Interfaces
Vol. 37, No. 4, July–August 2007, pp. 355–369
ISSN 0092-2102 | EISSN 1526-551X | 07 | 3704 | 0355

DOI 10.1287/inte.1070.0291

Nurse Scheduling: From Academia to Implementation or Not?

Deborah L. Kellogg, Steven Walczak
School of Business, University of Colorado at Denver and Health Science Center, PO Box 173364, Campus Box 165, Denver, Colorado 80217-3364 {deborah.kellogg@cudenver.edu, steven.walczak@cudenver.edu}

The scheduling of nursing staff is a long-standing problem with myriads of research models published by academia. The exploratory research that we discuss examines the models that academia has produced and the models that hospitals have actually used. We use data from many sources, including research articles, e-mail and telephone surveys, an industry database, and a software source catalog. Only 30 percent of systems that research articles discuss are implemented, and there is very little academic involvement in systems that third-party vendors offer. We examine causes for the research-application gap and discuss directions for future academic research to make it more applicable.

Key words: OR/MS implementation; personnel; manpower planning; hospitals.
History: This paper was refereed.

Nurse scheduling or rostering is the assignment of nurses to days and shifts over a specific scheduling period. Objectives of the scheduling task include minimizing staff to avoid wasted effort, while also ensuring sufficient staffing to provide adequate patient care and ensure service continuity. Any proposed scheduling schema must also satisfy organizational, legislative, and union policies (Sitompul and Randhawa 1990). In addition to these goals and constraints, effective nurse scheduling is critical to staff morale and directly impacts both patient care and nurse retention (Silvestro and Silvestro 2000).

Nurse scheduling is part of the larger capacity-planning problem, which involves staffing (how many nurses are needed, when, and where) and scheduling (which determines when and where each nurse works). These are part of an interrelated, hierarchical problem. The staffing problem is generally solved first and involves forecast of demands, acuity of care forecasting, and integration with nursing availability and skills. Once a staffing plan is finalized, a schedule is constructed that informs individual nurses and nurse managers of who is assigned when and where. This research considers only the scheduling aspect of the larger problem.

The nursing shortage further complicates the nurse-scheduling problem. According to estimates by the Joint Commission on Accreditation of Healthcare Organizations (2005), there were 126,000 unfilled nursing positions in the United States in 2005; in addition, there will be 400,000 fewer nurses than are needed in 2020. The nurse-shortage problem is a global problem (World Health Organization 2000, Pan American Health Organization 2002). This global shortage of nursing staff adds another constraint to the development of nurse-scheduling systems. In addition to the optimization goals and constraints we described in the first paragraph, an efficient and efficacious nurse-scheduling system must satisfy the following conditions: (1) schedules should not require excess hours, (2) scheduling time required by nurse managers must be minimized, and (3) schedules must be acceptable to nurses such that they enhance retention of this already scarce resource.

Management science, operations research, and computer science have offered many solutions to the employee-scheduling problem. For over 40 years, academic literature has addressed nurse scheduling specifically. There are several excellent review articles that summarize this literature (Choi et al. 1991, Siferd and Benton 1992, Hung 1995, Cheang et al. 2003, Burke et al. 2004b). The research articles provide a wide variety of solutions, incorporating almost every conceivable work environment and constraint, including the nuances of adjusting a roster when a scheduled nurse fails to appear. Solutions range from simple algorithms to complex artificial intelligence and decision-support systems. What is unclear is if and how these solutions are used in practice.

There is great potential for improving the use of these solutions. In 2003, the International Council of Nurses (2002–2003) estimated that there were 12 million nurses worldwide, and in 2005, the American College of Healthcare Executives (2005) estimated that 2.3 million were in the United States. Simulating a pencil-and-paper scheduling solution (Hung 1991), we estimate that even a 10 percent time-savings improvement in the scheduling task in the United States could save 130,000 nurse-manager hours per year. This represents about 90 full-time-equivalent (FTE) nurse managers. This estimate includes only time savings and does not consider other benefits that would accrue from using a management science approach to the scheduling problem. Admittedly, there are many commercial vendors of computerized scheduling techniques that could or do reduce scheduling time. That market is huge. We estimate projected costs to hospitals in the United States for nurse-scheduling software in 2005 at $156 million. This does not include associated training and maintenance costs. Part of our research will explore the extent to which these software firms utilize academic solutions.

One might expect that there would be some gap in the application of academic solutions to practice. This gap has been evident in production-scheduling techniques (King 1976) and requirements-modeling methods for systems development (Maiden et al. 2005). Our exploratory research investigates how academic research of the nurse-scheduling and rostering problem is used in practice.

In the first section of this paper, we discuss how academic research is used in practice. We then discuss the implementation of nurse-scheduling solutions in the United States and follow with a discussion of the research-application gap in nurse scheduling and an exploration of future research directions.

Current Academic Nurse-Scheduling Research

As we mentioned above, academic research into the nurse-scheduling and rostering problem has a long and well-summarized history. It is not our intent to duplicate that effort. Instead, our research investigates the extent to which academic research that is specifically related to nurse scheduling is transferred to practice.

For the purposes of this research, we defined *academic research* as research that has been published in an academic journal. While not all hospitals use computers for their scheduling task, almost all of the academic solutions do. We limited the search for published academic research to the period from 1985 to 2005. We chose 1985 as the initial date because inexpensive yet sufficiently powerful PCs were available. It would be unreasonable to expect that a computerized solution would be feasible in practice unless the technology was readily and inexpensively available.

To locate the academic articles, we used standard, academic-library search engines. We used the key words, *nurse scheduling* and *nurse rostering*, in the Academic Search Premier, OneTrack (Expanded Academic), Medline, and IEEE Explore search engines and limited publication dates to 1985 through 2005 to represent 20 years of academic research. We did not include Ph.D. dissertations or published papers from symposia. We also did not include anecdotal, referential, tutorial, or case studies. It was important that the research we included not only present a model but also perform a rigorous analysis of the optimality or utility of the technique. In general, we included proceedings articles and used the bibliographies of the aforementioned review articles to validate the library database searches.

To analyze the data, we required access to the full articles or proceedings papers. If we could not obtain such access after performing an extensive online search and enlisting the help of a reference librarian with interlibrary-loan capabilities, we excluded that work. We excluded several white papers because they focused on demonstrating the abilities of an optimization language, not on solving the nurse-scheduling problem. We also excluded articles that modeled the staffing decision (i.e., the number of nurses required).

There are many excellent academic articles on general labor-scheduling techniques that are applicable to a nursing environment. However, we excluded these because our intent was to look at implementation issues with work that was specifically directed toward nurse scheduling. This is not to imply that general scheduling models are not applicable to a nursing environment. However, the effort to move from a general solution to a specific environment is more difficult than moving from a model created for a specific environment to that same environment. In looking ahead to the data in which we were interested, we decided that the extra implementation hurdles faced by general scheduling models (e.g., nursing shortage, regulatory compliance, and improvement in patient-care quality) would complicate the analysis.

