intention: An individual differences analysis. *International Journal of Nursing Studies*, 48(12), 1562-1569.

Deb, K., Pratap, A., Agarwal, S. & Meyarivan. T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions On Evolutionary Computation*, 6(2), 182-197.

Department of Community Medicine and School of Public Health, The University of Hong Kong. (2008). *Synopsis of healthcare financing study: Hong Kong's domestic health accounts*. Retrieved from http://www.fhb.gov.hk/beStrong/files/consultation/hkdha_eng.pdf

Department of Overall Planning. (2013). Important Issue. *Taiwan Economic Forum, 11*(10), 27-34.

DeVandry, S. N., & Cooper, J. (2009). Mandating nurse staffing in Pennsylvania: More than a numbers game. *Journal of Nursing Administration*, *39*(11), 470-478.

Di Gaspero, L., Gartner, J., Kortsarz, G., Musliu, N., Schaerf, A., & Slany, W. (2007). The minimum shift design problem. *Annals of Operations Research*, 155(1), 79-105.

Douglas, K. (2010). Ratios - If it were only that easy. *Nursing Economic*, *28*(2), 119-125.

Duan, L., Street, W. N., & Xu, E. (2011). Healthcare information systems: Data mining methods in the creation of a clinical recommender system. *Enterprise Information Systems*, 5(2), 169-181.

El-Jardali, F., Dimassi, H., Dumit, N., Jamal, D., & Mouro, G. (2009). A national cross-sectional study on nurses' intent to leave and job satisfaction in Lebanon: Implications for policy and practice. *BMC Nursing*, 8(3), doi:10.1186/1472-6955-8-3.

Ellenbecker, C. H. (2004). A theoretical model of job retention for home health care nurses. *Journal of Advanced Nursing*, *47*(3), 303-310.

Erhard, M., Schoenfelder, J., Fugener, A., & Brunner, J.O. (2018). State of the art in physician scheduling. *European Journal of Operational Research*, 265, 1-18.

Ernst, A. T., Jiang, H., Krishnamoorthy, M., & Sier, D. (2004b). Staff scheduling and rostering: A review of applications, methods and models. *European Journal of Operational Research*, *153*(1), 3-27.

Ernst, A. T., Jiang, H., Krishnamoorthy, M., Owens, B., & Sier, D. (2004a). An annotated bibliography of personnel scheduling and rostering. *Annals of Operations Research*, 127(1), 21-44.

Estryn-Behar, M., van der Heijden, B. I. J. M., Fry, C., & Hasselhom, H. M. (2010). Longitudinal analysis of personal and work-related factors associated with turnover among nurses. *Nursing Research*, 59(3), 166-177.

Farrell, D., Frank, B., Brady, C., McLaughlin, M., & Gray, A. (2006). The case for consistent assignment in the nursing home setting. *Medicine and Health/Rhode Island*, *89*(5), 187-188.

Fathollahi-Fard, A.M., Hajiaghaei-Keshteli, M., & Tavakkoli-Moghaddam, R. (2018). A bi-objective green home health care routing problem. *Journal of Cleaner Production*, 200, 423-443.

Fernandez-Olano, C., Lopez-Torres Hidalgo, J. D., Cerda-Diaz, R., Requena-Gallego, M., Sandcez-Castano, C., Urbistondo-Cascales, L., & Otero-Puime, A. (2006). Factors associated with health care utilization by the elderly in a public health care system. *Health Policy*, 75(2), 131-139.

Finstad, K. (2010). Response interpolation and scale sensitivity: Evidence against 5-point scales. *Journal of Usability Studies*, 5(3), 104-110.

Flinkman, M., Laine, M., Leino-Kilpi, H., Hasselhorm, H. M., & Salantera, S. (2008). Explaining young registered Finnish nurses' intention to leave the profession: A questionnaire survey. *International Journal of Nursing Studies*, 45(5), 727-739.

Flynn, L., & Deatrick, J. A. (2003). Home care nurses' descriptions of important agency attributes. *Journal of Nursing Scholarship*, *35*(4), 385-390.

Flynn, M., & McKeown, M. (2009). Nursing staffing levels revisited: A consideration of key issues in nurse staffing levels and skill-mix research. *Journal of Nursing Management*, *17*(6), 759-766.

