VILNIUS UNIVERSITY

MINDAUGAS LIOGYS

HEURISTIC ALGORITHMS FOR NURSE ROSTERING PROBLEM

Summary of Doctoral Dissertation

Technological Sciences, Informatics Engineering (07 T)

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Doctoral dissertation was prepared at the Institute of Mathematics and Informatics of Vilnius University in 2008–2013.

Scientific supervisor

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The dissertation will be defended at the Council of the Scientific Field of Informatics Engineering at the Institute of Mathematics and Informatics of Vilnius University:

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Prof. Dr. Leonas Valius (Lithuanian University of Health Sciences, Biomedical Sciences, Medicine – 07 B).

Opponents:

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The dissertation will be defended at the public meeting of the Council of the Scientific Field of Informatics Engineering in the auditorium number at 203 at the Institute of Mathematics and Informatics of Vilnius University, at 1 p.m. on the 27th of September, 2013.

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A copy of the doctoral dissertation is available for review at the Library of Vilnius University.

VILNIAUS UNIVERSITETAS

MINDAUGAS LIOGYS

Darbų grafikų sveikatos priežiūros įstaigose optimizavimas

Daktaro disertacijos santrauka

Technologijos mokslai, informatikos inžinerija (07 T)

Vilnius, 2013

Disertacija rengta 2008–2013 m. Vilniaus universiteto Matematikos ir informatikos institute.

Mokslinis vadovas

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Oponentai:

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prof. habil. dr. Rimantas Šeinauskas (Kauno technologijos universitetas, technologijos mokslai, informatikos inžinerija – 07 T),

Disertacija bus ginama Vilniaus universiteto viešame Informatikos inžinerijos mokslo krypties tarybos posėdyje 2013 m. rugsėjo 27 d. 13 val. Vilniaus universiteto Matematikos ir informatikos instituto 203 auditorijoje.

Adresas: Akademijos g. 4, LT-08663 Vilnius, Lietuva.

Disertacijos santrauka išsiuntinėta 2013 m. rugpjūčio 27 d.

Disertaciją galima peržiūrėti Vilniaus universiteto bibliotekoje.

Introduction

Relevance of the Problem

Nurse rostering problem is a complex combinatorial problem, which is still, in many cases, solved manually, despite the fact it is frustrating and time consuming task. The planner always has to consider various government regulations, healthcare organization regulations, the preferences of the personnel.

Nurses constantly work under highly stressed conditions, like the death of the patient or severe trauma. The researches made on relation between nurse working schedule and her stress condition prove that work schedule has a great impact to nurse stress condition, so the planners task is to create schedules having minimized impact to nurse stress condition.

While there are many already proposed solutions in the market that automate the scheduling process, but still these solutions, usually, are restricted by one usual case and is not applicable to solve every rostering problem. In general, each nurse rostering problem is different nurse rostering problem and the solution to automate construction of the rosters must be developed individually.

The Aim and Tasks

The key aim of the dissertation is to develop a method for nurse rostering problem, which is common in one of the largest Lithuania healthcare centers that would automate the rosters optimization process.

To achieve the aim, it was necessary to solve the following tasks:

- To analyze the methods for solving single objective nurse rostering problem.
- To compare the performance of the shift sequence based and simulated annealing methods for solving single objective nurse rostering problem.
- To propose a method for solving single objective nurse rostering problem that outperforms the shift sequence based and simulated annealing methods.
- To analyze simulated annealing method versions for solving multi-objective nurse rostering problem.
- To adapt the shift sequence based approach and proposed method for solving multi-objective nurse rostering problem.

- To compare the methods for solving multi-objective nurse rostering problem.

The object of research

The object of the research is the nurse rostering problem, both, single objective and multi-objective optimization problems.

Research methods

To summarize the results of other researches the exploratory research has been used. To evaluate the methods for solving nurse rostering problem experimental research approach has been used.

Scientific novelty

A new algorithm for single objective and multi-objective nurse rostering problem has been proposed, that outperforms some of the state of the art methods.

Practical Significance

Practical significance is that a software is developed that can automate the rosters optimization process for one of the largest healthcare centers of Lithuania.

The defended statements

The defended statements based on the research are the following:

1. Simulated annealing method is more efficient method for solving single objective nurse rostering problem formulated in dissertation than shift sequence based method.

