Personnel scheduling: A literature review

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Abstract

This paper presents a review of the literature on personnel scheduling problems. Firstly, we discuss the classification methods in former review papers. Secondly, we evaluate the literature in the many fields that are related to either the problem setting or the technical features. Each perspective is presented as a table in which the classification is displayed. This method facilitates the identification of manuscripts related to the reader's specific interests. Throughout the literature review, we identify trends in research on personnel staffing and scheduling, and we indicate which areas should be subject to future research.

1. Introduction

In the last few decades, personnel scheduling problems have been studied widely. The increase in research attention could be motivated by economic considerations. For many companies, labor cost is the major direct cost component. Cutting this cost by only a few percent by implementing a new personnel schedule could therefore prove very beneficial.

The personnel scheduling problem today is very different from the one introduced by Dantzig [99] and Edie [111] in the 1950s. The relative importance of satisfying employee needs in staffing and scheduling decisions has grown. Companies offer part-time contracts or flexible work hours and take into account employee preferences (e.g., working together with someone, preference for a specific shift type, specific days off or on and many more) when creating work schedules.

One of the first classification methods for personnel scheduling problems was proposed by Baker [32]. According to Baker, three main groups can be distinguished: shift scheduling, days off scheduling and tour scheduling, which combines the first two types.

In shift scheduling, also called time-of-day scheduling, one has to schedule across a daily planning horizon. The simplest type of schedule involves non-overlapping shifts. This implies that the staff requirements on each shift can be treated independently in determining appropriate allocations. This type of problem is typical for industrial companies. Its main advantage is that the allocation problem is easy to solve, and the solution is relatively easy to implement. However, when demand fluctuates over small intervals compared to the shift length, this configuration is no longer useful and a model for allocations with overlapping shifts is needed. Call centers, for instance, encounter this kind of scheduling problem.

In the second group of problems (days off or day-of-week scheduling), the length of the operating week in the facility does not match the length of an employee's working week. A widely used version of this problem is the instance of 5-day work weeks for employees and a 7-day operating week. A variation of the problem integrates the assumption that the employee's days off have to be consecutive.

As already mentioned, the third case is a combination of the shift scheduling and the days off scheduling problem. In personnel tour scheduling, organizations operate seven days a week, with more than one shift a day (e.g., airlines, hotels, hospitals, etc.). Since employees must be given daily and weekly breaks, the particular tour (i.e., hours of the day and days of the week) in which the employee must work has to be specified. As with shift and days off scheduling problems, the complexity and size of the tour scheduling problems depend on a number of factors [12]. What really influences the complexity of the problem is the duration of the minimum planning interval, which typically ranges from 15 min to 8 h.

A popular classification method is one based on the solution method applied. Bechtold et al. [42] classify personnel scheduling solution methods in two categories: linear programming or construction based. Subsequently, a number of categories have been added by different authors. In his survey, Alfares [12] proposes ten categories for tour scheduling approaches: (1) manual solution, (2) integer programming, (3) implicit modeling, (4) decomposition, (5) goal programming, (6) working set generation, (7) LP-based solution, (8) construction/improvement, (9) metaheuristics and (10) other methods.

Ernst et al. [118] present a review of staff scheduling and rostering. Their classification presents the rostering (or personnel scheduling) process as a number of modules: demand modeling, days off scheduling, shift scheduling, line of work construction, task assignment and staff assignment. The requirement of different modules depends on the application. It is often possible to combine several modules into the same procedure. This classification is used to discuss the key problems related to staff scheduling in different application areas, such as transportation systems, call centers, health care systems, etc. In the remainder of their paper Ernst et al. [118] review rostering methods and techniques. They classify the different approaches into five groups: (1) demand modeling, (2) artificial intelligence approaches (fuzzy set theory, search and expert systems), (3) constraint programming, (4) metaheuristics and (5) mathematical programming approaches.

A second paper by these authors [117] gives an annotated bibliography of about 700 references in personnel scheduling. The papers are classified according to the type of problem, the application area and the solution method. The application areas are the same as in the review paper and the classification based on the type of problem uses the proposed modules with some extra subgroups to categorize the references. The solution methods are now classified into 29 different categories. Other popular review papers are written by Tien [276] and Thompson [268-271], who both divide the personnel scheduling process into a number of steps.

Burke et al. [73] present a review paper on nurse rostering problems. They not only categorize papers according to solution methods, constraints and performance measures, but they also provide tables with information on the planning period, the data that were used (i.e., real-world or theoretical), the number of skills and their substitutability, etc. This approach, one that focuses on multiple perspectives, is comparable to our classification process.

We started our search process with the review articles, published in 2004 [12, 73, 118, 175] and used the database *Web of Knowledge* to check which manuscripts cited these review articles. For any article found, written in English and appearing in 2004 or later, we checked the complete reference list and continued our search process. When this search ended, we also searched the databases *Web of Science, Academic Search Premier, Business Source Premier* and *EconLit* for relevant articles until July, 1st 2012. We mainly address combinations of the search phrases: personnel scheduling, workforce scheduling, staff scheduling and staffing. We ended up with a set of 291 articles. We do not presume to have collected all the articles on personnel scheduling or staffing from 2004 onwards, but we believe we have identified a set that is representative of the work carried out by the research community.

A distinction is made between managerial and technical papers. A paper is considered managerial if no algorithmic description of a solution method is given. Books are also considered managerial, since it is not possible to classify all the information of the different book chapters. Only the technical papers contribute to our classification process. When one of the managerial papers highlights relevant insights into one of our (sub)topics, we will refer to it in our text.

Table 1 gives information on the journals that contribute most to the research area of personnel scheduling. It is clear that the European Journal of Operational Research and the Annals of Operations Research publish most of the personnel scheduling literature.

Table 1: Journal perspective (journals with 4 or more publications).

Journal	Frequency
European Journal of Operational Research	47
Annals of Operations Research	35
Journal of the Operational Research Society	16
Journal of Scheduling	13
Computers & Operations Research	11
IIE Transactions	7
Health Care Management Science	6
Journal of Heuristics	6
Interfaces	5
International Journal of Production Economics	5
International Journal of Advanced Manufacturing Technology	4
Manufacturing & Service Operations Management	4
Omega	4
Operations Research	4

We share the preference of Beliën and Forcé [48] and Cardoen et al. [78] for organizing the literature review using different perspectives. This method allows researchers to query a list of manuscripts according to their specific needs. Taxonomies based on strategic (long term), tactical (medium term) and operational (short term) approaches are often not very efficient due to their interpretation bias and lack of detail.

The classification fields are the following:

- Personnel characteristics, decision delineation and shifts definitions (Section 2): information on personnel criteria such as skills, full- or part-time contracts, etc., and indicating what type of decision has to be made (time, tasks, group or shift sequence), followed by information on the shifts definitions;
- Constraints, performance measures and flexibility (Section 3): information on the hard and soft constraints that occur in addressing the problem, as well as the parameters researchers could change in order to cope with coverage constraints;
- Solution method and uncertainty incorporation (Section 4): indicating which type of solution or evaluation technique is used and distinguishing between deterministic and stochastic manuscripts;
- Application area and applicability of research (Section 5): indicating in which area the problem is situated and information on the testing (data) and its implementation in practice.

In a similar manner to Beliën and Forcé [48] and Cardoen et al. [78], each section clarifies the terminology and contains a brief discussion based on a selection of appropriate manuscripts, as well as detailed tables in which all relevant manuscripts are listed and categorized. It should be noted that, if not stated otherwise, the percentages are calculated in relation to the total number of technical papers. Some of the methods cannot be classified in terms of the categories outlined and some articles contain more than one single method.

2. Personnel characteristics, decision delineation and shifts definition

One way in which to classify personnel members is to look at their labor contract, namely distinguishing between full-time and part-time workers. As shown in Table 2, the vast majority of the papers study full-time personnel problems. A number of papers also incorporate part-time personnel in their model, resembling real-world problem instances where a mixed workforce is usually available. Akbari [6] and Hojati and Motil [157] are the only two papers that tackle the scheduling problem of part-time workers on its own. Hojati and Motil [157] minimize the overstaffing and try to meet the target total working hours for each employee during the scheduling period in a service organization. When the regular workforce is not able to deal with the coverage constraints or other requirements, casual workers have to be scheduled in as well. This group of workers consists of, for instance, interim workers or workers from another company division.

Table 2: Personnel characteristics.