Fochsen, G., Sjogren, K., Josephson, M., & Langerstrom, M. (2005). Factors contributing to the decision to leave nursing care: A study among Swedish nursing personnel. *Journal of Nursing Management*, 13, 338-344.

Fong, A. C. M., Fong, B., & Hong, G. (2018). Short-range tracking using smart clothing sensors: A case study of using low power wireless sensors for patients tracking in a nursing home setting. In: *2018 IEEE 3rd International Conference on Communication and Information Systems (ICCIS)*, Singapore, pp. 169-172.

Food and Health Bureau, & Hospital Authority. (2011). *Administration's paper on issues relating to manpower and wastage of nurses in the Hospital Authority*. Retrieved from: https://www.legco.gov.hk/yr10-11/english/panels/hs/papers/hs0509cb2-1648-5-e.pdf.

Food and Health Bureau. (2008). *Healthcare reform consultation document - Your health your life*. Retrieved from: http://www.fhb.gov.hk/beStrong/files/consultation/exsummary_eng.pdf.

Food and Health Bureau. (2008). *Your health, your life - Healthcare reform consultation document - Appendix B Hong Kong's current healthcare system*. Retrieved from http://www.fhb.gov.hk/beStrong/files/consultation/appendixb_eng.pdf

Food and Health Bureau. (2010). *Primary care development in Hong Kong: Strategy document.*

Food and Health Bureau. (2017). *Report of the strategic review on healthcare manpower planning and professional development*. Retrieved from: https://www.fhb.gov.hk/download/press_and_publications/otherinfo/180500_sr/e_sr_final_report.pdf.

Fook, V. F. S., Jayachandran, M., Jiliang, E. P., Yongwei, Z., & Jianzhong, E. H. (2018). Fiber Bragg Grating-based monitoring and alert system for care of residents in nursing homes. In: *2018 IEEE 4th World Forum on Internet of Things (WF-IoT)*, Singapore, pp. 195-200.

Fowler, J. W., Wirojanagud, P., & Gel, E. G. (2008). Heuristics for workforce planning with worker differences. *European Journal of Operational Research*, *190*(3), 724-740.

Freeman, J. (1992). Planning police staffing levels. *Journal of the Operational Research Society*, *43*(3), 187-194.

Golden, B. L., Raghavan, S., & Wasil, E. A. (2008). The vehicle routing problem: Latest advances and new challenges. Vol. 43. Springer US.

Greaves, J., Goodall, D., Berry, A., Shrestha, S., Richardson, A., & Pearson, P. (2018). Nursing workloads and activity in critical care: A review of the evidence. *Intensive & Critical Care Nursing*, 48, 10-20.

Green, L. V., Savin, S., & Savva, N. (2013). "Nursevendor problem": Personnel staffing in the presence of endogenous absenteeism. *Management Science*, 59(10), 2237-2256.

Griffiths, F., Cave, J., Boardman, F., Ren, J., Pawlikowska, T., Ball, R., Clarke, A., & Cohen, A. (2012). Social networks -The future for health care delivery, *Social Science & Medicine*, *75*(12), 2233-2241.

Guo, Z. X., Wong, W. K., Leung, S. Y. S., Fan, J. T., & Chan, S. F. (2006). Mathematical model and genetic optimization for the job shop scheduling problem in a mixed-and multi product assembly environment: A case study based on the apparel industry. *Computers & Industrial Engineering*, *50*, 202-219.

Hancock, W. M., Pollock, S. M., & Kim, M. K. (1987). A model to determine staff levels, cost, and productivity of hospital units. *Journal of Medical Systems*, *11*(5), 319-330.

Harper, P. R., Powell, N. H., & Williams, J.E. (2010). Modelling the size and skill-mix of hospital nursing teams. *Journal of the Operational Research Society*, *61*(5), 768-779.

Hayes, L. J., O'Brien-Pallas, L., Duffield, C., Shamian, J., Buchan, J., Hughes, F., Laschinger, H. K. S., & Morth, N. (2012). Nurse turnover: A literature review – An update. *International Journal of Nursing Studies*, 49(7), 887-905.