Seventy-two research articles met our criteria. Some of these described different aspects of the same scheduling technique or enhancements to a previously published technique; some discussed the same technique for different audiences. The unit of analysis was not an individual research article, but a nurse-scheduling model or application. Combining articles where we deemed it appropriate resulted in 50 nurse-scheduling models. Initially, we gathered data about the techniques from the research articles.

We first examined the articles considering descriptive information such as geographic location, type of platform, and problem type (Table 1).

A personal computer was used in 34 cases (68 percent). In two cases, these were Apple/Mac machines; in two cases, workstations; and in two cases, larger minicomputer or mainframe computers. One case presents a pencil-and-paper system. Nine cases give no indication of the type of computer used.

We categorized how the scheduling problem was conceptualized and solved in two ways (Tables 2 and 3).

We assessed the research articles based on the degree to which the researchers utilized data in the development and/or testing of the scheduling technique. In two cases (4 percent), it was clear that they did not use data in developing their model. In 40 cases (80 percent), it was clear that they did use actual data. In two cases (four percent), it was evident that the researcher consulted with persons at a hospital; however, it was not clear if or how actual

Country	Number	Number implemented	Implementation (percentage)
Australia	1	0	0
Belgium	1	1	100
Brazil	1	1	100
Canada	5	0	0
France	2	2	100
Germany	1	1	100
Greece	1	0	0
Hong Kong	3	1	33
Italy	1	1	100
Japan	8	1	12.5
Morocco	1	0	0
The Netherlands	1	1	100
New Zealand	1	0	0
Poland	1	0	0
Portugal	1	0	0
Saudi Arabia	1	1	100
Taiwan	3	1	33
United Kingdom	3	1	33
United States	14	3	21

Table 1: We show nurse-scheduling model development by geographic location. While researchers in the United States provided the most publications (28 percent), there was wide representation from many countries.

Problem type	Count	Percentage
Artificial intelligence	4	8
Constraint programming	5	10
Decision support	5	10
Goal programming	1	2
Heuristic	16	32
Optimization	8	16
Other algorithms (e.g., tabu search)	11	22

Table 2: We categorized the problem using the descriptive language in the research article, e.g., the author(s) referred to the problem as an optimization problem or as a constraint-programming problem.

Problem type	Count	Percentage
Artificial intelligence	4	8
Decision support	5	10
Heuristic	27	54
Mathematical programming	14	28

Table 3: We also provided an alternative categorization using the categories that Cheang et al. (2003) defined (mathematical programming, heuristic, and artificial intelligence). We added the decision support category to Cheang's categorization because we could not categorize the use of these systems using the definitions provided.

Model-testing types	Count	Percentage
Not tested in real time	5	10
Shared development results, but not tested	3	6
Tested in real time	19	38
Cannot be determined	23	46

Table 4: We show the frequency of model-testing methods.

data were used. Six cases (12 percent) did not provide enough information to categorize.

While using actual data in model development is important, real-time testing is a more critical step in the transfer of technology. We classified the models into categories as Table 4 shows. Two researchers reported survey results from nurses about their perceptions of the model-generated schedule.

We also assessed research articles for implementation information. However, it was far more difficult to assess actual implementation by examining the research articles because the focus of many research articles and academic journals does not extend to a discussion of implementation issues. It would be faulty logic to conclude that the model in question had not been implemented merely because a research article did not discuss its implementation. It is also not logical to assume that all models that were tested in real time were implemented. To augment the implementation data we gathered from the articles, we tried to verify implementation by using an e-mail survey (Appendix 1). We received responses from 11 researchers (a response rate of 22 percent). In 11 cases, we did not have e-mail contacts. In other cases, we had invalid e-mail addresses. Our study shows a bias toward recent research because e-mail addresses prior to 1995 were less valid. We were able to locate only one researcher who published before 1995.

Fifteen of the 50 models (30 percent) had been implemented. Table 5 shows summary results. We reference the models by the last name of the primary researcher. (Appendix 2 shows full citation information.)

Existing models primarily were implemented on PCs and utilized heuristic approaches. However, there does not seem to be any relationship between problem modeling and subsequent implementation. The implemented models used both standard mathematical-programming techniques and the newer heuristic approaches. This contradicts the prediction of Jelinek and Kavois (1992) that artificial intelligence and decision-support systems would be more applicable in the future than other techniques.

Model	Implementation-knowledge source	Still in use	Model type*	Location	Implementation site and number	Product name if commercialized
Azaiez	Article	Unknown	MP	Saudi Arabia	1 hospital	
Bellanti	Article	Unknown	H	Italy	1 ward/unit	
Liao	Article	Unknown	H	Taiwan	1 hospital	
Weil	Article	Unknown	H	France	Commercial product	Gymnaste
Darmoni	E-mail verification	No	MP	France	1 hospital	HOROPLAN
Dowsland	E-mail verification	No	H	United Kingdom	1 hospital	
Meyer auf'm Hofe	E-mail verification	Yes	MP	Germany	150 hospitals	ORBIS Dienstplan
Bard	E-mail verification	Yes	H	United States	Commercial product	Care Systems Inc.
Burke	E-mail verification	Yes	H	Belgium	40+ hospitals, beginning implementation in UK	PLANE
Cheng	E-mail verification	Unknown	MP	Hong Kong	1 ward/unit	
Diaz	E-mail verification	Yes	H	Brazil	1 hospital	
Isken	E-mail verification	Partially	H	United States	1 hospital	
Kawanaka	E-mail verification	Yes	H	Japan	Some hospitals	
Kostreva	E-mail verification	Yes	H	United States	1 hospital	
Van Wezel	E-mail verification	Yes	DS	The Netherlands	Multiple hospitals	ZKR-nurse-scheduling support system

Table 5: We summarize the implemented models.
*H = heuristic; MP = mathematical program; DS = decision support.

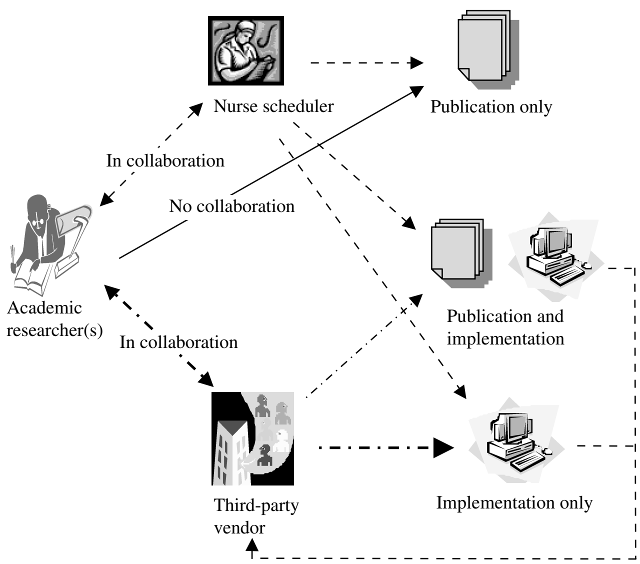

Figure 1: We show possible collaboration paths among researchers, nurse schedulers, and vendors in the development of nurse-scheduling models.

Only one successful implementation was classified as a decision-support system.

Implemented models differed greatly in the extent of their utilization. Two were small efforts that were used in a single ward or nursing unit. About half were implemented in only one hospital. Four are used in many hospitals and two were developed as commercial packages. Of the 15 models reported as having been implemented, six are currently available commercially.