Contract		
	Full-time	2, 3, 4, 5, 7, 9, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 33, 34, 35, 36, 37, 38, 39, 40, 41, 43, 44, 45, 46, 47, 49, 50, 51, 52, 53, 54, 56, 57, 58, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 75, 76, 77, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 103, 104, 105, 106, 107, 108, 109, 110, 112, 113, 114, 115, 116, 119, 120, 121, 122, 124, 126, 127, 128, 130, 131, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 151, 152, 153, 154, 155, 156, 158, 159, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 173, 174, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 206, 207, 208, 210, 211, 212, 213, 214, 215, 216, 218, 219, 220, 221, 222, 223,

		226, 227, 228, 229, 230, 231, 235, 236, 237, 238, 239, 240, 242, 243, 244, 245, 246, 247, 248, 249, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 272, 273, 274, 277, 278, 279, 281, 282, 283, 284, 285, 287, 288, 289, 290, 291, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306
	Part-time	6, 19, 25, 29, 30, 34, 35, 36, 37, 38, 40, 41, 43, 53, 54, 58, 60, 61, 64, 65, 66, 69, 70, 72, 74, 77, 80, 83, 85, 86, 87, 103, 105, 113, 114, 119, 121, 122, 134, 136, 137, 144, 151, 154, 157, 159, 165, 170, 174, 186, 187, 195, 200, 201, 204, 206, 208, 209, 220, 221, 222, 236, 238, 239, 240, 245, 246, 248, 249, 260, 264, 272, 274, 279, 281, 284, 287, 289, 291, 295, 296, 298, 299, 300, 306
	Casual	17, 33, 35, 36, 37, 38, 58, 60, 61, 75, 85, 90, 92, 103, 112, 121, 122, 127, 141, 149, 152, 162, 168, 176, 192, 202, 204, 206, 263, 266, 283, 288, 291, 298, 299, 300
Skills		3, 4, 5, 6, 10, 17, 21, 22, 23, 24, 25, 26, 30, 33, 34, 35, 38, 40, 41, 43, 44, 50, 51, 52, 53, 54, 56, 61, 62, 65, 66, 70, 72, 75, 76, 77, 79, 81, 89, 90, 94, 106, 109, 112, 113, 119, 121, 122, 124, 127, 128, 137, 138, 139, 142, 143, 144, 146, 147, 149, 152, 153, 156, 157, 159, 162, 173, 176, 177, 180, 182, 186, 188, 189, 190, 192, 195, 196, 202, 204, 206, 208, 216, 219, 221, 222, 223, 227, 228, 229, 235, 238, 239, 247, 248, 249, 251, 252, 255, 256, 258, 260, 261, 266, 267, 272, 274, 277, 283, 284, 285, 287, 288, 289, 290, 291, 294, 295, 296, 301, 302, 305, 306
Entity		
	Individual	2, 3, 4, 5, 6, 7, 9, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 33, 34, 35, 36, 37, 38, 39, 40, 41, 43, 44, 45, 46, 47, 49, 50, 51, 52, 53, 54, 56, 58, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 75, 76, 77, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 103, 104, 105, 106, 107, 108, 109, 112, 113, 114, 115, 119, 120, 121, 122, 124, 126, 127, 128, 130, 131, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 146, 148, 149, 151, 152, 153, 154, 155, 156, 157, 159, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 173, 174, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 206, 207, 208, 209, 211, 212, 213, 214, 215, 216, 218, 219, 220, 221, 222, 223, 226, 227, 228, 229, 230, 231, 235, 236, 237, 238, 239, 240, 242, 243, 244, 245, 246, 247, 248, 249, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 272, 273, 274, 277, 278, 279, 281, 282, 283, 284, 285, 287, 288, 289, 290, 291, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 305, 306
	Crew	88, 110, 116, 147, 158, 210, 267, 304

When certain tasks demand specific skills, the personnel are considered to form a heterogeneous set of employees, each with a number of specific skills. In relation to certain problems, tasks could be carried out by personnel members who do not possess the specific skills. This typically leads to a cost increase, since these employees are less efficient and consequently yield a lower productivity rate.

Another classification is based on the grouping of employees. Some problems require the scheduling of a crew (or team) instead of considering each employee on their own. Applications for this kind of scheduling problems can be found in the transportation area, where one has to combine personnel scheduling with vehicle routing. The number of vehicles and/or routes is typically constrained and each vehicle needs a number of staff members with or without specific skills. We did not include all papers on this topic in our set, since it can be seen as a different research field with other constraints and objectives than the personnel scheduling problem. An example of airline crew scheduling can be found in Chu [88] and Thiel [267]. Hanne et al. [147] study the crew rostering problem in a railway environment and Horn et al. [158] develop a method for scheduling patrol boats and their crews.

Examples of less frequent personnel characteristics are productivity levels [6, 29, 63, 210, 290, 297] and seniority [6, 31, 91, 93, 146, 156, 277, 278, 288]. Categorizing personnel members in terms of different productivity levels is closely related to the skill-based classification. When less efficient personnel members are assigned to do jobs, this now leads to a lower “profit” or a postponed due date (which also incurs a cost). As in the skill-based classification, this would typically add a penalty to the objective function. However, both characteristics can be combined when employees differ in the productivity rate they possess for their specific skill set. Bhatnagar [51] adds an extra factor to the productivity rates and incorporates learning effects in his scheduling problem. Seniority could also have an impact on the decision making policy. Older members could have privileges like an increased number of (consecutive) days off, or their preferences for specific days or shifts off might be considered more important than those of their younger colleagues. One could also restrict the instances of older people being assigned specific shifts (e.g., night duties) or tasks (e.g., no heavy lifting). Asensio-Cuesta et al. [18] incorporate employees' injuries to create ergonomic job rotation schedules.

Personnel scheduling problems consist of various decisions that have to be taken. Table 3 indicates the type of decisions examined in the manuscripts, such as the assignment of tasks (e.g., employee A is assigned to job K), groups (e.g., multiple workstations), shift sequence (e.g., employee A works the night shift on Monday, is free on Tuesday and works the morning shift on Wednesday), time (e.g., employee A is busy in time periods 1 to 4) or "Other". The group decision entails a number of different decisions where employees are combined into subsets, such as skills, different locations or workstations, etc. "Other" represents a heterogeneous group of assignments, for example when a worker needs a specific vehicle or tool to do his tasks. For each decision, we distinguish between individual personnel members and teams.

Table 3: Type of decisions.

	Team	Individual personnel member
Tasks	110, 158, 202, 210, 253, 267	7, 15, 16, 17, 18, 35, 40, 45, 46, 51, 75, 76, 77, 83, 90, 96, 97, 98, 104, 105, 109, 112, 114, 121, 122, 124, 127, 135, 143, 145, 152, 162, 163, 174, 176, 177, 180, 182, 186, 196, 202, 206, 208, 216, 221, 226, 240, 242, 244, 247, 251, 252, 255, 261, 264, 265, 281, 283, 288, 290, 291, 297, 302
Group	88, 193, 202, 253, 267	9, 10, 11, 33, 34, 35, 36, 41, 44, 51, 62, 63, 76, 88, 90, 104, 119, 127, 128, 138, 142, 143, 149, 157, 159, 162, 169, 171, 179, 185, 186, 202, 219, 220, 221, 238, 247, 251, 252, 262, 287, 290, 291, 298, 299, 300, 301
Shift sequence	88, 116, 158, 202, 267, 304	2, 3, 4, 5, 6, 7, 9, 10, 11, 13, 14, 15, 16, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 33, 34, 35, 36, 37, 38, 39, 41, 43, 45, 46, 47, 49, 50, 51, 52, 53, 54, 56, 58, 60, 61, 62, 64, 65, 66, 67, 69, 70, 71, 72, 74, 75, 76, 77, 79, 80, 82, 84, 85, 86, 87, 88, 89, 91, 92, 93, 94, 95, 103, 104, 105, 108, 109, 112, 113, 114, 115, 119, 120, 121, 122, 124, 126, 128, 130, 131, 134, 136, 137, 138, 141, 142, 143, 144, 145, 146, 148, 151, 152, 153, 154, 155, 156, 157, 159, 161, 164, 166, 167, 169, 170, 171, 173, 177, 178, 179, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 207, 208, 209, 211, 212, 213, 214, 218, 219, 220, 222, 226, 227, 228, 229, 230, 231, 236, 237, 238, 239, 240, 243, 244, 245, 246, 247, 249, 251, 252, 254, 256, 257, 258, 260, 261, 263, 266, 272, 274, 277, 278, 279, 281, 282, 283, 284, 285, 291, 294, 295, 296, 297, 301, 303, 306
Time	110, 158, 202, 253, 267	7, 15, 17, 18, 58, 63, 77, 90, 96, 97, 104, 105, 114, 121, 122, 124, 127, 135, 152, 162, 163, 174, 176, 180, 186, 196, 202, 206, 216, 221, 242, 244, 252, 255, 263, 265, 281, 291, 302
Other	110, 116, 158, 215, 253, 267	143, 173

The paper of Horn et al. [158] provides an example of highlighting the decision taxonomy. To help the Royal Australian Navy's Patrol Boat Force make efficient use of a new generation of boats, they develop optimization procedures to schedule the activities of the boats and their crews. The main scheduling tasks are to establish timings for all the activities ("time-team" and "shift sequence-team" assignment) and to assign each activity to a specific boat ("other-team" assignment) and a specific crew ("task-team" assignment). Associated tasks are to assign each crew to a home port, and to determine the location of each boat when not deployed at sea. The Navy specifies the work of the Patrol Boat Force as a set of mission groups, each group comprising a number of missions of a particular type that are planned during a specified time-window. For example, a mission group can be defined as six fisheries-patrol missions. Another paper that focuses on team-based decisions is written by Thiel [267]. Given the published flight schedule of an airline, the key task is to assign all necessary crew members of cockpit and cabin crew ("task-team", "time-team", "shift sequence team" and "group-employee" assignment) in such a way that the airline is able to operate all its flights at minimal expense in terms of personnel costs. This assignment has to consider all the restrictions enforced by government regulations, union agreements and company-specific rules. In addition, time- and location-dependent crew availabilities have to be accounted for, especially in a setting where a crew is stationed at one of many airports ("other-team" assignment). De Matta and Peters [104] focus on an individual-based decision problem of finding the cost-minimizing mix of primary and secondary jobs in work schedules for bus drivers belonging to an inter-city public transport firm in India. The task, time and shift sequence decision comes down to the assignment of drivers to a number of bus itineraries (series of legs assigned to a bus leaving the depot, cities visited on its timetable and returning back to the depot) and possible shift schedules. A depot operates several bus fleets, categorized into deluxe, express and ordinary. Every bus driver has a designated bus fleet (group-individual assignment).