Hayes, L. J., O'Brien-Pallas, L., Duffield, C., Shamian, J., Buchan, J., Hughes, F., Laschinger, H. K. S., North, N., & Stone, P. W. (2006). Nurse turnover: A literature review. *International Journal of Nursing Studies*, 43(2), 237-263.

Health, Welfare and Food Bureau. (2005). *Discussion paper on the future service delivery model for our health care system – Building a healthy tomorrow*. Retrieved from: http://www.legco.gov.hk/yr04-05/english/panels/hs/papers/hs0719cb2-hmdac_paper-e.pdf.

Helmer, F. T., Olson, S. F., & Heim, R. I. (1993). Strategies for nurse aide job satisfaction. *Journal of Long Term Care Administration*, *21*(2), 10-14.

Hiermann, G., Prandtstetter, M., Rendl, A., Puchinger, J., & Raidl, G. R. (2015). Meta-heuristics for solving a multimodal home-healthcare scheduling problem. *Central European Journal of Operational Research*, 23 (1), 89-113.

Hodge, M. B., Romano, P. S., Harvey, D., Samuels, S. J., Olson, V. A., Sauve, M. J., & Kravitz, R. L. (2004). Licensed caregiver characteristics and staffing in California acute care hospital units. *Journal of Nursing Administration*, *34*(3), 125-133.

Holder, A. (2005). Navy personnel planning and the optimal partition. *Operations Research*, *53*(1), 77-89.

Holland, J. H. (1975). *Adaptation in natural and artificial systems: An introduction analysis with applications to biology, control, and artificial intelligence*. MI: University of Michigan Press.

Hong Kong Special Administrative Region Government. (2014). *The 2014 policy address - Policy agenda.* Tamar, Hong Kong: Office of the Chief Executive.

Hospital Authority. (2005). *Annual plan 2005/06*. Retrieved from: http://www.ha.org.hk/haho/ho/ap/AP0506E.pdf

Hospital Authority. (2011). *Hospital Authority Annual Plan 2011-2012.* Retrieved from https://www.ha.org.hk/upload/publication_12/318.pdf

Hospital Authority. (2014). *Hospital Authority Annual Plan 2014-2015.* Retrieved from https://www.ha.org.hk/upload/publication_12/478.pdf

Hospital Authority. (2015). *Hospital Authority statistical report 2013 - 2014*. Retrieved from: http://www.ha.org.hk/haho/ho/stat/HASR1314_2.pdf.

Hospital Authority. (2017). *Annual report 2016 - 2017*. Retrieved from: http://www.ha.org.hk/ho/corpcomm/AR201617/PDF/HAAR_2016-17_PDF_final.pdf.

Huang, H., Lin, W. J., Lin, Z. Y., Hao, Z. F., & Lim, A. (2014). An evolutionary algorithm based on constraint set partitioning for nurse rostering problems. *Neural Computing and Applications*, *25*, 703-715.

Imai, A., Nishimura, E., & Papadimitriou, S. (2001). The dynamic berth allocation problem for a container port. *Transportation Research Part B: Methodological*, *35*(4), 401-417.

Issaoui, B., Zidi, I., Marcon, E., & Ghedira, K. (2015). New multi-objective approach for the home care service problem based on scheduling algorithms and variable neighborhood descent. *Electronic Notes in Discrete Mathematics*, 47, 181-188.

Jiang, S., Li, M., Hyer, K. & Kong, N. (2020). Optimal Nursing Home Shift Scheduling: A Two-Stage Stochastic Programming Approach. In: *Proceedings of 2020 16th IEEE International Conference on Automation Science and Engineering (CASE)*, August 20-21 2020.

Johns, R. (2010). *SQB Methods fact sheet 1*. Retrieved from: https://www.ukdataservice.ac.uk/media/262829/discover_likertfactsheet.pdf

Johnson, J. E., & Buelow, J. R. (2003). Providing staff feedback to nurse managers using internal resource. *Journal of Nursing Administration*, 33(7/8), 391-396.

Jorn, V. D. B., Jeroen, B., Philippe, D. B., Erik, D., & Liesje, D. B. (2013). Personnel scheduling: A literature review. *European Journal of Operational Research*, *226*(3), 367-385.

Jourdain, G., & Chenevert, D. (2010). Job demands–resources, burnout and intention to leave the nursing profession: A questionnaire survey. *International Journal of Nursing Studies*, 47(6), 709-722.