2. Newly proposed method is more efficient method for solving single objective nurse rostering problem formulated in dissertation than simulated annealing and shift sequence based methods.

3. Newly proposed method is more efficient method for solving multi-objective nurse rostering problem formulated in dissertation than simulated annealing and shift sequence based methods.

Approbation and Publications of the Research

The main results of the investigation are published in three scientific publications; one publication is published in proceedings of international conference, two publications were published in reviewed international journals.

The scope of the scientific work

The dissertation is written in Lithuanian. The thesis consists of 5 sections. There is 1 annex as well. The volume of work is 107 pages, excluding annex; are used 49 numbered formulas, 26 figures and 29 tables in the text. The thesis lists 93 references.

1. Review of Nurse Rostering Problem

In this chapter the review of nurse rostering problem most recently tackled by other researchers is presented.

After review of most recently published publications can be concluded that most of the problems are dealing with roster optimization of three different types of shifts, planning horizon is one week. Mostly considered hard constraints are the shift coverage constraint and one shift per day constraint. Also constraints that define the minimum or maximum rest time between assignments or after a certain number of the assignments.

Mostly considered soft constraints in the literature are minimum and maximum number of consecutive working days of assignments, nurse preferences (preferred shift, unwanted shift and etc.).

Categorization of nurse rostering problems, using $\alpha|\beta|\gamma$ notation, reveals that most nurse rostering problems tackled in literature are different problems: one part of the problems are less constrained, the other part is more constrained. Each problem is tackled using different approach and to identify which of the methods is the most efficient is impossible because it may be efficient for one problem but less efficient for another problem.

2. Nurse Rostering Problem

In this chapter the investigated nurse rostering problem is described. The problem is to maximize the compliance of the roster to nurses' preferences (soft constraints) with assurance that all necessary to satisfy constraints (hard constraints) are fulfilled.

Single objective nurse rostering problem is formulated as the following:

$$\min_{C_q \in D_q} f(C_q), q \in Q. \quad (1)$$

Here

Q is the set of skills,

E_q is the set of nurses having skill q,

c_e is the schedule of the nurse $e \in E_q$,

C_q is the roster of nurses having skill q, $C_q = (c_{e_1}, c_{e_2}, \dots, c_{e_m})^T$, m is the number of nurses having skill q,

D_q is the objective space of rosters for nurses having skill q,

f – objective function of rosters for nurses having skill q.

Objective function f is described in the following way:

$$f(C_q) = \sum_{c_e \in C_q} p(c_e), q \in Q. \quad (2)$$

Here

$p(c_e)$ is the penalty cost function.

The problems objective space D_q, $q \in Q$ is constrained by the following hard constraints:

- Shift coverage requirements must be fulfilled,
- Only one shift can be assigned to the nurse on the same day (exception is made for nurses working in several positions),
- At most two night shifts in seven days period are allowed to be scheduled,
- At most forty hours allowed be worked for one person per week,
- After night shift must be at least twenty four hours long rest time,
- Morning, day, night shifts must be assigned only on working days,
- Watch shift must be assigned only on weekends or bank holidays,

- Schedules of nurses working in several positions must not overlap,
- Must be no empty spaces between assignments on the same day for nurses working in several positions.

The penalty cost function $p(c_e)$, $e \in E_q$ is evaluated according to violations to these soft constraints:

- Assigned workload is equal to the demand workload (demand workload is the workload defined in nurse's working contract, assigned workload is the workload really assigned to the nurse in planning horizon),
- Maximum number of night shifts during scheduling period,
- Maximum number of watch shifts during scheduling period,
- Minimize number of consecutive night shifts,
- Requested shifts for each weekday,
- Unwanted shift,
- Requested days off,
- Working separately (nurse can specify a nurse she does not want to work together with),
- Working together (nurse can specify a nurse she wants to work together with).

Optimal roster to single objective nurse rostering problem is the roster having minimal penalty cost value.

Single objective nurse scheduling problem can be decomposed into several objective sub-problems. This comes out naturally, because planner usually has key objectives / goals that are very important and pays extra attention to it and the ones that are not very important. Using single-objective manner we cannot say if one goal or another is reached or close to it. Satisfaction with fulfillment of very important objectives can be very poor even then the penalty cost of the roster is very low under single-objective manner. To overcome this, nurse rostering problem can be solved as multi-objective optimization problem.