In reviewing the literature on the decision-making policies, it soon became apparent that most of the papers only focus on creating feasible shift sequences or job schedules for their workers, considering a deterministic workload. Hardly ever, the personnel scheduling problem is integrated with other scheduling problems such as machine scheduling, operating room scheduling, etc. Apart from the lack of integration with other scheduling problems, one seldom integrates all the decisions of the personnel scheduling problem, such as forecasting and adjusting the workload distribution, break placements, hiring/firing, training skills, considering employee preferences for holidays or shifts, etc. This is one of the major areas of future research opportunities: joining all these decisions into one single personnel scheduling problem.

Flexibility receives particular attention in the literature. Topaloglu and Ozkarahan [279] state that organizations use different shift start times, shift lengths, daily break windows and days-on work patterns in order to provide flexibility. When the number of flexibility alternatives increases, developing tour schedules becomes more complex.

Table 4 lists the different alternatives where shift decisions are concerned. The first decision is based on the overlap of shifts. When demand is rather fairly distributed over the day and the operating day length is too large to be covered by a single shift, a possible method is to create multiple non-overlapping shifts. This method is very common in hospitals and industrial organizations. When the organization operates all day long, the day is often divided into three distinct shifts with a length of 8 hours (e.g., early from 6 AM to 2 PM, late from 2 PM to 10 PM and night from 10 PM to 6 AM). Personnel schedulers in call centers had to come up with a different approach, since incoming calls arrive at very irregular intervals during the day. When allowing shifts to overlap, it is possible to increase the number of staff present at work at certain (peak) times. This way one can deal with demand peaks without being forced to schedule expensive overtime or to hire extra employees and one can avoid excess staff during low demand periods. When personnel has to be assigned to pre-specified shift patterns, it is not always clearly mentioned in the text whether these shifts overlap or not (see for instance [4, 261]).

Table 4: Flexibility with respect to shift decisions.

Shifts overlap		
	Distinct	3, 4, 5, 6, 9, 10, 11, 30, 34, 36, 37, 40, 41, 44, 49, 50, 51, 70, 86, 89, 105, 113, 119, 120, 131, 136, 137, 146, 149, 151, 154, 155, 183, 184, 189, 190, 193, 194, 197, 199, 200, 207, 210, 211, 212, 213, 214, 226, 227, 231, 238, 245, 246, 249, 255, 258, 274, 277, 278, 282, 283, 291, 301, 303
	Overlap allowed	2, 7, 14, 15, 16, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 33, 34, 35, 36, 38, 39, 41, 43, 47, 52, 53, 54, 56, 58, 60, 61, 62, 64, 65, 66, 69, 70, 71, 72, 74, 76, 77, 80, 81, 82, 84, 85, 87, 88, 92, 97, 98, 103, 104, 105, 107, 108, 109, 112, 114, 116, 119, 121, 122, 126, 134, 138, 141, 143, 144, 147, 148, 153, 156, 157, 159, 163, 164, 165, 169, 170, 171, 173, 177, 178, 179, 185, 187, 188, 191, 195, 196, 201, 203, 204, 208, 209, 215, 218, 219, 220, 222, 228, 230, 236, 237, 238, 239, 240, 243, 244, 248, 252, 256, 257, 259, 262, 263, 264, 267, 272, 273, 279, 281, 284, 287, 291, 295, 296, 298, 299, 300, 304, 305, 306
Shift start times		
	Fixed	3, 4, 5, 6, 9, 10, 11, 25, 26, 30, 33, 34, 36, 37, 38, 39, 40, 41, 43, 44, 47, 49, 50, 51, 53, 54, 56, 65, 66, 69, 70, 71, 72, 74, 86, 87, 89, 96, 105, 114, 119, 120, 131, 134, 137, 143, 146, 149, 151, 153, 154, 155, 159, 163, 177, 179, 181, 183, 184, 185, 187, 188, 189, 190, 193, 194, 195, 197, 199, 200, 201, 203, 204, 207, 210, 211, 212, 213, 214, 222, 227, 230, 231, 236, 237, 238, 239, 245, 249, 255, 256, 258, 261, 264, 274, 277, 278, 281, 282, 283, 284, 287, 291, 296, 301, 303, 305
	Definable	2, 7, 14, 15, 16, 19, 21, 22, 23, 24, 27, 28, 29, 34, 35, 36, 41, 52, 58, 60, 61, 62, 64, 76, 77, 80, 81, 82, 84, 85, 88, 92, 97, 98, 103, 104, 105, 107, 108, 109, 112, 113, 114, 116, 119, 121, 122, 126, 136, 138, 141, 144, 147, 148, 156, 157, 164, 165, 169, 170, 171, 173, 178, 191, 196, 208, 209, 215, 218, 219, 220, 226, 228, 238, 240, 243, 244, 246, 248, 252, 257, 259, 262, 263, 267, 272, 273, 279, 291, 295, 298, 299, 300, 304, 306
Shift length		
	Fixed	3, 4, 5, 6, 7, 9, 10, 11, 14, 21, 25, 26, 30, 33, 34, 35, 36, 37, 38, 39, 40, 41, 43, 44, 47, 49, 50, 51, 53, 54, 56, 64, 65, 66, 69, 70, 71, 72, 74, 80, 82, 86, 87, 88, 89, 96, 105, 108, 114, 116, 119, 120, 126, 131, 134, 136, 137, 143, 146, 149, 151, 153, 154, 155, 156, 159, 163, 165, 177, 179, 181, 183, 184, 185, 187, 188, 189, 190, 193, 194, 195, 197, 199, 200, 201, 203, 204, 207, 210, 211, 212, 213, 214, 222, 227, 230, 231, 236, 237, 238, 239, 244, 245, 246, 248, 249, 255, 256, 258, 261, 264, 272, 274, 277, 278, 281, 282, 283, 284, 287, 291, 296, 301, 303, 305
	Definable	2, 15, 16, 19, 22, 23, 24, 27, 28, 29, 34, 35, 36, 41, 52, 58, 60, 61, 62, 76, 77, 80, 81, 84, 85, 92, 97, 98, 103, 104, 105, 107, 109, 112, 113, 114, 119, 121, 122, 138, 141, 144, 147, 148, 157, 161, 164, 169, 170, 171, 173, 178, 191, 196, 208, 209, 215, 218, 219, 220, 226, 228, 238, 240, 243, 252, 257, 259, 262, 263, 267, 273, 279, 291, 295, 298, 299, 300, 304, 306

The first shift decision does not contribute greatly to the flexibility of the scheduler, because the shifts are predetermined. Allowing the user to differentiate concerning the starting/finishing hours (between boundaries) and concerning the shift length further contributes to flexibility. Sometimes, fixed and definable shift start times and/or shift lengths are combined in order to address the same issue. Bard carried out a number of studies (with different authors) on a personnel scheduling problem at the US Postal Service mail processing and distribution center in Dallas [34-36, 40, 41, 238, 291]. The problem consisted of scheduling full-time regular and part-time flexible employees. Regular full-time employees have to be assigned to one of the three possible day shifts with a predefined length of 8.5 hours. For part-timers, there are generally 24 different start times and 5 different shift lengths.

The increasing importance of personnel preferences and a flexible work environment will result in the dominance of tour scheduling problems in the research of personnel scheduling. In our set most of the papers study shift scheduling or tour scheduling problems. Therefore, we did not include a classification table based on Baker's classification [32]. We strongly advice the research community to incorporate all the aspects of tour scheduling, creating a more valuable scheduling algorithm for the company.

3. Constraints, performance measures and flexibility

In this section, we classify the variety of constraints that appear in personnel scheduling problems. If possible, we distinguish between hard and soft constraints per category. The different categories are coverage, time-related, and fairness and balance constraints. In addition, the flexibility which allows the user to cope with these constraints, is discussed.

Table 5 lists the coverage constraints. With a presence at a level of almost 75%, the hard coverage constraint is the key characteristic of personnel scheduling problems. The coverage constraint is also one of the most popular soft constraints in personnel scheduling problems. This is straightforward, since an important aspect of personnel scheduling problems is deciding on the number of employees needed to cover the workload. Therefore, some papers are listed twice in the table: the hard constraint ensure that enough workers are available during each time period, whereas the objective function minimizes the total workforce.

Table 5: Coverage constraints.

	Hard	Soft
Coverage	2, 3, 4, 5, 6, 7, 9, 10, 11, 13, 14, 15, 16, 18, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 33, 34, 35, 36, 38, 39, 40, 41, 44, 45, 46, 47, 50, 51, 52, 54, 56, 58, 60, 61, 62, 64, 65, 69, 70, 71, 72, 74, 76, 79, 80, 81, 82, 85, 86, 87, 88, 89, 90, 94, 95, 96, 98, 103, 104, 105, 106, 109, 110, 112, 114, 115, 116, 120, 121, 122, 124, 126, 127, 130, 131, 134, 135, 136, 137, 138, 139, 140, 144, 146, 147, 148, 149, 151, 152, 153, 154, 155, 156, 157, 158, 159, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 173, 174, 176, 177, 180, 181, 185, 186, 187, 189, 190, 191, 192, 193, 194, 195, 196, 199, 206, 207, 209, 211, 214, 218, 222, 227, 228, 229, 230, 235, 236, 237, 238, 239, 240, 243, 244, 245, 246, 247, 248, 249, 251, 252, 253, 255, 256, 258, 259, 261, 262, 263, 264, 267, 272, 273, 277, 278, 281, 282, 283, 284, 285, 287, 289, 290, 291, 295, 296, 297, 298, 299, 300, 302, 303, 304, 305	9, 11, 19, 26, 29, 34, 37, 38, 39, 41, 43, 49, 53, 63, 72, 75, 76, 85, 92, 97, 107, 108, 113, 114, 116, 119, 131, 139, 141, 142, 143, 155, 157, 161, 163, 168, 171, 177, 178, 179, 182, 186, 188, 191, 197, 198, 200, 201, 202, 203, 204, 208, 211, 214, 216, 218, 219, 220, 230, 237, 238, 246, 251, 254, 259, 274, 279, 289, 290, 294, 295, 298, 299, 300, 302, 303, 306

When focusing on capacity as a soft constraint or performance measure, the difference from the optimal or minimal capacity is typically of interest. Bard and Purnomo have written a number of papers on the nurse scheduling problem [37-39, 237]. They define the workload demand as a lower and upper limit on the number of nurses needed per shift. Because of nationwide staff shortages, they assume it would be unusual to be able to cover all demand. Therefore, gaps in the schedule could be filled by (limited) outside resources. One objective is to generate a set of rosters that minimizes the number of uncovered shifts over the planning horizon (i.e., the cost of filling gaps with outside nurses). Nissen and Günther [141-143, 219, 220] consider coverage constraints as a set of soft constraints. When a discrepancy arises from the workstation staffing target, error points are generated for the duration and size of the erroneous assignment based on the error point size. They distinguish different types of errors for overstaffing and understaffing demand.