We conceived of several collaboration paths as Figure 1 illustrates.

First, a researcher might work in collaboration with a nurse scheduler. The results of this collaboration could be academic publication only, publication and implementation, or implementation only. In this scenario, implementation with or without publication could then lead to commercialization through a vendor. Alternatively, researchers might align themselves with or create a third-party vendor to commercialize a nurse-scheduling project. This path could result in publication and implementation or implementation only. We anticipate that we would see no evidence of publication only and little publication and implementation with third-party vendor collaboration because much of this work would be proprietary; thus, by contractual agreement, it would not be published. Finally, we may see a researcher working without collaboration with a publication-only result. We searched for the collaboration types and publication and implementation patterns in the research articles.

We see evidence of researcher and nurse-scheduler collaboration in the United States, Canadian, Japanese, and Taiwanese-based research. By definition, all are published. Not all are implemented. There is evidence of attrition. Not all models that are proposed are tested and even fewer are implemented. The US-based research accounted for 14 models (28 percent). Of those, one did not use actual scheduling data; presumably, implementation was not a primary objective. In three cases, the research articles did not supply enough information about the use of actual scheduling data. Of those 14, only six indicated that real-time testing was done. Only three were implemented and one of those is probably not used currently.

The researcher and nurse-scheduler collaboration is also evident in Europe (Burke et al. 2001, 2003, 2004a; Meyer auf'm Hofe 1998, 2001; Van Wezel and Jorna 1996; Weil et al. 1995, 1998) with two significant differences: there is very little attrition and these models moved to commercialization. While fewer European models result in published research, most achieve successful implementation in multiple sites and move to commercially available systems. Of the six models that have resulted in a commercially available product, five were developed in Europe and one in the United States.

There is little evidence of the research-vendor path in published research. Only one the US model (Bard) and one European model (Darmoni) demonstrated this route.

Not all implemented solutions are still in use. In two cases, the researchers indicated that their models were no longer used. The Isken model has not been maintained and its author is uncertain of how it is used. However, he has updated the model and expects that it will be used more extensively in the near future. The contact person (J. Lee) for the Cheng model was uncertain if the model is currently in use. This is probably common over the 20-year span of covered research.

An examination of the research literature can only partially address the issues of implementation. As we indicated in Figure 1, there are circumstances in which an academic researcher may be involved in creating a nurse-scheduling model without publication. The next section outlines how we addressed these cases.

Nonpublished Commercial Nurse-Scheduling Models

As we discussed above, published academic research in nurse-scheduling solutions typically involve sophisticated, complex optimization and heuristic models. Interestingly, the most successful adoption of nurse-scheduling research appears to be in the European Union (Belgium, Germany, France, and The Netherlands). With one exception (the Bard model), none of the US models was implemented in more than one hospital. Clearly, there are many more hospitals than nurse-scheduling models. This raises the question of what hospitals are utilizing for scheduling nurses.

It could be that individual hospitals or third-party vendors have developed sophisticated and complex systems with or without academic input and without publication in the research literature. Alternatively, simpler manual systems might be the norm in hospitals. For example, Drouin and Potter (2005), Hung (2002), and Robb et al. (2003) acclaim self-scheduling and flexible scheduling, where nurses participate in the determination of their schedules, as a solution to employee satisfaction. Self-scheduling is frequently performed manually—members of the nursing staff fill in a blank schedule with their desired times. A nurse manager may then transfer the filled-in sheet to a spreadsheet or other application; however, the self-scheduling process is largely manual (Burke et al. 2004b). Still, nursing managers encourage the use of technology to facilitate the scheduling process (Robb et al. 2003).

We used two primary resources to identify nonpublished nurse-scheduling software-application providers for hospitals and other health-care organizations. The first is the Dorenfest Complete Integrated Healthcare Delivery System (IHDS+) database, which a grant from Sheldon I. Dorenfest & Associates made available; the second is the Healthcare Software Sourcebook (Aspen Health and Administration

Algorithm/vendor	Number of health-care facilities reporting	Percentage
None	393	29.18
Self-developed	26	1.93
Not disclosed	26	1.93
Per se technologies	474	35.19
Meditech	62	4.60
Res-Q Healthcare Systems	53	3.93
Siemens	42	3.12
Healthcare Management Systems	37	2.75
Keane	32	2.38
Quadramed	27	2.00
Other (less than 12)	175	13
Total	1,347	

Table 6: We show the responses to our IHDS+ database survey by nurse-scheduling vendor.

Development Group 2001), which serves as a resource for health-care CIOs who are soliciting requests for proposals to satisfy health-care information systems needs. These data sources address primarily US experience, although many vendors do serve countries outside of the United States. We conducted a telephone survey with providers who were listed in one of the sources. When a specific provider requested an e-mail version of the survey, we transmitted it. Additionally, we also sent e-mail surveys to hospitals that indicated they had developed their own scheduling system to learn how they developed their nurse-scheduling software algorithm.

Table 6 shows the number of hospitals that responded to the IHDS+ database survey with respect to software vendors. We included only responses for an algorithm vendor that at least 12 health-care facilities used. The IHDS+ database included 1,347 hospitals or health-care facilities and 34 nurse-scheduling application vendors. We assumed that if a vendor product was cited, scheduling functions in that product were being utilized. Almost 30 percent of the respondents report that they do not use a nurse-scheduling, software-system application. There is one dominant vendor; the other 33 vendors comprise a market segment that is approximately equivalent to the single largest vendor with 34 percent of the market.

We conducted a telephone survey of the top 10 IHDS+ corporations, as well as all corporations listed in the Healthcare Software Sourcebook (Aspen Health and Administration Development Group 2001) that manufacture nurse-scheduling software products. The combined list contained 22 companies, which is 54 percent of the possible 41 companies. The goal of the survey was to answer these questions:

- How many software units have been sold?
- Was there any academic involvement in the development of the scheduling algorithm (full time, part time, consulting, or as a contract or grant)?
- What type of general class of algorithm is used for performing scheduling (to compare with academic-research models)?

We obtained 17 responses from the 22 companies we contacted by telephone and e-mail, yielding a response rate of almost 78 percent. Of the 22 companies, two (9 percent) were out of business and three (over 13 percent) no longer carried a nurse-scheduling product. We included the three companies that no longer carried a nurse-scheduling product with the valid responses because all were able to provide details concerning their nurse-scheduling algorithm's development. When asked why it no longer participated in the nurse-scheduling marketplace, one company indicated that another software vendor had acquired the product; another indicated that it no longer perceived the nurse-scheduling software to be profitable.

All companies we contacted that were still in business regardless of current product type were willing to answer the first two questions above; however, only 53 percent of the responding corporations answered the third question. All companies had headquarters offices in Canada or the United States.