Kane, R. L., Shamliyan, T. A., Mueller, C., Duval, S., & Wilt, T. J. (2007). The association of registered nurse staffing levels and patient outcomes: Systematic review and meta-analysis. *Medical Care*, *45*(12), 1195-1204.

Kazakovtsev, L. A., & Antamoshkin, A. N. (2014). Genetic algorithm with fast greedy heuristic for clustering and location problems. *Informatica*, *38*, 229-240.

Khera, N., Tiwari, S., Singh, R. P., Ghosh, T., & Kumar, P. (2016). Development of android based smart home and nurse calling system for differently abled, In: *2016 5th International Conference on Wireless Networks and Embedded Systems (WECON)*, Rajpura, pp. 1-4,

Kim, D. H., Abraham, A., & Cho, J. H. (2007). A hybrid genetic algorithm and bacterial foraging approach for global optimization. *Information Sciences*, *177*, 3918-3937.

Kim, K. & Mehrotra, S. (2015). A two-stage stochastic integer programming approach to integrated staffing and scheduling with application to nurse management. Operations Research, 63(6),1431–1451.

Kim, M. K., & Hancock, W. M. (1989). Applications of staffing, scheduling, and budgeting methodologies to hospital ancillary units. *Journal of Medical Systems*, *13*(1), 37-47.

Koeleman, P. M., Bhulai, S., & van Meersbergen, M. (2012). Optimal patient and personnel scheduling policies for care-at-home service facilities. *European Journal of Operational Research*, *219*(3), 557-563.

Komarudina, Guerry, M. A., De Feyter, T., & Berghe, G. V. (2013). The roster quality staffing problem - A methodology for improving the roster quality by modifying the personnel structure. *European Journal of Operational Research*, *230*(3), 551-562.

Kong, X., Yang, Y., Gao, J., Guan, J., Liu, Y., Wang, R., Xing, B., Li, Y., & Ma, W. (2015). Overview of the health care system in Hong Kong and its referential significance to mainland China. *Journal of the Chinese Medical Association,* 78(10), 569-573.

Koshiro, K. (1987). Personnel planning, technological changes and outsourcing in the Japanese automobile industry: Part 1. *Internal Journal of Technology Management*, *2*(2), 279-297.

Kuramoto, N., Jayatilake, D., Hidaka, K., & Suzuki, K. (2016). Smartphone-based swallowing monitoring and feedback device for mealtime assistance in nursing homes. In: *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Orlando, FL, pp. 5781-5784.

Lagodimos, A. G. & Mihiotis, A. N. (2006). Overtime vs. regular shift planning decisions in packing shops. *International Journal of Production Economics*, 101(2), 246-258.

Lagodimos, A. G., & Leopoulos, V. (2000). Greedy heuristic algorithms for manpower shift planning. *International Journal of Production Economics*, *68*(1), 95-106.

Landa-silva, D., & Le, K. N. (2008). A simple evolutionary algorithm with self-adaptation for multi-objective nurse scheduling. *Studies in Computational Intelligence*, *136*, 133-155.

Lanzarone, E. & Matta, A. (2014). Robust nurse-to-patient assignment in home care services to minimize overtimes under continuity of care. *Operations Research for Health Care*, 3, 48-58.

Lau, H. C. (1996). On the complexity of manpower shift scheduling. *Computers and Operations Research*, 23(1), 93-102.

Lee, C. Y., & Vairaktarakis, G. V. (1997). Workforce planning in mixed model assembly systems. *Operations Research*, *45*(4), 553-567.

Leshner, M., & Browne, A. (1993). Increasing efficiency through cross-training. *Best's Review / Life-Health Insurance Edition*, *94*(8), 39-40.

Li, G., Jiang, H., & He, T. (2015). A genetic algorithm-based decomposition approach to solve an integrated equipment-workforce-service planning problem. *Omega*, *20*, 1-17.

Li, L. L. X., & King, B. E. (1999). A healthcare staff decision model considering the effects of staff cross-training. *Health Care Management Science*, *2*(1), 53-61.

Li, N., & Li, L. (2000). Modeling staffing flexibility: A case of China. *European Journal of Operational Research*, *124*(2), 255-266.