When researchers classify coverage constraints as hard constraints, understaffing is not allowed. This does not mean that workforce demand has to be met exactly: one can still schedule some excess staff to deal with unexpected demand, etc. Table 6 lists the papers in a matrix according to the flexibility of the operator with respect to tackling coverage constraints.

Table 6: Flexibility with respect to coverage constraints.

Overstaffing	Allowed	Not allowed
Understaffing		

Allowed	17, 19, 26, 29, 33, 43, 49, 53, 63, 71, 75, 77, 80, 84, 87, 92, 97, 98, 103, 105, 108, 113, 128, 131, 140, 141, 142, 143, 153, 169, 171, 178, 188, 193, 197, 198, 202, 203, 204, 215, 216, 219, 245, 246, 254, 257, 272, 274, 279, 283, 288, 295, 296, 298, 299, 300, 303, 305, 306	294
Not allowed	2, 14, 15, 16, 27, 28, 30, 35, 36, 38, 50, 58, 60, 64, 72, 82, 88, 90, 94, 96, 104, 114, 116, 126, 138, 154, 155, 157, 161, 162, 166, 167, 173, 189, 191, 192, 199, 200, 201, 208, 211, 214, 218, 221, 229, 236, 240, 243, 244, 249, 252, 256, 258, 259, 262, 263, 264, 273, 281, 282, 285, 290, 302	7, 9, 11, 18, 25, 54, 65, 66, 69, 70, 86, 89, 95, 110, 115, 127, 134, 135, 147, 151, 156, 159, 163, 176, 177, 183, 194, 195, 196, 206, 207, 209, 212, 213, 220, 222, 226, 227, 231, 253, 284, 304

Table 6 indicates that the manuscripts are quite evenly distributed over the different alternatives, except for the case where understaffing is allowed and overstaffing is not, which is addressed in only one paper. In this exceptional paper, White et al. [294] evaluate heuristic algorithms used to produce duty rosters for medical trainees (residents and medical students) to man the overnight shift. Ideally, exactly 5 members are present, but for financial reasons only 4 or 3 may actually be scheduled.

When the personnel can be classified into different skill categories, a hard constraint is mostly added to ensure the presence of a number of workers per skill needed during a specific period. The necessity of a specific skill can be modeled either as a hard or a soft constraint (Table 7). In the case of a soft constraint, people with other skills could take over when there is a lack of employees with the right skill, which penalizes the objective value. In the nurse scheduling problem of Brucker et al. [56] constructing shift sequences for each nurse of different skills is considered a hard constraint. However, “alternative skills” are considered a soft constraint, if a nurse is able to cover a shift but prefers not to, since it does not require his/her primary skill.

Table 7: Skills.

	Hard	**Soft**
Skills	3, 4, 5, 6, 10, 17, 21, 22, 23, 24, 26, 30, 33, 34, 35, 38, 40, 41, 50, 52, 53, 56, 61, 62, 70, 72, 76, 77, 79, 81, 89, 90, 94, 106, 109, 112, 119, 121, 122, 124, 127, 128, 137, 138, 139, 144, 146, 147, 149, 152, 156, 157, 162, 169, 173, 176, 177, 180, 182, 186, 189, 190, 196, 202, 204, 206, 208, 216, 221, 223, 227, 229, 235, 238, 247, 249, 251, 252, 255, 256, 258, 261, 266, 267, 274, 277, 283, 285, 287, 288, 289, 290, 291, 295, 296, 301, 305, 306	25, 43, 53, 54, 56, 65, 124, 128, 142, 143, 188, 195, 219, 220, 222, 258, 283, 284, 287

We distinguish between three groups with respect to the extent to which skills are considered flexible (Table 8). The first group consists of skills that are user definable. In this case the scheduler has the freedom to define skills for every personnel member in the set. This could be the case when the company has the ability to easily hire (or train) employees with these specific skills. Extra constraints could limit the number of people with a specific skill or enforce a minimum on a set. The second group concerns problems with a hierarchical workforce. In this case, employees classified in a higher category are able to carry out the tasks of lower ranked employees, but not vice versa. In this way, companies could differentiate based on educational background, training and experience, junior and senior employees, etc. Generally, employees in a higher classified category receive a greater level of compensation than employees in a lower classified category. Examples can be found in hospitals, where schedules have to satisfy demand for a given number of nurses with different grades [189] or students have to be scheduled together with nurses or physicians [294]. Hierarchical workforce applications do not only arise in health care. Rong and Grunow [248] consider a qualification hierarchy when scheduling freight handling personnel at air cargo terminals and Li et al.

[192] propose an integrated (hierarchical) staff-sizing approach considering the feasibility of scheduling decisions for service organizations. In the last group, skills cannot be substituted. Tasks or jobs that need specific skills can only be covered by workers with those skills. Nevertheless, it is possible for workers to be cross-trained.

Table 8: Flexibility with respect to breaks and skills.

Skills		
	Hierarchical	3, 4, 5, 10, 26, 30, 34, 35, 38, 41, 43, 44, 56, 112, 127, 137, 138, 176, 189, 190, 192, 228, 229, 238, 247, 248, 256, 258, 274, 283, 288, 291, 294, 302
	Definable	70, 106, 143, 144, 208, 267
	Not allowed	6, 17, 21, 22, 23, 24, 25, 33, 40, 50, 51, 52, 53, 54, 61, 62, 65, 66, 72, 75, 76, 77, 79, 81, 89, 90, 94, 109, 113, 119, 121, 122, 124, 128, 139, 142, 146, 147, 149, 152, 153, 156, 157, 159, 162, 164, 173, 177, 180, 182, 186, 188, 195, 202, 204, 216, 221, 222, 223, 227, 235, 249, 251, 252, 255, 261, 266, 272, 277, 284, 287, 289, 290, 295, 296, 301, 305, 306
Breaks[1]		14, 16, 18, 22, 23, 24, 29, 34, 35, 36, 40, 41, 58, 60, 61, 76, 80, 82, 84, 88, 96, 97, 98, 105, 108, 109, 114, 131, 135, 138, 156, 164, 170, 171, 178, 202, 208, 218, 221, 238, 240, 243, 244, 247, 252, 253, 263, 267, 272, 273, 279, 283, 291, 304

As Table 7 and Table 8 show, skills are well-incorporated into personnel scheduling problems. In most papers, those skills are fixed, i.e., one cannot train or learn extra skills. The focus on hard constrained fixed skills does not reflect reality. Skills are too often considered as an input. Researchers should try to take advantage of a skills setting, by deciding on the assignment of (multiple) skills to workers at a certain training cost.

The coverage constraints could be defined in a way to incorporate breaks. In his model, Dantzig [99] created the possibility of adding meal breaks to every distinct shift schedule. Now, more than half a century later, scheduling breaks are often omitted from personnel scheduling problems (Table 8). A distinction can be made between the assignment of (long) meal breaks and (short) rest breaks. Quimper and Rousseau [240], for example, schedule a rest break, a lunch break and another rest break for every work shift of a full-time employee. The timing of breaks is usually limited. Often a predefined time window is set, based on the starting and finishing hours of the employee's working shift (see for instance [36, 41]). Both papers also differentiate between full- and part-time workers. Part-time workers only need a meal break if their shift length exceeds a certain threshold whereas full-time workers always need a break. Thompson and Pullman [273] present a paper in which the break assignment not only restrains the schedule possibilities, but actually forms the topic of the paper. They found that only 18% of the 64 papers they surveyed scheduled rest breaks or reliefs. The objective of their paper is to try to determine whether reliefs should be scheduled in advance (which confronts researchers with a growth in problem complexity) or scheduled in real-time (which permits researchers to continue to avoid scheduling reliefs). Scheduling reliefs in advance results in more costly schedules, but (according to the authors) will have undesirable outcomes such as a less profitable deployment of labor and a less productive workforce when some reliefs cannot be given. A third negative consequence can occur when scheduling relief breaks in real-time. These real-time schedule adjustments should be incorporated into the procedures developed by the researchers, as adjustments made by experienced managers are generally less profitable than adjustments made by computer-based heuristics.

[1] Note: In some personnel scheduling problems, the operator has to select one pattern out of a set of predefined shift patterns. These patterns could include breaks, but since no information is provided, we have not included these papers in Table 8.