Thirty percent of the companies responding to the survey reported total sales of less than 100 systems, which included systems in nursing homes, other types of health-care facilities, and hospitals. Thirty percent of the remaining companies (i.e., 21 percent) reported sales between 100 and 250 units, while the remainder all claimed sales of over 1,000 systems. The average of all nurse-scheduling system vendors is 571 current systems, with sales beyond September 2005 unaccounted. The breakout of the survey sales figures confirms the IDHS+ database results—a few dominant vendors control a majority of the market. However, there are numerous smaller players and thus competition. The marketplace dominance by a few vendors that control a relatively large share of the market may explain the perceived lack of profitability that some vendors who had left the nurse-scheduling software-application market noted.

Over 93 percent of the current nurse-scheduling algorithms and methods are developed in-house. Only one company indicated that the development of its current system involved the use of an academic researcher. A hospital recruited this company, which is a small entrepreneurial firm headquartered outside of the United States, to develop its system. Additionally, one other company that has a current product that was developed in-house indicated that an academic developed its original algorithm. However, market pressure had caused the company to migrate from the academic-based system to the current in-house developed systems that used self-scheduling as one of its components. One nurse-scheduling system manufacturer indicated that while the scheduling-algorithm development occurred in-house without academic involvement, it did recruit students from a local university to assist in developing the system's user interface. Finally, the Bard Care Systems product is a new entrant into the nurse-scheduling market (Bard is an academic with published research on his model); as such, it does not have an adoption track record yet.

Two companies indicated that they had purchased their algorithm from another company and one other company indicated that it had sold its product to another company. Because these systems were all acquired from other vendors, we count them as nonacademic. One of the purchased nurse-scheduling products was developed in-house and the other company is out of business; therefore, we could not obtain any information about them.

Hence, although the development of scheduling algorithms has used academic research for quite some time, the direct involvement of academics in the design and development of implemented scheduling solutions in the United States appears to be minimal to nonexistent.

Although only 53 percent of the industry providers we surveyed answered the "type of algorithm implemented" question, we compared their responses to the problem type or solution methodology that academic researchers reported (Tables 2 and 3). Table 7 shows a comparison of the specified algorithms.

Problem/solution type	Researcher count	Researcher percentage	Industry count	Industry percentage
Artificial intelligence	4	8	1	11
Constraint programming	5	10	2	22
Decision support	5	10	0	0
Goal programming	1	2	1	11
Heuristic	16	32	1	11
Optimization	8	16	0	0
Other algorithms (e.g., tabu search)	11	22	0	0
Multiple methods, not specified	N/A	N/A	2	22
Self-scheduling	N/A	N/A	7	78

Table 7: We compared researcher-specified problem types and industry-provided solution methods.

We suggest that the reader use some caution in interpreting Table 7 because the response rate was lower than we desired. While we attempted to interview system developers, in some cases we had to conduct the interview with a sales representative who may not have known the specifics of the algorithms used. Percentages exceed 100 percent because 56 percent of the respondents identified multiple methods. This was especially true with those identifying self-scheduling, where 43 percent of these vendors also identified a formal algorithm.

A majority of the industry-developed scheduling programs that hospitals are using employs some form of self-scheduling and frequently utilizes Web-based services for assisting with scheduling. There does not appear to be any correlation between industry-applied methods and academic research with respect to artificial intelligence methods, constraint programming, and goal-oriented programming. However, the overwhelming reliance on self-scheduling methodologies in commercial applications may be seen as another indicator that a mismatch exists between practical applications and the type of research that academia performs. Decision support and artificial intelligence methodologies can augment self-scheduling and this may indicate a need for more research in these areas.

Discussion

It is hard to avoid the conclusion that, in the United States at least, practitioners do not accept academically produced management and computer science solutions to the nurse-scheduling problem. Even developers of commercial products rarely consult academics. The data indicate that there may be several explanations for this: (1) the geographic location of the researcher(s); (2) the objective(s) of the research; (3) the narrow scheduling-problem focus that some researchers take; (4) the lack of customer support that academics offer; (5) the proprietary nature of commercially available software, leading companies to either not publish or advertise that their products use published research; (6) the lack of acceptance by nurses because of their lack of trust of the computerized models and the time required to learn and use new software—taking them away from patient care; and (7) little focus on the reality of self-scheduling that is currently predominate in nurse scheduling.

Geographic Location

Only 30 percent of published nurse-scheduling models are ever implemented and used in a hospital or other health-care facility (Table 5). The majority of such systems are implemented outside of the United States. European-based research bridges the research-application gap more successfully. However, all research articles describe the nurse-scheduling problem almost identically, despite geographic location. Many articles acknowledge a nursing shortage and the need for a schedule that satisfies not only organizational objectives but also individual nurse preference. Nursing is a 24/7 service that professional, licensed practitioners practice in much the same way around the world. If the problem is the same and the proposed solution(s) are similar, it may be that cultural factors account for the difference.

Table 1 shows the overall implementation percentage for published research models with respect to country of origin. European researchers may face fewer barriers in moving from theory to application. The United States, which has the largest number of published nurse-scheduling research models, has only 21 percent of the models that bridge the research-application gap. Japan and Canada, the next two largest producers of published nurse-scheduling models, have 12.5 percent and zero percent implementation percentages, respectively. Over 50 percent of the European scheduling models are implemented. Moreover, the non-European applications are limited in scope and frequently applied only in one hospital, while the European models are implemented in many hospitals. This is not to say that European researchers are more applied, but that others have barriers that could include the health-care environment, the academic environment, or the interaction between these environments.

While many US universities have medical schools and hospitals, many do not. Often, there is not a close tie between the health-care environment and the university system that would facilitate the transfer of technologies such as nurse-scheduling models. There are also many nongovernmental, for-profit hospital systems in the United States, in particular. Such systems are often not willing to experiment with untried technologies. The nationalized health-care systems that are common in many countries may aid in facilitating the implementation of nurse-scheduling models.

Table 8 reformats the information that we provided in Table 1 to view implemented research on a more regional basis and continues to support the suggested finding that differences exist between research published in Europe and in other parts of the world. An additional implication from Table 8 is the relative paucity of nurse-scheduling research being published in Africa, the Middle East, and South America. This may indicate a need for further investigation into nursing practices in these areas and may provide an opportunity for international collaboration for nurse-scheduling research in these areas of the world.

Research Objectives

Academic researchers may have several goals when conducting nurse-scheduling research. One of these is to satisfy the academic paradigm of "publish or perish." Research undertaken simply for publication may never be intended for anything beyond meeting this academic goal. When we asked the intent of their research, 14 percent of published academics indicated that they never intended their model to be implemented or used in a health-care setting. All of these academic models are from researchers outside of the United States. Interestingly, one of these models that the researchers never intended for implementation was actually implemented. This may be due to interest that publication generated for the model.

However, 86 percent of the academics publishing their nurse-scheduling systems stated an intention that their model be implemented and utilized at a health-care facility. Most sought consultation with the scheduler and many tested their models. Why did these models not bridge the research-application gap?

Region	Number	Number implemented	Implementation percentage
Africa	1	0	0†
Asia and Pacific Rim	16	3	19
Europe	12	7	58
Middle East	1	1	100†
North America	19	3	16
South America	1	1	100†

Table 8: We show nurse-scheduling model development based on region.
†The number of reported models within this region is too small to draw a significant conclusion based on the percentage of implemented systems.