Lin, C. C., & Wang, P. C. (2013). A greedy genetic algorithm for the TDMA broadcast scheduling problem. *IEICE Transactions on Information and Systems*, *E96-D*(1), 102-110.

Liou, S. R., & Cheng, C. Y. (2010). Organisational climate, organisational commitment and intention to leave amongst hospital nurses in Taiwan. *Journal of Clinical Nursing*, 19(11-12), 1635-1644.

Lu, H., While, A. E., & Barriball, K. L. (2005). Job satisfaction among nurses: A literature review. *International Journal of Nursing Studies*, 42(2), 211-227.

Lu, Z. P., & Hao, J. K. (2010). Adaptive tabu search for course timetabling. *European Journal of Operational Research*, *200*(1), 235-244.

Luque, G., & Alba, E. (2011). Parallel genetic algorithm for the workforce planning problem. *Studies in Computational Intelligence*, *367*, 115-134.

Lyons, R. F. (1992). Cross-training: A richer staff for leaner budgets. *Nursing Management*, *23*(1), 43-44.

Maenhout, B., & Vanhoucke, M, (2013). An integrated nurse staffing and scheduling analysis for longer-term nursing staff allocation problems. *Omega*, 41, 485-499.

Maghsoudlou, H., Afshar-Nadjafi, B., Niaki, S. T. A. (2016). A multi-objective invasive weeds optimization algorithm for solving multi-skill multi-mode resource constrained project scheduling problem. *Computers and Chemical Engineering*, 88, 157-169.

Majozi, T., & Zhu, X. X. (2005). A combined fuzzy set theory and milp approach in integration of planning and scheduling of batch plants-personnel evaluation and allocation. *Computers & Chemical Engineering*, *29*(9), 2029-2047.

Mankowska, D. S., Meisel, F., & Bierwirth, C. (2014). The home health care routing and scheduling problem with interdependent services. *Health Care Management Science*, *17*(1), 15-30.

Marchesi, J. F., Hamacher, S., & Fleck, J. L. (2020). A stochastic programming approach to the physician staffing and scheduling problem. *Computers & Industrial Engineering*, 142, 106281.

Marczyk, A. (2004). *Genetic algorithms and evolutionary computation*. Retrieved from http://www.talkorigins.org/faqs/genalg/genalg.html#examples:systems

Masterson, A. (2004). Towards an ideal skill-mix in nursing homes. *Nursing Older People*, *16*(4), 14-16.

Maxson-Cooper, P. A. (2011). Empowering nurses through an innovative scheduling model. *Nursing Clinics of North America*, 46(1), 59-65.

Mendoza, M. B., Bergado, C. A., De Castro, J. L. B., & Siasat, R. G. T. (2017). Tracking system for patients with Alzheimer's disease in a nursing home. In *TENCON 2017 - 2017 IEEE Region 10 Conference*, Penang, pp. 2566-2570.

Mercer, S. W., & Watt, G. C. M. (2007). The inverse care law: Clinical primary care encounters in deprived and affluent areas of Scotland. *Annals of Family Medicine*, 5(6), 503-510.

Miller, H. E., Pierskalla, W. P., & Rath, G. J. (1976). Nurse scheduling using mathematical programming. *Operations Research*, *24*(5), 857-870.

Mitchell, B. G., Gardner, A., Stone, P. W., Hall, L., & Pogorzelska-Maziarz, M. (2018). Hospital staffing and health care-associated infections: A systematic review of the literature. *The Joint Commission Journal on Quality and Patient Safety*; 44, 613-622.

Moeke, D., Koole, G., & Verkooijen, L. (2014). Scale and skill-mix efficiencies in nursing home staffing: Inside the black box. *Health Systems*, *3*(1), 18-28.

Montemanni, R., Moon, J. N. J., & Smith, D. H. (2003). An improved tabu search algorithm for the fixed-spectrum frequency-assignment problem. *IEEE Transactions on Vehicular Technology*, *52*(3), 891-901.

Mrayyan, M. T. (2005). Nurse job satisfaction and retention: Comparing public to private hospitals in Jordan. *Journal of Nursing Management*, 13, 40-50.