The flexibility alternatives discussed in this section are not exhaustive. The use of overtime also has an impact on the flexibility of the operator in dealing with coverage constraints. When scheduling overtime is allowed, a relation exists between assigning extra hours to employees and hiring a new employee (when possible). This relationship depends on the extra cost of overtime on top of the wage, the upper limit on the number of hours per day and/or per week per employee, etc.

Instead of limiting the number of work hours by week, one could also use annualized hours or working time accounts [27, 28, 92, 230]. This way, the operator keeps track of the number of hours a specific employee has worked during the past period (month, year, …). This gives the operator more flexibility in scheduling employees, since one can compensate for weeks when demand and thus workload is high without having to pay for expensive overtime or to hire new (part-time) workers.

Other factors of interest are the possibility of hiring interim or casual workers, outsourcing, etc.

Table 9: Financial measures for coverage constraints.

Personnel cost	2, 4, 10, 13, 14, 16, 20, 21, 22, 23, 24,29, 33, 34, 35, 36, 37, 41, 50, 51, 52, 58, 60, 61, 62, 64, 81, 82, 84, 85, 87, 88, 91, 93, 94, 96, 97, 104, 105, 106, 108, 110, 112, 115, 119, 121, 122, 124, 128, 144, 147, 149, 152, 153, 155, 164, 165, 168, 169, 170, 176, 177, 180, 192, 193, 194, 202, 204, 206, 208, 210, 218, 235, 238, 240, 243, 244, 245, 246, 248, 251, 252, 253, 254, 256, 259, 262, 263, 264, 266, 272, 273, 285, 291, 295, 296, 301, 304, 305, 306
Different cost per day	4, 10, 13, 37, 51, 85, 87, 115, 147, 153, 168, 194, 208, 218
Different cost per skill	4, 10, 14, 35, 37, 62, 128, 136, 147, 152, 153, 192, 204, 208, 229, 247, 248, 251, 256, 266, 272, 285, 305, 306
Overtime cost	33, 37, 38, 51, 60, 61, 82, 91, 93, 94, 112, 121, 122, 128, 144, 152, 155, 157, 176, 192, 193, 194, 202, 204, 206, 210, 253, 263, 264, 266, 291, 295, 296, 301
Outsource/Casual workers cost	33, 35, 37, 38, 51, 58, 60, 61, 85, 112, 121, 122, 127, 152, 168, 176, 192, 202, 204, 206, 263, 291, 295, 297, 298, 299, 300
Travel cost	83, 110, 120, 121, 122, 124, 144, 242, 251, 252, 253
Cost of executing tasks	37, 45, 46, 84, 91, 93, 97, 98, 104, 105, 127, 128, 153, 180, 202, 206, 208, 210, 229, 247, 251, 252, 253, 265, 288
Other costs	4, 16, 29, 37, 87, 91, 93, 110, 128, 153, 174, 192, 193, 248, 252, 254, 267, 305

The category of financial measures entails different costs (Table 9), such as personnel cost (regular wages), a cost depending on the day of the week (e.g., increased wage for weekend days), different cost per skill category (e.g., greater remuneration for a highly-skilled workforce), overtime cost, outsource cost, travel cost, cost or profit derived from carrying out various tasks and other costs. Minimizing personnel cost is closely related to minimizing the number of employees, but has more possibilities. When using personnel cost rather than the explicit number of employees, one can make a trade-off between hiring employees, overtime, casual workers, etc., by assigning a (relative) cost to all of these factors. The wider range of possibilities contributes to the popularity of this latter performance measure compared to the minimization of the number of employees. Helber and Henken [153] present a profit-oriented shift scheduling approach for inbound contact centers. The realized profit is influenced by the wage of the agents of a certain class working a specific shift (i.e., day and skill dependent), the line cost per period for a customer in the system (other costs) and the revenue for each processed customer (cost of carrying out tasks). Another example of incorporating multiple labor expenses is given by Brunner et al. [61]. They present a methodology to solve the flexible shift scheduling problem of physicians. The objective is to minimize the total assignment cost subject to individual contracts and prevailing labor regulations. The total assignment cost addressed in dealing with this problem consists of paid out time, planned overtime and the use of outside resources to cover shortfalls in coverage. Chen et al. [85] explicitly charge costs, on top of the crew salary and regular manpower cost per man-hour for different departments, for any surplus man-hour supply exceeding demand. Similarly, a cost is added for every temporary man-hour supply provided in order to deal with insufficient manpower for the departments. The authors do not restrict themselves to the costs we have discussed so far. Bagatourova [29], for instance, offers the possibility of adding penalty costs for missed deadlines. Li et al. [192] incorporate hiring costs when employing extra workers. In addressing their personnel scheduling problem for assembly lines, Sabar et al. [252] allow workers to move between workstations in order to fulfill specific assembly tasks. The proposed approach also considers the possibility of assigning employees to secondary activities, which could generate net revenue, when the employees are not assigned to an assembly workstation. Other costs are for example production costs [93], costs of missing calls [193] or missed production [128], training costs [128], different costs for a full-time or part-time employee [87], rejection costs [174], different costs per location [37], etc.

Table 10: Balance.

9, 10, 11, 17, 19, 26, 27, 28, 30, 49, 72, 79, 86, 89, 108, 112, 113, 120, 121, 122, 130, 131, 137, 146, 148, 151, 154, 158, 159, 163, 182, 183, 184, 196, 201, 202, 203, 204, 211, 214, 221, 226, 227, 236, 249, 251, 254, 274, 277, 278, 281, 282, 283, 285, 304

In personnel scheduling problems, the operators often want to create fairness in the work environments for different workers. Therefore, they try to balance dissimilarities between the workers. Table 10 lists the papers that incorporate balancing constraints. Most papers model these balancing constraints as soft constraints, except for [79] and [249]. Lucic and Teodorovic [196] develop a metaheuristic approach to the aircrew rostering problem. In their model they want to minimize the average relative deviation (per crew member) of the real monthly flight time from the ideal. Other balance constraints involve an equal number of weekend days spent outside the home, an equal number of departures before 7 A.M., etc. Lezaun et al. [184] balance between workers and between shifts when rostering employees in a rail passenger network. On the one hand, they want to distribute a driver’s morning, evening and night shifts and Sundays off evenly over the year. On the other hand, shifts should be distributed in an egalitarian fashion. At the end of the year, drivers should have been assigned a similar number of working days and hours, morning, evening and night shifts and Sundays off. Besides balancing the workload, the time between consecutive assignments or the number of assignments to a specific shift, one could also consider balancing the treatment of employee preferences. In the multiple shift scheduling problem of a hierarchical workforce with multiple work centers of Al-Yakoob and Sherali [10], the employees expressed preferences for specific shifts, work centers and weekly off-days. They formulate a mixed integer programming model that determines a minimum-cost workforce mix of the categories of employees needed to satisfy the specified demand requirements and to assign the selected employees to shifts and work centers while specifying their off-days based on their stated preferences.

Table 11: Preferences.

4, 17, 19, 25, 33, 47, 50, 54, 56, 65, 70, 71,120, 124, 138, 144, 173, 189, 195, 202, 203, 222, 229, 242, 243, 251, 252, 263, 274, 279, 284, 287, 295, 296

The granted personnel requests are not only being balanced, they could also come as separate soft constraints. A willingness of working together with (or separate from) a specific worker, the difference to preferred work duration, preferences towards a specific work location, days or shifts, etc., are examples of such preference constraints (Table 11).

Table 12: Time-related constraints[2].