Narrow Focus

The scope of models that academics create is relatively small. While some commercialized models incorporate many features, most focus on the single task of scheduling nurses. A former CIO of a large health-care system in the United States indicated that when deciding on a scheduling product, it makes sense (from an accounting perspective) to purchase a system that will satisfy the needs of multiple areas within the health-care facility.

The IHDS+ database queried CIOs on their future information technology plans. Each of the firms that answered this query indicated that they had plans to implement enterprise resource-planning systems. Clearly, their intent was to add larger systems that provide integrated solutions. Small scheduling systems that often do not even communicate with other systems do not meet current needs.

Customer Support Needs

Nonscheduling aspects, such as the perception of reliable customer support (Messerschmitt 2004), are equally important in the implementation and purchase decision of any information system. Due to tenure issues and other factors affecting movement of faculty among universities and to industry, there is a perception of a lack of a long-term, system-maintenance relationship with academics. Most academics are not equipped to provide the necessary support that implemented systems require.

Proprietary Concerns

It could be that researchers who see commercial value in their work are not willing to make techniques public in research articles. One does see some evidence of this in some of the US research prior to 1985. In a single article, Warner (1976) published a model that then became proprietary (the ANSOS system). Widely implemented, it is a shining example of an academically developed model bridging the application gap successfully. Some of its success seems to be linked to its ability to evolve and solve more than just the scheduling problem.

The work of Jelinek and Kavois (1992) resulted in a commercial product that was only written about in general terms. Academic researchers may be leaving academia to form their own companies or join existing industry providers. The vendors may be accurately reporting "no academic involvement" because they hired the expertise and did not partner with an academic associated with a university. The pattern that Burke and Bard set, where academics create commercially available products and publish them widely in academic venues, is unusual.

Academic solutions may have little value to either the health-care organization or a third-party vendor. Thelwall (2004) states that there is very little benefit to organizations for recognizing academic involvement other than to establish the credentials of the organization. In fact, utilizing published research may even be harmful by providing competitors with useful information.

Nursing Acceptance

Hung (1991) reports that nurses have little confidence in computer-generated solutions to the scheduling problem. Academic solutions are often not only computer dependent, but also involve very complex, cutting edge, mathematical-solution techniques. The nurse sees only a schedule to which he or she has had very little input. This stakeholder group sees a computerized scheduling system as adding little value. Nurses are caregivers. They see nuances in schedules that academics, with mathematical programs that minimize costs or some other objective function that includes nothing relative to the "caring" that is of primary concern to nurses, often miss. Additionally, members of the nursing staff at a local nonteaching hospital, when interviewed about the possibility of a new scheduling system, indicated that they were already satisfied with their current self-scheduling protocol and were concerned about the time it would take to learn a new system—time that might detract from caring for patients.

Self-Scheduling

As we previously mentioned, nurse scheduling uses self-scheduling widely. Self-scheduling requires a paradigm that probably includes more than optimization techniques. Only 18 percent of academic models utilized decision support or artificial intelligence methods, which are methods more appropriate for self-scheduling (Jelinek and Kavois 1992). While we found research that incorporated nurse preferences (Bard and Purnomo 2005a, b, c; Bell et al. 1986; Chen and Yeung 1992, 1993; Ozkarahan 1989, 1991a, b; Ozkarahan and Bailey 1988), none could be considered to be a true self-scheduling technique. Our literature review certainly identified many self-scheduling articles; however, none was rigorous enough to meet our criteria for inclusion in the data set. Most were written by nurses and were published in nursing-management journals. They tended to be anecdotal in nature and covered topics such as nurse satisfaction with self-scheduling, retention, or implementation issues or they were tutorials (Hung 2002).

In summary, although the scheduling models that academics developed solve the problem, they may fall short of meeting the complex needs of health-care organizations, third-party vendors, nurses, and patients.

The Future of Academic Involvement in Nurse-Scheduling Models

Academics certainly have much to offer in the arena of nurse scheduling. They are at the cutting edge of solution techniques and technological advances. They may have broader perspectives than those in health care and may see opportunities for transferring knowledge between industries (e.g., airline scheduling to nurse scheduling). While academics have time constraints, they often have the luxury to sit and think about a problem and its solution. However, at least in the United States, something must be done differently. We offer the following ideas.

Academics should think carefully about why they want to address the nurse-scheduling problem. Basic research is important; however, it can and should be published without the pretense of solving a real-world problem. When the objective is to solve a nurse-scheduling problem, contact with the nurse scheduler and nurses early in model development is critical. Models should be rich enough to capture the care-giving environment. Nurse X is not the same as Nurse Y; a scheduling model that considers them as interchangeable may not be solving the correct problem.

The nuances of the nurse-scheduling problem may be too complex for mathematical programming alone. Currently, self-scheduling is the de facto standard in most US hospitals. Nurses use complex decision-making skills when selecting their personal schedules. This goes far beyond wanting certain days off to maximize leisure-time activities. For example, a nurse might have excellent patient-teaching skills and may intuitively select days and shifts when the need for teaching is greater. Nurses may work better with some individuals than others and may select days and shifts purposely to form high-performing work teams. Nurses may not even be able to articulate these tacit preferences (Polanyi 1966); from years of experience, they just *know*. Any academic model that does not include some opportunity for self-scheduling will probably not be implemented—at least in the United States. Academic research should explore ways to support or improve upon the self-scheduling methodology that nurses and nurse managers currently favor.

Nurses have busy schedules and do not want to use patient-care time to create a schedule. Academic solutions may be best when they are designed to minimize the scheduling effort. Agent-based systems that utilize learning methods to analyze ongoing scheduling automatically to determine nurse preferences, as well as to guarantee the appropriate level of patient care, are another route for future research. The use of intelligent agent-based systems may be able to automatically produce schedules that nurses perceive as desirable, while providing cost and time savings related to the scheduling task.

Academics should also consider with whom and where they are publishing their work. Publishing with nurses as co-authors may aid in bridging the research-application gap. As we indicated previously, a nurse's time is at a premium. That nurse is typically not motivated to write articles for publication unless he or she is working in a university-related hospital (Schilling 2005) and requires publication for promotion. However, publication of novel nurse-scheduling models developed in conjunction with nurses and published in nurse-management journals may be the best way to share knowledge about best practices, potential time and cost savings, improved care, and new methods (Smith 2004). Publication of applied empirical results for new nurse-scheduling methods that can be integrated seamlessly into the current schedule of activities provides both organizational and communal benefit.

Novel academically developed approaches to nurse scheduling may provide benefits to the nursing community. However, this research must move away from the more traditional automatic scheduling systems of management science to include nurse self-choice as well as improvement in quality of care. An example of a novel approach is the utilization of an online auction format that allows nurses to bid for the shifts on which they desire to work (Grow and Sager 2003).

It appears that the more theoretically based research popular in the United States and some other countries does not apply well to existing nurse-scheduling best practices that typically utilize some form of self-scheduling. Nurse scheduling specifically must account for the empowerment and perceived job satisfaction that self-scheduling practices enable.

Academics may also benefit by forming alliances with third-party vendors. However, they must remember that vendors are moving to supplying full systems, e.g., enterprise resource planning systems where scheduling is only a minor part. There will be a need to see the scheduling problem in a much broader context. It could be that academic solutions are more appropriate for the staffing rather than the scheduling problem.