Nandhini, M., & Kanmani, S. (2010). Design of mathematical model and local search with heuristics optimization of course timetabling. *International Journal of Combinatorial Optimization Problems and Informatics*, *1*(2), 20-30.

Ngai, E. W. T., & Wat, F. K. T. (2002). A literature review and classification of electronic commerce research. *Information & Management*, 39(5), 415-429.

Nickel, S., Schroder, M., & Steeg, J. (2012). Mid-term and short-term planning support for home health care services. *European Journal of Operational Research*, *219*(3), 574-587.

Nunez-Letamendia, L. (2007). Fitting the control parameters of a genetic algorithm: An application to technical trading systems design. *European Journal of Operational Research*, *179*(3), 847-868.

Ozkarahan, I., & Bailey, J. E. (1988). Goal programming model subsystem of a flexible nurse scheduling support system. *IIE Transactions*, *20*(3), 306-316.

Paraskevopoulos, D.C., Laporte, G., Repoussis, P.P. & Tarantilis, C.D. (2017). Resource constrained routing and scheduling: Review and research prospects. *European Journal of Operational Research*, 263, 737–754.

Parr, D., & Thompson, J. M. (2007). Solving the multi-objective nurse scheduling problem with a weighted cost function. *Annals of Operations Research*, *155*(1), 279-288.

Petrovic, S., & Berghe, G. V. (2012). A comparison of two approaches to nurse rostering problems. *Annals of Operations Research*, *194*(1), 365-384.

Petrovic, S., & Berghe, G. V. (Eds.). (2007). *Annals of operations research, Special issue on personnel scheduling and planning*. Netherlands: Springer.

Ponti, M-A. D.; Germain, M. E. & Moulton, L.J. (2010). Staffing budgets: Planning, executing and managing into the future. *Nursing Management*, 41 (9), 34-38.

Portney, L. G., & Watkins, M. P. (2009). *Foundations of clinical research: Applications to practice*. 3rd Edition. Upper Saddle River, New Jersey: Pearson Education, Inc.

Pulido, R., Aguirre, A. M., Ortega-Mier, M., Garcia-Sanchez, A., & Mendez, C. A. (2014). Managing daily surgery schedules in a teaching hospital: A mixed-integer optimization approach. *BMC Health Services Research*, *14*, 464-476.

Punnakitikashem, P., Rosenberger, J. M., & Behan, D. B. (2008). Stochastic programming for nurse assignment. *Computational Optimization and Applications*, *40*(3), 321-349.

Punnakitikashem, P., Rosenberger, J. M., Behan, D. B., Baker, R. L., & Goss, K. (2006). An optimization-based prototype for nurse assignment. Proceedings from: *The 7th Asia Pacific Industrial Engineering and Management Systems Conference 2006.* Bangkok, Thailand.

Querstret, D., O'Brien, K., Skene, D. J., & Maben, J. (2020). Improving fatigue risk management in healthcare: A systematic scoping review of sleep-related/fatigue-management interventions for nurses and midwives. *International Journal of Nursing Studies*, 106, 103513.

Rahman, A., Straker, J. K., & Manning, L. (2009). Staff assignment practices in nursing homes: Review of the literature. *Journal of the American Medical Directors Association*, *10*(1), 4-10.

Rajecki, R. (2009). Mandatory staffing ratios: Boon or bane?. *RN*, *72*(1), 22-25.

Rantz, M. J., Hicks, L., Grando, V., Petroski, G. F., Madsen, R. W., Mehr, D. R., Conn, V., Zwygart-Staffacher, M., Scott, J., Flesner, M., Bostick, J., Porter, R., & Maas, M. (2004). Nursing home quality, cost, staffing, and staff mix. *The Gerontologist*, *44*(1), 24-38.

Reeves, R., West, E., & Barron, D. (2005). The impact of barriers to providing high-quality care on nurses' intentions to leave London hospitals. *Journal of Health Service Research & Policy*, 10(1), 5-9.

Research Office of Legislative Council Secretariat. (2015). Information note - Population profile of Hong Kong. Retrieved from: http://www.legco.gov.hk/research-publications/english/1415in07-population-profile-of-hong-kong-20150416-e.pdf.

Restrepo, M. I., Rousseau, L.-M., & Vallee, J. (2020). Home healthcare integrated staffing and scheduling. *Omega*, 95, 102057.