	Hard	Soft
Max # assignments	4, 9, 10, 11, 26, 27, 28, 35, 36, 38, 39, 47, 49, 58, 62, 69, 74, 77, 88, 103, 104, 108, 113, 120, 137, 138, 146, 148, 151, 154, 156, 157, 159, 170, 181, 183, 184, 185, 187, 192, 196, 200, 203, 204, 207, 208, 212, 213, 231, 237, 240, 243, 248, 256, 261, 262, 278, 295, 296	25, 34, 40, 41, 44, 54, 56, 65, 70, 71, 134, 142, 143, 187, 188, 195, 199, 201, 219, 220, 222, 226, 238, 278, 284
Min # assignments	26, 50, 137, 156, 228, 262, 296	2, 44, 187, 199, 201, 231
Max # assignments to a shift type	16, 26, 38, 39, 47, 50, 61, 74, 103, 105, 108, 113, 134, 138, 144, 147, 151, 171, 181, 187, 198, 200, 202, 203, 204, 207, 208, 237, 239, 281	43, 53, 56, 60, 70, 71, 72, 188, 199, 201, 207, 213, 231, 236, 274, 282, 287
Min # assignments to a shift type	120	201
Max # consecutive days	9, 10, 11, 13, 14, 15, 19, 26, 34, 38, 39, 41, 47, 49, 50, 64, 74, 77, 86, 87, 88, 113, 115, 119, 131, 134, 136, 146, 151, 166, 167, 181, 183, 184, 187, 191, 194, 196, 198, 200, 202, 203, 204, 211, 214, 228, 237, 238, 239, 243, 247, 249, 254, 262, 272, 282, 285, 306	4, 25, 38, 43, 53, 54, 56, 65, 69, 70, 71, 72, 74, 126, 134, 187, 188, 195, 199, 201, 207, 222, 274, 279, 284, 287, 294
Min # consecutive days	113, 131, 146, 166, 167, 173, 181, 183, 185, 198, 200, 204, 211, 214, 243, 261, 285	25, 26, 38, 39, 43, 53, 54, 56, 65, 69, 70, 71, 72, 74, 86, 134, 137, 184, 187, 188, 195, 199, 201, 204, 207, 222, 237, 239, 284, 287
Max # consecutive days off	38, 47, 86, 92, 158, 166, 183, 197, 200	25, 54, 56, 65, 70, 71, 72, 134, 144, 166, 167, 188, 195, 199, 204, 222, 284, 287
Min # consecutive days off	13, 27, 28, 64, 79, 92, 93, 95, 113, 115, 154, 158, 166, 171, 173, 183, 185, 189, 194, 197, 200, 208, 247, 304	4, 25, 26, 34, 38, 39, 43, 54, 56, 65, 69, 70, 71, 72, 74, 86, 126, 137, 148, 167, 188, 195, 199, 207, 222, 237, 238, 239, 261, 281, 284, 287
Max # hours & overtime	1, 4, 6, 7, 15, 16, 19, 27, 28, 29, 30, 33, 34, 36, 37, 38, 39, 41, 51, 60, 61, 69, 76, 77, 88, 89, 91, 92, 93, 94, 97, 98, 103, 104, 105, 109, 112, 114, 116, 121, 122, 124, 134, 135, 144, 151, 152, 154, 159, 170, 174, 176, 180, 182, 185, 186, 191, 192, 196, 197, 200, 202, 204, 208, 209, 210, 212, 213, 216, 218, 230, 231, 237, 238, 239, 240, 244, 246, 249, 252, 253, 258, 265, 266, 281, 283, 285, 287, 290, 291, 295, 296, 301, 303, 306	19, 27, 28, 43, 44, 53, 56, 70, 71, 72, 141, 148, 158, 173, 188, 220, 226, 279, 298, 299, 300
Min # hours	6, 19, 29, 38, 60, 76, 91, 92, 93, 94, 97, 103, 109, 124, 151, 157, 180, 191, 197, 208, 218, 238, 240, 249, 252, 253, 258, 266, 295, 306	19, 38, 43, 53, 56, 70, 71, 72, 141, 158, 173, 178, 188, 220, 226, 279
Days/shifts on/off	19, 38, 45, 46, 49, 74, 76, 83, 86, 89, 90, 94, 134, 138, 143, 154, 162, 173, 187, 203, 208, 212, 213, 231, 236, 249, 253, 277, 294, 306	3, 4, 5, 6, 9, 10, 11, 25, 28, 29, 30, 33, 43, 44, 45, 46, 49, 50, 53, 54, 56, 60, 65, 69, 70, 71, 72, 79, 120, 121, 122, 124, 130, 137, 138, 141, 144, 147, 151, 156, 158, 182, 183, 188, 189, 190, 195, 198, 199, 201, 202, 203, 204, 209, 213, 222, 228, 231, 249, 251, 258, 263, 274, 278, 282, 284, 287, 295, 296, 301
Time between assignments	16, 19, 26, 30, 38, 51, 58, 60, 61, 62, 69, 76, 77, 86, 89, 103, 104, 110, 120, 126, 134, 135, 138, 144, 151, 171, 181, 182, 184, 200, 202, 203, 204, 208, 212, 213, 216, 218, 227, 231, 236, 249, 253, 258, 261, 262, 263, 281, 287, 291, 295, 296, 303, 304	49, 53, 56, 130, 201, 207, 239, 274

[2] Papers could be listed in both columns of the table, concerning different employee types, different time intervals, different shift types, soft intervals and hard upper/lower bounds, hard constraints versus preferences, etc.

Patterns, consecutive shifts and sequence of shift type	3, 4, 9, 11, 30, 47, 49, 61, 64, 84, 103, 106, 113, 116, 121, 122, 126, 131, 134, 137, 138, 144, 146, 147, 148, 151, 171, 173, 181, 183, 184, 185, 187, 190, 191, 198, 199, 200, 202, 203, 207, 211, 212, 213, 214, 228, 231, 236, 239, 249, 258, 267, 282, 285	26, 38, 39, 43, 44, 49, 53, 56, 69, 70, 71, 72, 74, 89, 126, 134, 144, 146, 148, 151, 187, 188, 199, 204, 236, 237, 239, 261, 274, 277
Free days after night shift	49, 61, 69, 74, 151, 185, 187, 204, 239, 263	25, 49, 54, 56, 65, 70, 72, 86, 188, 195, 222, 239, 284
Max # weekends in # weeks	9, 10, 11, 13, 19, 26, 38, 39, 69, 74, 103, 134, 147, 167, 181, 184, 185, 187, 200, 204, 208, 237, 239, 247, 287, 296, 304	25, 43, 53, 54, 56, 65, 70, 71, 72, 148, 188, 195, 207, 222, 277, 278, 279, 284, 294, 295
Complete (and extended) weekends	39, 50, 113, 151, 173, 181, 185, 204, 237, 249	19, 25, 34, 38, 43, 54, 56, 65, 69, 70, 71, 72, 74, 86, 134, 144, 148, 151, 187, 188, 195, 207, 222, 238, 239, 277, 281, 284, 287
Max # consecutive weekends	151, 183, 204, 227	25, 43, 53, 54, 56, 65, 70, 72, 188, 195, 222, 284
Identical weekends	204	25, 54, 56, 65, 70, 71, 72, 195, 222, 284
Time windows and deadlines	7, 17, 76, 83, 90, 108, 124, 127, 135, 162, 163, 176, 177, 182, 206, 216, 221, 242, 244, 253, 255, 265, 297	15, 77, 90, 109, 162, 206, 251, 283, 301
Resource-related	51, 83, 91, 93, 147, 158, 168, 210, 221, 242, 302, 305	9, 11, 141, 158, 255
Ratio groups of personnel	6, 14, 34, 35, 36, 41, 58, 64, 87, 105, 146, 152, 165, 170, 176, 236, 238, 248, 266, 272, 291, 295	

The idea of using time-related constraints rather than categorizing the constraint according to a tour scheduling or shift scheduling classification, originates from Brucker et al. [56], when representing all the constraints that appeared when introducing benchmarks in dealing with the nurse scheduling problem. They created a number of problem instances, with different subsets of these constraints.

One way of making the schedule attractive to workers is to limit the number of assignments per day (e.g., the number of jobs done per day, which comes down to limiting the number of switches per worker) or per week (typically the number of active shifts per week is limited). Instead of limiting the number of assignments, often a minimum number of consecutive free days is enforced (for instance [9, 11, 158]). Since the maximum number of hours that an employee is allowed to work per week is typically limited by regulations, this measure is actually applied to avoid employees being scheduled for many short shifts. In order to ensure a minimum variation in a worker's shift pattern, a constraint can be set on the number of assignments to a specific day or shift.

Organizations frequently impose limits on the number of consecutive working and non-working shifts. The lower limit of consecutive (non-)working shifts ensures that workers do not have to switch too often from working to non-working patterns. This lower limit is mainly used to avoid the existence of a single working shift between two non-working shifts (or a single non-working shift between two working shifts), which is considered undesirable by the personnel. Another constraint based on consecutiveness is a maximum number of consecutive assignments to the same shift type.

The most popular time-related soft constraints are those that consider consecutive (non-) working shifts. Whereas a measure such as the maximum number of hours worked is usually dictated by official regulations (i.e., hard constraints), the modification of the maximum and minimum number of consecutive shifts is less restricted. When doing so, one has to take into account employee satisfaction, as the minimum number of consecutive working and non-working shifts is related to single stand-alone shifts, which are considered undesirable.

Aside from official regulations, organizations themselves can also impose hard constraints on the (regular) number of hours an employee is allowed to work per day or/and per week/month. If regular work hours do not suffice to cover all the workload, the organizations can switch to overtime, but the use of overtime is often restricted. In the personnel scheduling problem at USPS mail processing and distribution centers of Bard et al. [34-36, 40, 41, 238, 291], for instance, the use of overtime is restricted to 6% of the total number of hours worked.

Days on/off and shifts on/off refer to problems where the workers have announced that they will not be available on specific days/shifts (i.e., the label “Days off” addresses the papers in which the user is asked to deliberately consider holidays of the personnel or requests for days off, which is a restriction on assigning an employee to a specific day, whereas “Max # consecutive days off” considers the regular rest days after a working period). With this in mind, the scheduler has to consider other workers to solve the coverage problems.

When a worker has to change from one shift type to another, one has to make sure that the specific pattern is allowed. When a worker works late one day, (s)he will not be thrilled to start early the next day and one wants to ensure a minimum rest time between assignments. For this reason, some shift type successions will not be tolerated. These restrictions can be modeled by allowing the user to choose from a predefined set of patterns, by prohibiting certain shift sequences, by ensuring a minimum time between consecutive assignments or shifts, etc.

Weekends are quite important for workers and organizations have to be thoughtful when scheduling weekend days. The most popular of the set of weekend constraints is the creation of complete weekends. Employees prefer to work one full weekend with the knowledge they have another weekend off, rather than working two weekends for a single day. Another constraint is the limit set upon the number of allowable weekends within a planning period, and even the number of consecutive weekends could be restricted. Knust and Schumacher [173] combine the complete weekend constraint with the restriction that no single active shift is allowed in the shift scheduling for tank trucks. When a worker has Tuesday off, (s)he is not allowed to work on Monday, i.e., an enlarged weekend off is enforced.

Task are often scheduled by adding hard or soft constraints that create a time window during which the execution is allowed. One could also add a soft constraint to minimize the makespan or to make sure that all jobs are finished before a given deadline.

Workers or jobs may require specific resources, which are not always available. Zhu and Sherali [305] have to schedule workers on the basis of a limited number of desks. In other scheduling instances, restrictions correspond to the number of resources [221], the number of machines [210], the available tools [168], etc. A special constraint is used in the personnel scheduling approach of Yaoyuenyong and Nanthavanij [302] which emphasizes the health and safety issues of workers. Depending on the energy costs of required tasks, the number of workers who can be safely assigned to perform the tasks on a rotational basis might have to be greater than the number of tasks. The energy-based personnel scheduling arrangement is intended to find the minimum number of workers and their daily work assignments such that their working energy capacities are not exceeded.