Those academics who have found success in implementation should be telling their stories. While describing their models may be more intellectually stimulating, the research community needs to know more about bridging the research-application gap, both in general terms and as it applies to nurse-scheduling systems specifically.

Appendix 1

E-mail survey: Could you please respond to this e-mail by simply indicating your choices?

1. Part of the original intent of this research was:

—To develop a useable scheduling tool with the intention that it be applied in a health-care setting.

—To demonstrate applications for a mathematical/decision-support technique using actual scheduling data, however, with no intention of actually implementing the technique.

—To demonstrate an application for a mathematical decision-support technique using the nursing problem, but without actual data or intention for implementation.

2. Was your research ever implemented for an actual medical facility?

——, Yes, at what facility: ——

——, No

——, I don't know.

3. If your model was implemented, is it still in use?

——, Yes

——, No

——, I don't know.

4. May we contact you again for additional information?

Appendix 2

Model reference	Citation(s)
Anzia	Anzia and Miura (1987)
Azaiez	Azaiez and Al Sharif (2005)
Bailey	Bailey et al. (1997)
Bard	Bard and Purnomo (2005a, b, c)
Bell	Bell et al. (1986)
Bellanti	Bellanti et al. (2004)
Berrada	Berrada et al. (1996)
Burke	Burke et al. (2001, 2003, 2004a)
Chen	Chen and Yeung (1992, 1993)
Cheng	Cheng et al. (1997, 1999)
Cowling	Cowling et al. (2002)

Appendix 2 (continued)

Model reference	Citation(s)
Darmoni	Darmoni et al. (1995)
Diaz	Diaz et al. (2003)
Dowsland	Aickelin and Dowsland (2000, 2004), Aickelin and White (2004), Dowsland (1998), Dowsland and Thompson (2000)
Easton	Easton et al. (1992)
Ferland	Ferland et al. (2001)
Franz	Franz et al. (1989)
Gray	Gray et al. (1993)
Harmeier	Harmeier (1991)
Huang	Huang et al. (2001)
Huarng	Huarng (1999)
Hung	Hung (1991)
Ikegami	Ikegami and Niwa (2003)
Inoue	Inoue et al. (1999, 2000, 2003)
Isken	Isken and Hancock (1990), Isken (2004)
Jan	Jan et al. (2000)
Jaszkiewicz	Jaszkiewicz (1997)
Jaumard	Jaumard et al. (1998)
Kawanaka	Kawanaka et al. (2001, 2003)
Kostreva	Kostreva and Jennings (1991)
Li	Li et al. (2003)
Liao	Liao and Kao (1997)
Lukman	Lukman et al. (1990)
Meyer auf'm Hofe	Meyer auf'm Hofe (1998, 2001)
Millar	Millar and Kiragu (1998)
Miwa	Miwa et al. (2002)
Moz	Moz and Vaz Pato (2003, 2004)
Nonobe	Nonobe and Ibaraki (1998)
Okada	Okada (1992)
Ozkarahan	Ozkarahan (1989, 1991a, 1991b), Ozkarahan and Bailey (1988)
Randhawa	Randhawa and Sitompul (1993)
Rosenbloom	Rosenbloom and Goertzen (1987)
Scott	Scott and Simpson (1998)
Thornton	Thornton and Sattar (1996, 1997)
Valouxis	Valouxis and Housos (2000)
Van Wezel	Van Wezel and Jorna (1996)
Venkataraman	Venkataraman and Brusco (1996)
Weil	Weil et al. (1995, 1998)
Wong	Wong and Chun (2004)

References

Aickelin, U., K. Dowsland. 2000. Exploiting problem structure in a genetic algorithm approach to a nurse rostering problem. *J. Scheduling* **3**(3) 139–153.

Aickelin, U., K. Dowsland. 2004. An indirect genetic alogrithm for a nurse-scheduling problem. *Comput. Oper. Res.* **31**(5) 761–778.

Aickelin, U., P. White. 2004. Building better nurse scheduling algorithms. *Ann. Oper. Res.* **128**(1) 159–177.

American College of Healthcare Executives. 2005. Key industry facts. *Healthcare Executive* (Sept./Oct.) 1–4.

Anzia, M., Y. Miura. 1987. Computer program for quick work scheduling of nursing staff. *Medical Informatics* **12** 43–52.

Aspen Health and Administration Development Group. 2001. *Health Care Software Sourcebook*. Aspen, Gaithersburg, MD.

Azaiez, M. N., S. S. Al Sharif. 2005. A 0-1 goal programming model for nurse scheduling. *Comput. Oper. Res.* **32**(3) 491–507.

Bailey, R., K. Garner, M. Hobbs. 1997. Using simulated annealing and genetic algorithms to solve staff scheduling problems. *Asia-Pacific J. Oper. Res.* **14**(2) 27–43.

Bard, J., H. Purnomo. 2005a. A column generation-based approach to solve the preference scheduling problem for nurses with downgrading. *Socio-Econom. Planning Sci.* **39**(3) 193–213.

Bard, J., H. Purnomo. 2005b. Hospital-wide reactive scheduling of nurses with preference considerations. *IIE Trans.* **37**(7) 589–608.

Bard, J., H. Purnomo. 2005c. Preference scheduling for nurses using column generation. *Eur. J. Oper. Res.* **164**(2) 510–534.

Bell, P., G. Hay, Y. Liang. 1986. A visual interactive decision support system for workforce (nurse) scheduling. *Inform. Systems Oper. Res.* **24**(2) 133–144.

Bellanti, F., G. Carello, R. Della Croce, R. Tadei. 2004. A greedy-based neighborhood search approach to a nurse rostering problem. *Eur. J. Oper. Res.* **153**(1) 28–40.

Berrada, I., J. Ferland, P. Michelon. 1996. A multi-objective approach to nurse scheduling with both hard and soft constraints. *Socio-Econom. Planning Sci.* **30**(3) 183–193.

Burke, E., P. De Causmaecker, G. V. Berghe. 2004a. Novel metaheuristic approach to nurse rostering problems in Belgian hospitals. J. Leung, ed. *Handbook of Scheduling.* CRC Press, Boca Raton, FL, 44-1–44-18.

Burke, E., P. Cowling, P. De Causmaecker, G. V. Berghe. 2001. A memetic approach to the nurse rostering problem. *Appl. Intelligence* **15**(3) 199–214.

Burke, E. K., P. De Causmaecker, G. V. Berghe, H. Van Landeghem. 2004b. The state of the art of nurse rostering. *J. Scheduling* **7**(6) 441–499.

Burke, E., P. De Causmaecker, S. Petrovic, G. V. Berghe. 2003. Variable neighbourhood search for nurse rostering problems. M. Resende, M. J. de Sousa, eds. *Metaheuristics: Computer Decision-Making.* Kluwer, Dordrecht, The Netherlands, 187–172.

Cheang, B., H. Lim, B. Rodrigues. 2003. Nurse rostering problems—A bibliographic survey. *Eur. J. Oper. Res.* **151**(3) 447–460.