Rice, T. (2001). Production scheduling with a spreadsheet. *Quality & Productivity Journal*, *1*. Retrieved from http://symphonytech.com/articles/pdfs/schedulexl.pdf

Rogers, A. E. (2008). The effects of fatigue and sleepiness on nurse performance and patient safety. In: Hughes, R.G. (Ed.), *Patient Safety and Quality: An Evidence-Based Handbook for Nurses*. Agency for Healthcare Research and Quality (US), Rockville, MD, pp. 509-545.

Roshan, K., Seifarghy, M., & Pishva, D. (2017). Multi-objective evolutionary algorithms for a preventive healthcare facility network design. *International Journal of Industrial Engineering and Production Research, 26(4)*, 403-427.

Savage, D. W., Woolford, D. G., Weaver, B., & Wood, D. (2015). Developing emergency department physician shift schedules optimized to meet patient demand. *Canadian Journal of Emergency Medicine*, 17(1), 3-12.

Sellgren, S. F., Kajermo, K. N., Ekvall, G., & Tomson, G. (2009). Nursing staff turnover at a Swedish university hospital: An exploratory study. *Journal of Clinical Nursing*, 18(22), 3181-3189.

Shi, J., Mu, H., Yang, S., Chen, D., & Wang, M. (2019). A security monitoring and alarm system for nursing homes based on ZigBee technology. In: *2019 IEEE International Conference on Real-time Computing and Robotics (RCAR)*, Irkutsk, Russia, pp. 586-591.

Shi, Y. Boudouh, T. & Grunder, O. (2017). A hybrid genetic algorithm for a home health care routing problem with time window and fuzzy demand. *Expert Systems With Applications*, 72, 160-176.

Shi, Y., Boudouh, T., Grunder, O., & Wang, D. (2018). Modeling and solving simultaneous delivery and pick-up problem with stochastic travel and service times in home health care. *Expert Systems with Applications*, 102, 218-233.

Shin, S., Park, J. D., & Shin, J. H. (2020). Improvement Plan of Nurse Staffing Standards in Korea. *Asian Nursing Research*, 14, 57-65.

Smet, P., Bilgin, B., De Causmaecker, P., & Vanden Berghe, G. (2014). Modelling and evaluation issues in nurse rostering. *Annals of Operations Research*, *218*(1), 303-326.

Social Welfare Department. (2011). *SWD review 2009-10 & 2010-11*. Retrieved from http://www.swd.gov.hk/doc/annreport/SWD%20Review%202009-10_and_2010-11_txt_eng.pdf

Spratt, B., & Kozan, E. (2016). Waiting list management through master surgical schedules: A case study. *Operations Research for Health Care*, 10, 49-64.

Srinivas, C., Ramgopal Reddy, B., Ramji, K., & Naveen, R. (2014). Sensitivity analysis to determine the parameters of genetic algorithm for machine layout. *Procedia Materials Science*, *6*, 866-876.

Srinivas, M., & Patnaik, L. M. (1994). Genetic algorithms: A survey. *Computer*, *27*(6), 17-26.

T'Jonck, K., Strauven, H., Vankeirsbilck, J., Hallez, H., & Boydens, J. (2019). Design and implementation of an unobtrusive sensor system to support incontinence care of elderly in nursing homes. In: *2019 IEEE XXVIII International Scientific Conference Electronics (ET),* Sozopol, Bulgaria, pp. 1-4.

Tian, M., Gong, X., Yin, L., Li, H., Ming, W., Zhang, Z., & Chen, J. (2017). Multi-objective optimization of injection molding process parameters in two stages for multiple quality characteristics and energy efficiency using Taguchi method and NSGA-II. *The International Journal of Advanced Manufacturing Technology*, 89, 241-254.

Todorovic, N., & Petrovic, S. (2013). Bee colony optimization algorithm for nurse rostering. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *43*(2), 467-473.

Trinkoff, A. M., Johantgen, M., Storr, C. L., Gurses, A. P., Liang, Y., & Han, K. (2011). Nurses' work schedule characteristics, nurse staffing, and patient mortality. Nursing Research, 60, 1-8 .