In some situations, ratios between groups of workers are added as a constraint to make sure that the relative share of the workforce does not become too large. In the nurse scheduling problem of Wright and Bretthauer [295], the number of float nurses is restricted as compared to the regular workforce. Heimerl and Kolisch [152] add a constraint to ensure that a minimum ratio exists between the work performed by internal and by external resources.

Besides minimizing crew costs and ensuring fairness to all regular crew members regarding the workload, the aircrew rostering problem in Maenhout and Vanhoucke [202] also takes into account crew members' preferences for certain roster attributes. The crew members not only express their preferences for specific pairings and reserve duties, but also for more general scheduling preferences such as the moment (day/time) they want to be scheduled.

Aside from the soft constraints or performance measures illustrated so far, researchers have defined many others, such as the minimization of the possibility of getting injured from doing a specific job sequence [223], profit maximization [153], the maximization of the net present value [136], the minimization of the (mean) lateness of the completion of tasks [109, 301], minimizing the permitted number of distinct shift types [1, 2, 107, 131, 211, 214], maximizing employee satisfaction [138], minimizing service criteria (e.g., waiting time and probability of waiting in a call center environment [119], length of stay of patients in a hospital [259]), minimizing travel distance [7, 185], maximizing fleet availability [255], etc.

It is noteworthy that most authors develop a multi-objective model for the personnel scheduling problem. When developing a personnel schedule, one has to consider a group of stakeholders, each with their own priorities. The organization itself, for instance, wants to cover the workload at minimum cost. The operations manager could insist on limiting the number of casual workers to ensure continuity and the availability of knowhow. The importance of every priority has to be determined in order to combine them all into one objective function by assigning a weight factor to all of them.

In this section, we have shown that personnel scheduling problems come in many variations regarding the hard and soft constraints. The effect of those constraints on the complexity, however, has barely been studied. Brucker et al. [57] present mathematical models which cover specific aspects in the personnel scheduling literature and address complexity issues by identifying polynomial solvable and NP-hard special cases. Nevertheless, the effect on the complexity of many characteristics is still unclear. We think a dedicated theoretic exploration benefits the development of well-suited algorithms to deal with the numerous constraints.

4. Solution method and uncertainty incorporation

The literature on personnel scheduling exhibits a wide range of research methodologies that combine a certain type of analysis with some solution or evaluation technique. A large number of papers are classified into mathematical programming categories such as integer programming, linear programming, dynamic programming, goal programming, etc., or as constructive or improvement heuristics (Table 13). Other categories are simulation, constraint programming and queuing. In "Other", we classify the less frequent solution methods such as piecewise linear approximation [245], analytical hierarchy process (AHP) [192, 277, 278], spreadsheet models [227], DEA [80], etc. Usually they are used to find the minimal staff size in solving small problems, to analyze demand patterns or to roster personnel members by hand after the optimal shift patterns have been computed.

Table 13: Solution technique.

Mathematical programming		
	Linear programming	51, 81, 82, 94, 110, 128, 149, 155, 157, 163, 192, 197, 226, 288
	Goal programming	26, 88, 138, 159, 187, 258, 277, 279, 306
	Integer programming	13, 14, 33, 34, 37, 40, 41, 74, 77, 87, 95, 104, 106, 112, 113, 116, 119, 126, 158, 166, 167, 168, 183, 184, 185, 193, 194, 209, 210, 212, 223, 227, 229, 238, 247, 249, 256, 267, 273, 284, 296, 302, 304, 305, 306
	Mixed integer programming	9, 20, 21, 22, 23, 24, 27, 35, 36, 52, 60, 76, 85, 91, 92, 93, 96, 97, 98, 103, 120, 127, 134, 135, 152, 153, 154, 162, 164, 165, 169, 170, 171, 173, 186, 191, 204, 216, 230, 235, 246, 248, 251, 252, 253, 255, 257, 259, 262, 263, 264, 266, 278, 281, 290, 295, 298, 299, 300, 303
	Column generation	11, 38, 62, 104, 105, 110, 151, 216, 244, 253, 304
	Branch-and-price	16, 37, 45, 46, 47, 58, 61, 65, 66, 104, 113, 182, 201, 204, 218, 237, 242, 261, 285
	Dynamic programming	46, 110, 115
	Lagrange relaxation	39, 235
Constructive heuristic		10, 19, 28, 29, 35, 36, 40, 56, 60, 61, 69, 72, 75, 79, 80, 90, 106, 107, 114, 121, 122, 135, 136, 137, 141, 156, 157, 159, 162, 166, 180, 189, 195, 208, 213, 223, 240, 245, 246, 253, 265, 296
Improvement heuristic		
	Simulated annealing	6, 90, 124, 136, 158, 196, 272, 274
	Tabu search	30, 40, 49, 50, 64, 72, 76, 89, 104, 107, 109, 114, 116, 124, 131, 163, 180, 186, 196, 214, 215, 258, 265, 294
	Genetic algorithm	2, 3, 4, 5, 18, 30, 44, 69, 114, 130, 141, 147, 190, 196, 200, 202, 203, 211, 213, 231, 236, 254, 282, 283, 287, 297, 306
	Other	3, 6, 7, 17, 19, 21, 22, 23, 25, 38, 39, 43, 49, 52, 53, 54, 56, 65, 66, 67, 70, 71, 74, 81, 83, 86, 89, 107, 109, 131, 137, 139, 142, 143, 144, 148, 164, 174, 176, 177, 178, 179, 180, 187, 188, 189, 195, 198, 199, 202, 207, 208, 214, 215, 219, 220, 221, 228, 230, 235, 237, 243, 245, 246, 258, 260, 284, 287, 290, 291, 294, 302
Simulation		15, 20, 21, 22, 23, 24, 29, 52, 80, 81, 103, 110, 119, 136, 139, 144, 149, 153, 170, 193, 210, 221, 223, 238, 245, 246, 254, 257, 259, 289, 300, 301
Constraint programming		76, 84, 89, 97, 98, 105, 124, 151, 181, 186, 207, 222, 239, 281, 304
Queuing		14, 22, 80, 108, 119, 139, 140, 164, 174, 289, 296
Other		34, 80, 84, 119, 161, 166, 192, 193, 206, 227, 246, 277, 278

Mathematical programming approaches group most of the considered solution methods. In these approaches, the personnel scheduling problem is modeled as a linear, integer or mixed integer program. The set covering formulation for the general shift scheduling problem, introduced by Dantzig (Section 1), is still very popular among researchers. This formulation permits researchers to add a number of constraints based on their own particular needs. Many of these variations to the set-covering model tend to create linear integer programs with a huge number of variables. As discussed by Ernst et al. [118], researchers are used to trying to overcome these large scale formulations by decomposition techniques and heuristic algorithms.

Several large-scale problems benefit from a decomposition method in solving the problem. Decomposition methods essentially consider the problem in two parts, one with the “easy” and one with the more “complicating” constraints. Detienne et al. [106] present two cut generation based approaches for a particular employee timetabling problem. One cut generation scheme is used for heuristic resolution and the other for exact resolution. The exact cut generation scheme is based on applying Benders' decomposition, where the relaxed master problem is a multi-dimensional multi-choice knapsack problem and every sub-problem is a b-matching problem. Bard and Wan [41] develop a multi-stage approach to determining the optimal size and composition of a permanent workforce needed to run a facility. One of the alternatives is based on the idea of partitioning the workstation groups into manageable clusters and then solving them in series. In a second paper [40], they study the task assignment problem and develop a solution method that decomposes the full problem into seven daily IP sub-problems in order to obtain greater computational tractability. A similar approach is followed by Brunner et al. [60], who decompose the shift scheduling problem of physicians into weekly segments.

When column generation is applied, large linear programming models can be solved to optimality without holding all columns (variables) in the model at once. Column generation establishes a lower limit to the solution which is guaranteed to be LP optimal. In each iteration, a linear program with only a small subset of the decision variables, known as the restricted master problem, is created. Using the current dual vector, a pricing sub-problem is solved to identify variables that may potentially improve the current solution based on their reduced costs. Branch-and-price algorithms combine an LP-based branch-and-bound algorithm with a column generation algorithm to solve each LP relaxation. To take advantage of the column generation approach, the pricing sub-problems should be easy to solve quickly and branching rules should not destroy the structure of the pricing sub-problem [218]. Beliën and Demeulemeester [47] show how the column generation technique, often employed for solving nurse scheduling problems, can easily be extended to integrate building both nurse and surgery schedules. The approach involves the solution of two types of pricing problems. In a second paper, Beliën and Demeulemeester [46] present two ways of decomposing a staff scheduling problem by using column generation. In the first approach, decomposition takes place on the staff members, whereas in the second approach decomposition takes place on the activities that have to be performed by the staff members. In [113], Eitzen et al. present a model for the generation of personnel rosters for a very general class of non-hierarchical skill level situations. Since the number of possible tours may exceed memory capacity requirements, they compare a branch-and-price method with a reduced column subset and column expansion method in order to generate cost-effective solutions. Branch-and-price methods have also been applied to schedule feasible trips carried out by train drivers [16], general personnel scheduling problems [261], nurse scheduling problems [201], etc.