Chen, J., T. Yeung. 1992. Development of a hybrid expert system for nurse shift scheduling. *Internat. J. Indust. Ergonomics* **9**(4) 315–328.

Chen, J., T. Yeung. 1993. Hybrid expert-system approach to nurse scheduling. *Comput. Nursing* **11**(4) 183–190.

Cheng, B., J. Lee, J. Wu. 1997. A nurse rostering system using constraint programming and redundant modeling. *IEEE Trans. Inform. Tech. Biomedicine* **1**(1) 44–54.

Cheng, B., K. Choi, J. Lee, J. Wu. 1999. Increasing constraint propagation by redundant modeling: An experience report. *Constraints* **4**(2) 167–192.

Choi, T., H. Jameson, M. Brekke. 1991. Operations research in nurse scheduling. *People and Technology in the Workplace.* National Academy Press, Washington, D.C., 189–225.

Cowling, P., G. Kendall, E. Soubeiga. 2002. Hyperheuristics: A robust optimisation method applied to nurse scheduling. *Lecture Notes in Computer Science*, Vol. 2439. Springer, Berlin, Germany, 851–860.

Darmoni, S., A. Fajner, N. Mahe, N. Leforestier, M. Vondracek, O. Stelian, M. Baldenweck. 1995. HOROPLAN: Computer-assisted nurse scheduling using computer-based programming. *J. Soc. Health Systems* **5**(1) 41–54.

Diaz, T., D. Ferber, C. deSouza, A. Moura. 2003. Constructing nurse schedules at large hospitals. *Internat. Trans. Oper. Res.* **10**(3) 245–265.

Dowsland, K. 1998. Nurse scheduling with tabu search and strategic oscillation. *Eur. J. Oper. Res.* **106**(2–3) 393–407.

Dowsland, K., J. Thompson. 2000. Solving a nurse scheduling problem with knapsacks, networks, and tabu search. *J. Oper. Res. Soc.* **51**(7) 825–833.

Drouin, R., M. Potter. 2005. Flexible scheduling. *Amer. J. Nursing* **105**(11) 72E–72F.

Easton, F., D. Rossin, W. Borders. 1992. Analysis of alternative schedulings policies for hospital nurses. *Production Oper. Management* **1**(2) 159–174.

Ferland, J., I. Berrada, I. Nabli, B. Ahiod, P. Michelon, V. Gascon, E. Gange. 2001. Generalized assignment type goal programing problem: Application to nurse scheduling. *J. Heuristics* **7**(4) 391–413.

Franz, L., H. Baker, G. Leong, T. Rakes. 1989. A mathematical model for scheduling and staffing multiclinic health regions. *Eur. J. Oper. Res.* **41**(3) 277–289.

Gray, J., D. McIntire, H. Doller. 1993. Preferences for specific work schedules: Foundation for an expert-system scheduling program. *Comput. Nursing* **11**(3) 115–121.

Grow, B., I. Sager. 2003. How much do I hear for this nurse? *Bus. Week* (3861) 14.

Harmeier, P. 1991. Linear programming for optimization of nurse scheduling. *Comput. Nursing* **9**(4) 149–151.

Huang, Y., L. Tsao, S. Tang, M. Hsiao, T. Lee, S. Young. 2001. A role-specific nurse scheduling system. Engineering in Medicine and Biology Society. *Proc. 23rd Annual Internat. Conf. IEEE*. IEEE, Piscataway, NJ. Vol. 4, 3728–3730.

Huarng, F. 1999. A primary shift rotation nurse scheduling using zero-one linear programming. *Comput. Nursing* **17**(3) 135–144.

Hung, R. 1991. A cyclical schedule of 10-hour, four-day workweeks. *Nursing Management* **22**(9) 30–33.

Hung, R. 1995. Hospital nurse scheduling. *J. Nursing Admin.* **25**(7–8) 21–25.

Hung, R. 2002. A note on nurse self-scheduling. *Nursing Econom.* **20**(1) 37–38.

Ikegami, A., A. Niwa. 2003. A subproblem-centric model and approach to the nurse scheduling problem. *Math. Programming* **97**(3) 517–541.

Inoue, T., T. Furuhashi, H. Maeda, M. Takaba. 2003. A proposal of combined method of evolutionary algorithm and heuristics for nurse scheduling support system. *IEEE Trans. Indust. Electron.* **50**(5) 833–838.

Inoue, T., T. Furuhashi, M. Fujii, H. Maeda, M. Takaba. 1999. Development of nurse scheduling support system using interactive EA. *IEEE Systems, Man, and Cybernetics 1999 Conf. Proc.*, Vol. 5, 533–537.

Inoue, T., T. Furuhashi, M. Fujii, H. Maeda, M. Takaba. 2000. A study on bacterial evolutionary algorithm engine for interactive nurse scheduling support system. *IECON 2000 26th Annual Conf. IEEE*, Vol. 1, 22–28.

International Council of Nurses. 2002–2003. Tackling the UN millennium development goals. Biennial Report. Retrieved December 15, 2005 http://www.icn.ch/02-03BiennialReport.pdf.

Isken, M. 2004. An implicit tour scheduling model with applications in healthcare. *Ann. Oper. Res.* **128**(1) 91–109.

Isken, M., W. Hancock. 1990. A heuristic approach to nurse scheduling in hospital units with non-stationary, urgent demand, and a fixed staff size. *J. Soc. Health Systems* **2**(2) 24–40.

Jan, A., M. Yamamoto, A. Ohuchi. 2000. Evolutionary algorithms for the nurse scheduling problem. *Proc. 2000 Congress Evolutionary Comput.*, Vol. 1, 96–203.

Jaszkiewicz, A. 1997. A metaheuristic approach to multiple objective nurse scheduling. *Foundations Comput. Decision Sci.* **22**(3) 169–183.

Jaumard, B., F. Semet, T. Vovor. 1998. A generalized linear programming model for nurse scheduling. *Eur. J. Oper. Res.* **107**(1) 1–18.

Jelinek, R., J. Kavois. 1992. Nurse staffing and scheduling: Past solutions and future directions. *J. Soc. Health Systems* **3**(4) 75–82.

Joint Commission on Accreditation of Healthcare Organizations. 2005. Health care at the crossroads: Strategies for addressing the evolving nursing crisis. Retrieved December 15, 2005 http://www.jointcommission.org / NR / rdonlyres / 5C138711-ED76-4D6F-909F-B06E0309F36D / 0 / health_care_at_the_ crossroads.pdf.

Kawanaka, H., T. Yoshikawa, T. Shinogi, S. Tsuruoka. 2003. Constraints and search efficiency in nurse scheduling problem. *Proc. 2003 Internat. Sympos. Comput. Intelligence Robotics Automation*, Vol. 1, 312–317.

Kawanaka, H., K. Yamamoto, T. Yoshikawa, T. Shinogi, S. Tsuruoka. 2001. Genetic algorithm with constraints for nurse scheduling problem. *Proc. 2001 Congress on Evolutionary Comput.*, Vol. 2, 1123–1130.

King, J. R. 1976. The theory-practice gap in job-shop scheduling. *Production Engrg.* **55** 137–143.