Multi-objective nurse rostering problem is formulated as the following:

$$\min_{C_q \in D_q} F(C_q) \tag{3}$$

Here

F is the vector of objective functions, $F = (f_1, f_2, \dots, f_n)$, n is the number of objective functions.

Objectives targeted in nurse rostering problem are the following:

- To minimize absolute value of difference between demand workload and assigned workload,
- Minimize amount of consecutive two night or watch shifts,
- Evenly distribute night shifts among nurses,
- Evenly distribute watch shifts among nurses,
- Minimize violations to nurses' preferences, like requested shifts on and off.

In multi-objective optimization, there does not typically exist one feasible solution that minimizes all objective functions. Solutions are called Pareto optimal solutions if their components cannot be improved without worsening others. This concept is called Pareto optimality.

Decision vector $x^* \in X$ is Pareto optimal if does not exists another $x \in X$ such that $f_i(x) \leq f_i(x^*)$ for all i and $f_j(x) < f_j(x^*)$ for at least one index j.

To compare the Pareto sets of different methods the hypervolume indicator have been used. Hypervolume indicator measures the volume of the dominated section of the objective space delimited by reference point, usually worst solution in the Pareto set. The higher hypervolume indicator value is the better set of solutions is said to be.

3. Methods for solving nurse rostering problem

In this chapter two state of the art (shift sequence based and simulated annealing) and newly proposed methods for solving single objective nurse rostering problem are described. Adaptation of the methods to solve multi-objective nurse rostering problem also described in this chapter.

After analysis and observation of results of shift sequence based approach and simulated annealing method the new method have been proposed combining those two methods.

Proposed method selects the employee with the worst schedule and randomly selects the shift sequence used in previous iteration. The selected sequence is replaced

with it‘s feasible neighbor shift sequence. Feasibility of the sequence is determined with hard constraints that limit the total weekly working hours, minimum rest time after night shift and maximum number of night shifts in 7 days period. If none of the neighbors are feasible the current sequence is replaced with empty shifts (rest days).

If neighbor shift sequence is feasible and shorter than the current sequence, then the shifts of current sequence are replaced with shifts from neighbor sequence, the rest part of current sequence, uncovered by neighbor sequence, is replaced with empty shifts.

If the neighbor sequence is feasible and it‘s length is equal to the current sequence all shifts of current sequence are replaced with neighbor sequence shifts.

If neighbor sequence is feasible and longer than the current sequence then all shifts of current sequence are replaced with neighbor sequence shifts and if neighbor sequence does not overlap the other sequence in the schedule, shifts from neighbor sequence are assigned to the schedule. If the neighbor sequence overlaps the next sequence in the schedule then the next sequence shifts are replaced with neighbor sequence shifts and uncovered part of the next sequence is replaced with empty shifts.

After this procedure there might be violations to shift coverage requirements. To fix violations to coverage requirements greedy local search procedure is carried out – it selects the nurse whose schedule will improve most by assigning or removing a shift. If no nurse whose schedule improves, then it selects the nurse whose schedule will be worsen less.

Then shift is removed the current sequence is updated by splitting it to two different sequences: sequence in the left side of the removed shift and sequence in the right side of the removed shift.

The new roster is compared with the best found so far and if it is better it is saved and if the end of construction is not reached the new iteration is carried out. If the new roster is worse than the best found so far, the new roster is accepted with probability *P*.

General procedure of proposed method to deal with single objective nurse rostering problem is the following:

1. *Generate shift sequences.*
2. *Evaluate shift each sequence.*
3. *Order shift sequences of a nurse in non-decreasing order by its penalty.*
4. *Construct initial roster*

5. *Set maximal iteration counter value*
6. *Generate new solution Y in neighborhood X.*
7. *If coverage requirements violated – repair using greedy local search.*
8. *If Y is better than $Best$, accept and set $Best = Y, X = Y$.*
9. *Else if Y is better than X, accept and set $X = Y$, else accept it with probability P.*
10. *If Y is not accepted keep X as background for neighbor solutions.*
11. *Increase iteration counter.*
12. *If counter value is not reached maximum allowed value repeat (6-12).*