Unruh, L. (2008). Nurse staffing and patient, nurse and financial outcomes. *The American Journal of Nursing*, *108*(1), 62-71.

Vairaktarakisa, G. L., Cai, X., & Lee, C. Y. (2002). Workforce planning in synchronous production systems. *European Journal of Operational Research*, *136*(3), 551-572.

Vile, J. L., Gillard, J. W., Harper, P. R., & Knight, V. A. (2016). Time-dependent stochastic methods for managing and scheduling Emergency Medical Services. *Operations Research for Health Care*, 8, 42-52.

Volland, J., Fugener, A., & Brunner, J. O. (2017). A column generation approach for the integrated shift and task scheduling problem of logistics assistants in hospitals. *European Journal of Operational Research*, 260, 316-334.

Waddington, H., Masset, E., & Jimenez, E. (2018). What have we learned after ten years of systematic reviews in international development? *Journal of Development Effectiveness*, 10(1), 1-16.

Wamba, S. F., Anand, A., & & Carter, L. (2013). A literature review of RFID-enabled healthcare applications and issues. *International Journal of Information Management*, 33(5), 875-891.

Waxman, H. W., Carner, E. A., & Berkenstock, G. (1984). Job turnover and job satisfaction among nursing home aides. *The Gerontologist*, *24*(2), 503-509.

Whitcombe, J. M., Cropp, R. A., Braddock, R. D., & Agranovski, I. E. (2006). The use of sensitivity analysis and genetic algorithms for the management of catalyst emissions from oil refineries. *Mathematical and Computer Modelling*, *44*(5-6), 430-438.

World Health Organization. (2012). The health-care challenges posed by population ageing. *Bullet of the World Health Organization*, *90*(2), 77-156.

World Health Organization. (2014). *The health of older people in selected countries of the Western Pacific Region*. Retrieved from: http://www.wpro.who.int/topics/ageing/health_of_older_people_in_selected_WPR_countries.pdf.

Xu, E., Wermus, M., & Bauman, D. B. (2011). Development of an integrated medical supply information system. *Enterprise Information Systems*, 5(3), 385-399.

Xu, Z.; Ming, X.G.; Zheng, M.; Li, M.; He, L.; Song, W. (2015). Cross-trained workers scheduling for field service using improved NSGA-II. *International Journal of Production Research*, 53(4), 1255-1272.

Yam, H. K., Mercer, S. W., Wong, L. Y., Chan, W. K., & Yeoh, E. K. (2009). Public and private healthcare services utilization by non-institutional elderly in Hong Kong: Is the inverse care law operating?. *Health Policy*, 91(3), 229-238.

Yang, C., & Wang, N. (2010). A solution method for berth-quay crane allocation problem. Proceedings from ICCET: *2010 2nd International Conference on Computer Engineering and Technology*. Chengdu: IEEE.

Yeung, M. (2011, April 21). Nurses charge workload threatens healthcare. *China Daily*. Retrieved from: http://www.chinadaily.com.cn/hkedition/2011-04/21/content_12365510.htm.

Zanda, S., Zuddas, P. & Seatzu, C. (2018). Long term nurse scheduling via a decision support system based on linear integer programming: A case study at the University Hospital in Cagliari. *Computers & Industrial Engineering*, 126, 337-347.

Zapfel, G., & Bogl, M. (2008). Multi-period vehicle routing and crew scheduling with outsourcing options. *International Journal of Production Economics*, *113*(2), 980-996.

Zeytinoglu, I. U., Denton, M., Davies, S., Baumann, A., Blythe, J., & Boos, L. (2007). Deteriorated external work environment, heavy workload and nurses' job satisfaction and turnover intention. *Canadian Public Policy*, 33, 31-47.

Zhang, N. J., Unruh, L., Liu, R., & Wan, T. T. H. (2006). Minimum nurse staffing ratios for nursing homes. *Nursing Economic*, *24*(2), 78-87.

Zitzler, E. (1999). Evolutionary Algorithms for Multi-objective Optimization: Methods and Applications. Dissertation. ETH No. 13398. Swiss Federal Institute of Technology.

Zulch, G., Rottinger, S., & Vollstedt, T. (2004). A simulation approach for planning and re-assigning of personnel in manufacturing. *International Journal of Production Economics*, *90*(2), 265-277.