Kostreva, M., K. Jennings. 1991. Nurse scheduling on a microcomputer. *Comput. Oper. Res.* **18**(8) 731–739.

Li, H., A. Lim, B. Rodrigues. 2003. A hybrid AI approach for nurse rostering problem. *Proc. 2003 ACM Sympos. Appl. Comput.* 730–735.

Liao, C., C. Kao. 1997. Scheduling nursing personnel on a microcomputer. *Health Manpower Management* **23**(2) 100–106.

Lukman, D., J. May, L. Shuman, H. Wolfe. 1990. Knowledge-based schedule formulation and maintenance under uncertainty. *J. Soc. Health Systems* **2**(2) 42–64.

Maiden, N. A. M., S. Manning, S. Jones, J. Greenwood. 2005. Generating requirements from systems models using patterns: A case study. *Requirements Engrg.* **10**(4) 276–288.

Messerschmitt, D. G. 2004. Marketplace issues in software planning and design. *IEEE Software* **21**(3) 62–70.

Meyer auf'm Hofe, H. 1998. Nurse rostering constraint satisfaction with fuzzy constraints and inferred control strategies. *Constraints Programming Large Scale Discrete Optim.* **57** 67–99.

Meyer auf'm Hofe, H. 2001. Solving rostering tasks by generic methods for constraint optimization. *Internat. J. Foundations Comput. Sci.* **12**(5) 671–693.

Millar, H., M. Kiragu. 1998. Cyclic and non-cyclic scheduling of 12 h shift nurses by network programming. *Eur. J. Oper. Res.* **104**(3) 582–592.

Miwa, M., T. Inoue, M. Matsuzaki, T. Furuhashi, S. Okuma. 2002. Nurse scheduling using bacterial evolutionary algorithm hardware. *IEEE 2002 28th Annual Conf. Indust. Electronics Soc.*, Vol. 3, 1801–1805.

Moz, M., M. Vaz Pato. 2003. An integer multicommodity flow model applied to the rerostering of nurse schedules. *Ann. Oper. Res.* **119**(1) 285–301.

Moz, M., M. Vaz Pato. 2004. Solving the problem of rerostering nurse schedules with hard constraints: New multicommodity flow models. *Ann. Oper. Res.* **128**(1) 179–197.

Nonobe, K., T. Ibaraki. 1998. A tabu search approach to the constraint satisfaction problem as a general problem solver. *Eur. J. Oper. Res.* **106**(2–3) 599–623.

Okada, M. 1992. An approach to the generalized nurse scheduling problem: Generation of a declarative program to represent institution-specific knowledge. *Comput. Biomedical Res.* **25**(5) 417–434.

Ozkarahan, I. 1989. A flexible nurse scheduling support system. *Comput. Methods and Programs in Biomedicine* **30** 145–153.

Ozkarahan, I. 1991a. A disaggregation model of a flexible nurse scheduling support system. *Socio-Econom. Planning Sci.* **25**(1) 9–26.

Ozkarahan, I. 1991b. An integrated nurse scheduling model. *J. Soc. Health Systems* **3**(2) 76–101.

Ozkarahan, I., J. Bailey. 1988. Goal programming model subsystem of a flexible nurse support system. *IIE Trans.* **20**(3) 306–316.

Pan American Health Organization. 2002. Nursing and midwifery services contributing to equity, access, coverage, quality, and sustainability in the health services. Retrieved February 4, 2006 http://www.paho.org/English/AD/THS/OS/nur-svcs-eng.pdf.

Polanyi, M. 1966. *The Tacit Dimension.* Routledge and Kegan Paul, London, UK.

Randhawa, S., D. Sitompul. 1993. A heuristic-based computerized nurse scheduling system. *Comput. Oper. Res.* **20**(8) 837–844.

Robb, E. A., A. C. Determan, L. R. Lampat, M. J. Scherbring, R. M. Slifka, N. A. Smith. 2003. Self-scheduling: Satisfaction guaranteed. *Nursing Management* **34**(7) 16–18.

Rosenbloom, E., N. Goertzen. 1987. Cyclic nurse scheduling. *Eur. J. Oper. Res.* **31**(1) 19–23.

Schilling, L. S. 2005. Publish or perish: Writing under pressure. *Pediatric Nursing* **31**(3) 234–236.

Scott, S., R. Simpson. 1998. Case-bases incorporating scheduling constraint dimensions: Experiences in nurse rostering. *Lecture Notes in Computer Science*, Vol. 1488. Springer, Berlin, Germany, 392–401.

Siferd, S., W. Benton. 1992. Workforce staffing and scheduling: Hospital nursing specific models. *Eur. J. Oper. Res.* **60**(3) 233–246.

Silvestro, R., C. Silvestro. 2000. An evaluation of nurse rostering practices in the National Health Service. *J. Advanced Nursing* **32**(3) 525–535.

Sitompul, D., S. Randhawa. 1990. Nurse scheduling models: A state-of-the-art review. *J. Soc. Health Systems* **2**(1) 62–72.

Smith, A. P. 2004. Publish or perish: The write thing for nursing. *Nursing Econom.* **22**(6) 342–343.

Thelwall, M. 2004. Can the Web give useful information about commercial uses of scientific research? *Online Inform. Rev.* **28**(2) 120–130.

Thornton, J., A. Sattar. 1996. An integer programming-based nurse rostering system. *Lecture Notes in Computer Science*, Vol. 1179. Springer, Berlin, Germany, 357–358.

Thornton, J., A. Sattar. 1997. Nurse rostering and integer programming revisited. B. Verma, X. Yao, eds. *Internat. Conf. Comput. Intelligence Multimedia Appl., ICCIMA'97*. Gold Coast, Queensland, Australia, 49–58.

Valouxis, C., E. Housos. 2000. Hybrid optimization techniques for the workshift and rest assignments of nursing personnel. *Artificial Intelligence in Medicine* **20**(2) 156–175.

Van Wezel, W., R. Jorna. 1996. Scheduling in a generic perspective: Knowledge-based decision support by domain analysis and cognitive task analysis. *Internat. J. Expert Systems* **9**(3) 357–381.

Venkataraman, R., M. Brusco. 1996. An integrated analysis of nurse staffing and scheduling policies. *OMEGA, Internat. J. Management Sci.* **24**(1) 57–71.

Warner, M. 1976. Scheduling nursing personnel according to nursing preference: A mathematical programming approach. *Oper. Res.* **24**(5) 842–856.

Weil, G., K. Heus, P. Chan, P. Francois. 1998. The nurse scheduling problem: A combinatorial problem, solved by the combination of constraint programming and real users heuristics. *Medinfo* **98** 508–512.

Weil, G., K. Heus, P. Francois, M. Paujade. 1995. Constraint programming for nurse scheduling. *IEEE Engrg. Medicine and Bio.* **14**(4) 417–422.

Wong, G., A. Chun. 2004. Constraint-based rostering using meta-level reasoning and probability-based ordering. *Engrg. Appl. Artificial Intelligence* **17** 599–601.

World Health Organization. 2000. Global advisory group on nursing and midwifery. Retrieved February 4, 2006 http://www.who.int/hrh/nursing_midwifery/gag_sixth_report.pdf.