General procedure of proposed method to deal with multi-objective nurse rostering problem is the following:

1. *Generate shift sequences.*
2. *Evaluate shift each sequence.*
3. *Order shift sequences of a nurse in non-decreasing order by its penalty.*
4. *Construct initial roster*
5. *Set maximal iteration counter value*
6. *Generate new solution Y in neighborhood X.*
7. *Compare the generated solution vector with all the solutions in Pareto set and update Pareto set if needed.*
8. *If coverage requirements violated – repair using greedy local search.*
9. *If Y is archived accept and set $X = Y$.*
10. *If Y is not archived, accept with probability P.*
11. *If Y is not archived keep X as background for neighbor solutions.*
12. *Increase iteration counter.*
13. *If counter value is not reached maximum allowed value repeat (6-13).*

4. Research Results

Schedules are built for one month, using four different shift types, different in duration, start time and end time. Three types of shifts can be assigned only on working days and one shift only on weekends or bank holidays. Schedules were built for 50 nurses with different demand workload.

Tests were taken 90 times using the same initial roster and same set of penalties for violated soft constraints. Each test were ran 12 hours, saving results in intermediate points after 5, 15, 30 minutes, 1, 2, 3, 6 and 9 hours of execution.

The results of experiments shows that the proposed method outperforms the simulated annealing and shift sequence based methods (Figure 1).

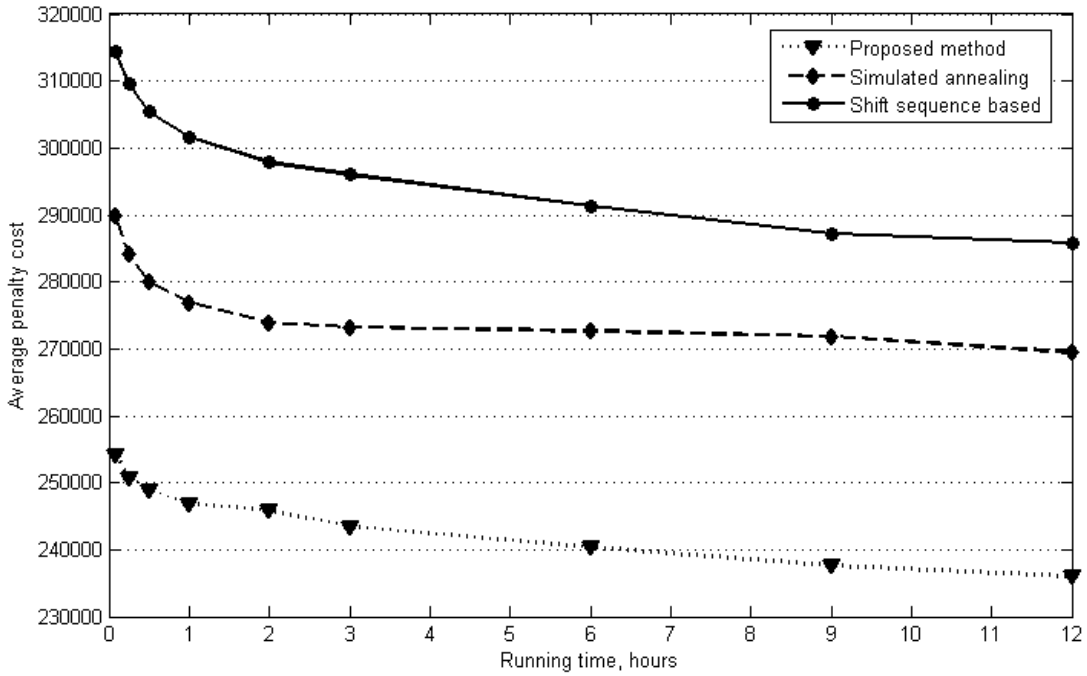


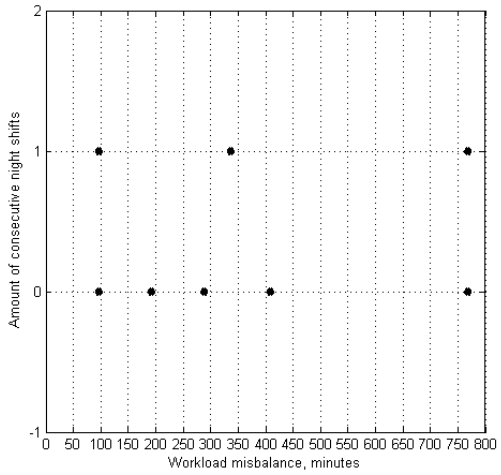
Figure 1. Average penalty cost values of rosters optimized by simulated annealing, shift sequence based and proposed methods.

Average hypervolume indicator value (Table 1) of Pareto sets then reference point is taken as (120, 1, 4, 4, 700), meaning that considered rosters having not bigger than 120 minutes of workload misbalance, not more than 1 pair of consecutive night shifts, not more than 4 night shifts not distributed evenly, not more than 4 watch shifts not distributed evenly and not more than 700 violations to nurses' preferences, shows that proposed method for solving multi-objective nurse rostering problem is more efficient than simulated annealing and shift sequence based methods.

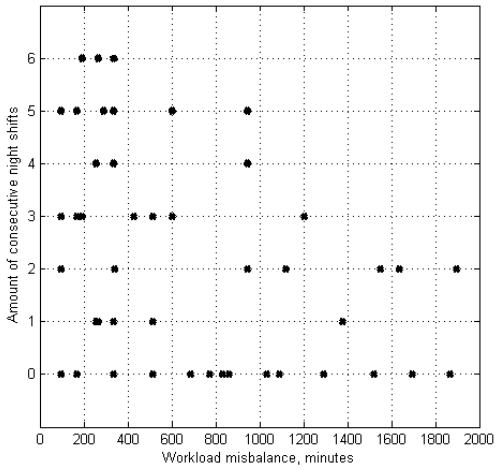
Table 1. Average hypervolume value.

Method	Hypervolume
Shift sequence based	25997
Proposed method	51444
Simulated annealing	36933

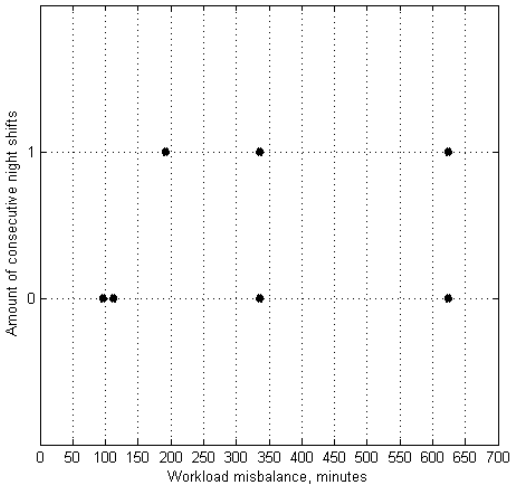
Considering minimized workload misbalance and minimized number of consecutive night shifts as the main objectives it is noticeable that all three methods find the solutions having the same minimum objectives values (Figure 2).



a) Simulated Annealing.



b) Shift Sequence Based.



c) Proposed method.

Figure 2. Relationship between workload misbalance and number of consecutive night shifts.

The whole solutions having the same solution pattern (96, 0, -, -, -):

- Simulated annealing: (96, 0, 2, 0, 660),
- Shift sequence based: (96, 0, 4, 0, 644), (96, 0, 3, 3, 651),
- Proposed method: (96, 0, 3, 2, 655), (96, 0, 2, 0, 657).

Which solution is considered as the best solution depends on what other objectives are more important. If the minimized number of violations to nurses' preferences, then

solution found by shift sequence based method will be accepted, if the minimized number of unfairly distributed night shifts then proposed method solution will be accepted.

General Conclusions

Based on findings solving nurse rostering problem for one of the largest healthcare centers of Lithuania, can be concluded that

- Simulated annealing method is more efficient method for solving single objective nurse rostering problem formulated in dissertation than shift sequence based method.
- Newly proposed method is more efficient method for solving single objective nurse rostering problem formulated in dissertation than simulated annealing and shift sequence based methods.
- Newly proposed method is more efficient method for solving multi-objective nurse rostering problem formulated in dissertation than simulated annealing and shift sequence based methods.

List of Publications on Topic of Dissertation

- Liogys, M., 2011.Adaptation of Shift Sequence Based Method for High Number in Shifts Rostering Problem for Healthcare Workers. *Social Technologies* 1(1): 151-162. ISSN 2029-7564 (online).
- Liogys, M., 2012. Comparison of Shift Sequence Based and Simulated Annealing Methods for Highly Constrained Medical Staff Rostering Problems. *Innovative Infotechnologies for Science, Business and Education* 1(12): 3-6. ISSN 2029-1035.
- Liogys, M., Žilinskas A., 2012. A Variable Neighbourhood Search Enhancement for the Shift Sequence Based Method of The Personal Scheduling in Hospitals. *Information and Software Technologies* (319): 15-24. ISSN 1865-0929.

About the Author

Mindaugas Liogys was born on the 16th of June in 1982, Vilkaviškis district. He received bachelor degree in mathematics in Vilnius University in 2004, and master's degree in mathematics in Vilnius University in 2006. From 2008 till 2012 he was a PHD student of Vilnius University, Institute of Mathematics and Informatics. From 2006 he works as a lecturer in Vilniaus kolegija \ University of Applied Sciences.

DARBŲ GRAFIKŲ SVEIKATOS PRIEŽIŪROS ĮSTAIGOSE OPTIMIZAVIMAS

Tyrimo sritis ir problemos aktualumas

Darbų grafikų sudarymas sveikatos priežiūros įstaigos darbuotojams (anglų kalba vadinamas *nurse rostering, nurse scheduling*), sudėtingas kombinatorinio optimizavimo uždavinys, kuris dažnai tebesprendžiamas rankiniu būdu, nors tai yra varginantis, ilgai trunkantis procesas. Tvarkaraščio sudarytojas, konstruodamas tvarkaraštį, turi atsižvelgti į šalyje galiojančius įstatymus, sveikatos priežiūros įstaigos vidaus taisykles bei darbuotojų pageidavimus. Be to, tyrimai rodo, kad darbuotojų darbų grafikai turi įtakos jų emocinei būklei. Sveikatos priežiūros įstaigos darbuotojai patiria daug, su darbu susijusių, įvairių emocinių dirgiklių (sunki paciento trauma, paciento mirtis ir pan.) dėl to tvarkaraščio sudarytojo vaidmuo yra sudaryti kaip įmanoma mažesnę įtaką darbuotojų blogai emocinei būklei, turinčius darbų grafikus.

Tyrimų objektas

Tyrimo objektas sveikatos priežiūros darbuotojų darbų grafikų vienakriterio ir daugiakriterio optimizavimo uždaviniai.

Darbo tikslas ir uždaviniai

Darbo tikslas pasiūlyti naują efektyvesnį metodą sveikatos priežiūros įstaigos darbuotojų darbų grafikų sudarymo uždaviniams spręsti.

Siekiant užsibrėžto tikslo buvo sprendžiami šie uždaviniai:

- Apžvelgti metodus, naudojamus tvarkaraščių sudarymo uždaviniams spręsti.
- Pritaikyti pamainų sekų ir atkaitinimo modeliavimo metodus, šioje disertcijoje aprašyto uždavinio, sprendimui.
- Pasiūlyti naują metodą, kuris būtų efektyvesnis už atkaitinimo modeliavimo ir pamainų sekų metodus.
- Pritaikyti pamainų sekų ir pasiūlytąjį metodus daugiakriteriniam uždaviniui spręsti.
- Sukurti programinę įrangą tvarkaraščių sudarytojui, palengvinančią ir pagreitinančią darbų grafikų sudarymo procesą.

Mokslinis darbo naujumas

Šioje disertacijoje yra nagrinėjamas vienas sudėtingiausių, pastaruoju metu, spręstų sveikatos priežiūros įstaigos darbuotojų darbų grafikų sudarymo uždavinių. Šiam uždaviniui pasiūlytas naujas metodas, kuris yra efektyvesnis, lyginant su pamainų sekų ir atkaitinimo modeliavimo metodais.

Tyrimo metodika

Kitų autorių sprendžiamų uždavinių apibendrinimui naudojamas žvalgomasis tyrimas (angl. *exploratory research*). Metodų įvertinimui, naudojamas eksperimentinio tyrimo (angl. *experimental research*) metodas.

Darbo praktinė reikšmė

Sukurta programinė įranga, kurioje realizuotas naujai pasiūlytas metodas, skirta automatizuoti tvarkaraščio sudarymo procesą. Programinė įranga yra parengta įdiegimui realiam naudojimui.

Ginamieji teiginiai

- Atkaitinimo modeliavimo metodas yra efektyvesnis už pamainų sekų metodą, sprendžiant disertacijoje suformuluotą sveikatos priežiūros įstaigos darbuotojų darbų grafikų optimizavimo uždavinį.
- Naujai pasiūlytas metodas yra efektyvesnis už atkaitinimo modeliavimo metodą, sprendžiant disertacijoje suformuluotą sveikatos priežiūros įstaigos darbuotojų darbų grafikų optimizavimo uždavinį.
- Naujai pasiūlytas metodas yra efektyvesnis už atkaitinimo modeliavimo ir pamainų sekų metodus, sprendžiant disertacijoje suformuluotąjį daugiakriterį optimizavimo uždavinį.

Darbo rezultatų aprobavimas

Pagrindiniai tyrimo rezultatai atspausdinti 3 mokslinėse publikacijose, rezultatai pristatyti trijose tarptautinėse mokslininkų konferencijose ir vienoje respublikinėje konferencijoje.

Pranešimai skaityti šiose konferencijose:

- Respublikinė konferencija: Informacinės technologijos 2010: teorija, praktika, inovacijos, Lietuva, Alytus, gegužės 21 d., 2010.

- Tarptautinė konferencija: Kompiuterininkų dienos – 2011, Lietuva, Klaipeda, rugsėjo 22-24 d., 2011.
- Tarptautinė konferencija: 5th International Conference Innovative Information Technologies for Science, Business and Education, Lietuva, Vilnius, gegužės 10-12 d., 2012.
- Tarptautinė konferencija: The 18th International Conference on Information and Software Technologies (ICIST 2012), Lietuva, Kaunas, rugsėjis 13-14 d., 2012.

Disertacijos autoriaus publikacijų sąrašas:

- Liogys, M., 2011.Adaptation of Shift Sequence Based Method for High Number in Shifts Rostering Problem for Healthcare Workers. *Social Technologies* 1(1): 151-162. ISSN 2029-7564 (online).
- Liogys, M., 2012. Comparison of Shift Sequence Based and Simulated Annealing Methods for Highly Constrained Medical Staff Rostering Problems. *Innovative Infotechnologies for Science, Business and Education* 1(12): 3-6. ISSN 2029-1035.
- Liogys, M., Žilinskas A., 2012. A Variable Neighbourhood Search Enhancement for the Shift Sequence Based Method of The Personal Scheduling in Hospitals. *Information and Software Technologies* (319): 15-24. ISSN 1865-0929.

Disertacijos struktūra

Disertaciją sudaro 5 skyriai, literatūros sąrašas ir 1 priedas. Disertacijos apimtis 107 puslapiai (be priedo), 49 formulės, 26 paveikslai, 29 lentelės, literatūros sąrašą sudaro 93 literatūros šaltiniai.

Bendrosios išvados

Išnagrinėjus šioje disertacijoje suformuluotąjį sveikatos priežiūros įstaigos darbuotojų darbų grafikų optimizavimo uždavinį, gautos tokios išvados:

- Atkaitinimo modeliavimo metodas, efektyviau optimizuoja darbuotojų darbų grafikus nei pamainų sekų metodas. Išanalizavus pamainų sekų metodo trūkumus, pasiūlytas naujas metodas skirtas SPĮ darbuotojų darbų grafikų optimizavimo uždaviniams spręsti.

- Pasiūlytasis metodas efektyviau sprendžia darbuotojų darbų grafikų optimizavimo uždavinius nei pamainų sekų ir atkaitinimo modeliavimo metodai.
- Pasiūlytojo metodo versija, skirta daugiakriteriams SPĮ darbuotojų darbų grafikų optimizavimo uždaviniams spręsti, pagal hipertūrio indikatoriaus matą yra efektyvesnė už analogiškas atkaitinimo modeliavimo ir pamainų sekų metodų versijas.

Trumpai apie autorių

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