In addition to these decomposition methods, authors have used other exact methods to tackle the difficult (mixed) integer programming problem. Adding strong valid inequalities can be very effective in reducing the optimality gap [126]. Besides adding cutting plane inequalities, it can be worth the effort to design special branching rules [126] or tighter LP-bounds [152] through problem reformulation or cutting plane inequalities.

Not all problems related to personnel scheduling are modeled with a set-covering formulation. Jarray [167] presents an exact decomposition approach for an employee days off scheduling problem in relation to a homogeneous workforce. A three-step decomposition method is used to obtain the work assignments, while respecting the labor demands and a pre-specified number of workdays per employee over the planning horizon. The rests assignment corresponds to the feasible flow problem on a bipartite network. Moz and Pato [212] solve the problem of rerostering nurse schedules with a new multi-commodity flow model, a model shared by Cappanera and Gallo [77] in order to find a work assignment for airline crew members within a given time horizon. Other maximum flow problems can be found in [95, 166].

Metaheuristics form an important class of solution methods used to solve the personnel scheduling problem. Metaheuristics are designed to tackle complex optimization problems where other optimization methods have failed to be either effective or efficient. The practical advantage of metaheuristics lies in both their effectiveness and their general applicability. The effectiveness lies in the production of reasonably good feasible solutions within a limited amount of running time, whereas mathematical programming techniques run the risk of not returning any feasible solution for a long time. However, using metaheuristics also results in a number of drawbacks, since they cannot demonstrably produce optimal solutions nor can they demonstrably reduce the search space [74]. Researchers tend to prefer tabu search and genetic algorithms to the use of simulating annealing algorithms. In addition to these three general classes, a lot of alternative heuristics have been developed for dealing with the personnel scheduling problem: scatter search [70, 179, 198, 202], iterated local search [49, 71], variable neighborhood search [74, 207], particle swarm optimization [7, 142, 219], memetic algorithms [228], electromagnetic meta-heuristics [199], neural networks [148], ant colony optimization [144], greedy random adaptive search procedure (GRASP) [137], hill-climbing [89], hyper-heuristics [83], etc.

When simulation is used in personnel scheduling problems, researchers favor discrete event simulation (DES) over Monte Carlo simulation. Simulation methods can help researchers to validate their deterministic optimization approaches, to estimate labor requirements, etc. Harper et al. [149] use both simulation and optimization to define the size and skill-mix of nursing teams. Outputs from the three-phase discrete event simulation are fed into a stochastic program which suggests the optimal number of nurses to employ (whole time equivalents) according to skill-mix and the corresponding numbers according to shift. Qi and Bard [238] present a workforce simulation system designed to help management understand both the flow of mail through a mail processing work center and the consequent need for labor. The system couples simulation with optimization in an iterative fashion. Yang et al. [301] examine an environment where both cross training and flexible workdays are available to respond to workload variability. They use Monte Carlo simulation in order to simulate the operation of a job shop with both cross training and flexible workdays.

The highly constrained personnel scheduling problem offers an ideal framework for the use of constraint programming methods. These methods originate from Artificial Intelligence research and are exact methods that guarantee feasible solutions for constraint satisfaction problems or optimal solutions for constraint optimization problems. Côté et al. [98] use constraint programming and integrate it with mixed integer programming models in order to express constraints over sequences of decision variables, represented as a network flow problem. Other formal languages for integer programming formulations of shift scheduling problems are presented in [97]. In [105], constraint programming is combined with column generation and a new optimization constraint is introduced. Qu and He [239] apply a hybrid constraint programming approach to a nurse rostering problem. They decompose the problem into weekly sub-problems, modeled as a constraint satisfaction problem. Then an iterative forward search is used to extend the sub-solutions to form complete solutions. In the second stage, a variable neighborhood search is used to further improve the solution. Constraint programming algorithms can also be used for the construction of rotating schedules [181].

Queuing methods mainly occur in call center applications [14, 80, 119, 289], where they are used to determine call center staffing levels to satisfy specific service-level criteria. Wallace and Whitt [289] develop an algorithm based on queuing methods and simulation for both routing and staffing, aiming to minimize the total staff. Alfares [14] prefers a queuing model over simulation methods to estimate hourly staffing demands. An IP model is then constructed to find the optimum employee tour schedules that satisfy labor requirements with minimum cost.

The considered solution techniques can also be combined to increase the efficiency of the approach. A nice example is given in the paper of de Matta and Peters [104]. They study the problem of finding the mix of primary and secondary jobs in short term work schedules to meet, at minimum cost, the daily service requirements of an inter-city bus transit firm in India. The problem is formulated as a set-covering model with resource allocation constraints. The number of columns (integer variables) representing all potential feasible work schedules can be extremely large. By employing the column generation method, the linear programming relaxation of the master problem can be solved optimally. The pricing problem, used to generate new columns, is a resource-constrained shortest path problem. They decompose the pricing problem into a number of sub-problems, one per driver category. The procedure used to solve the pricing problem is a heuristic procedure, combining Lagrangian relaxation and tabu search. Burke et al. [74] present a hybrid model of integer programming and variable neighborhood search (VNS) for highly-constrained nurse rostering problems. The IP is used to solve a sub-problem including all hard constraints and a subset of soft constraints. The VNS is then used as a post-processing improvement procedure. The satisfaction of the constraints that are not included in the subset would be the major concern in designing the VNS's neighborhood structures. Li and Womer [186] describe a hybrid decomposition algorithm that incorporates constraint programming and a tabu search metaheuristic for solving the NP-hard project scheduling problem with multi-purpose resources where multi-skilled sailors form teams to accomplish interrelated onboard tasks.

One classification field that has not been discussed in any of the review papers is the incorporation of uncertainty. Deterministic staffing and scheduling approaches ignore every form of uncertainty, whereas stochastic approaches try to incorporate it. In our classification, we define three main categories of uncertainty:

- Uncertainty of demand: indicates the unpredictable workload. For example, in a maintenance division, one does not know upfront how long it will take to fix a certain problem. Other examples are the length of calls in a call center, the number of patients in a hospital, etc.;
- Uncertainty of arrival: points at the unpredictable arrival pattern of the workload. This includes, for instance, the distribution of failures over time of a specific machine (part) or the arrival of calls;
- Uncertainty of capacity: represents deviations between the planned and the actual manpower.

In Table 14, we list the relevant manuscripts based on their uncertainty incorporation.

Table 14: Uncertainty incorporation.

Deterministic	2, 3, 4, 5, 6, 7, 9, 10, 11, 13, 16, 18, 19, 25, 26, 27, 28, 30, 33, 34, 35, 37, 38, 39, 40, 41, 43, 44, 45, 46, 47, 49, 50, 51, 53, 54, 56, 57, 58, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 76, 77, 79, 82, 83, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 104, 105, 106, 107, 109, 112, 113, 114, 115, 116, 120, 121, 122, 124, 126, 127, 128, 130, 131, 134, 135, 137, 138, 141, 142, 143, 145, 146, 147, 148, 151, 152, 154, 155, 156, 157, 158, 159, 161, 162, 163, 165, 166, 167, 169, 171, 173, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 194, 195, 196, 198, 199, 200, 201, 202, 203, 204, 207, 208, 209, 211, 212, 213, 214, 215, 216, 218, 219, 220, 221, 222, 226, 227, 228, 229, 230, 231, 236, 237, 239, 240, 242, 243, 244, 247, 248, 249, 251, 252, 253, 256, 258, 260, 261, 262, 263, 264, 265, 266, 267, 273, 274, 277, 278, 279, 281, 282, 283, 284, 285, 287, 288, 290, 291, 295, 296, 297, 298, 299, 302, 303, 304, 306
Stochastic	
Demand	14, 15, 20, 21, 22, 23, 24, 29, 36, 52, 75, 80, 81, 84, 85, 108, 110, 119, 136, 139, 140, 144, 149, 153, 164, 168, 170, 174, 193, 197, 206, 210, 223, 235, 238, 245, 246, 254, 255, 259, 272, 289, 300, 301, 305
Arrival	14, 15, 20, 21, 22, 23, 24, 29, 52, 75, 80, 81, 84, 85, 108, 110, 119, 136, 139, 140, 144, 153, 164, 174, 193, 206, 235, 238, 254, 255, 259, 272, 289, 300, 301
Capacity	14, 29, 206, 257, 301

The vast majority of the manuscripts ignores all types of uncertainty and uncertainty in capacity in particular. This does not mean that one considers the workload to be constant over periods. In a large number of the included manuscripts, the workload is estimated based on historical data. These estimation methods have received much attention in the literature as well. However, when studying personnel scheduling problems, the stochastic component is often dropped. One way to deal with a variable workload in a deterministic environment is by adding capacity buffers to make personnel rosters more robust. Another frequently applied method is the creation of a set of test instances with different parameters (number of skills per person, demand, capacity) which are used to perform a sensitivity analysis on those parameters (see for example [13] and [152]).

Researchers hardly ever take into account the unpredictable presence of workers due to illness, arrival delay or the loss of capacity caused by a resource that is out of service [210], when scheduling employees. In Yang et al. [301], the availability of skilled workers is uncertain in the sense that they can decide whether they want to replace a day off by a day of overtime. They model the decision by presuming a 50% chance that a worker says yes (or no).

Uncertainty of arrival is mainly of interest in call center systems and is always coupled with uncertainty in demand (or duration). An example of a problem that uses these two sources of uncertainty is given by Campbell [75]. He develops a two-stage stochastic program for scheduling and allocating cross-trained workers in a multi-department service environment with random demands. The two stages correspond to two different planning periods. In the first stage a worker gets assigned days off over a time horizon of a week or a month. The second stage deals with allocating available workers at the beginning of a day to accommodate realized demands. Yan et al. [300] use a stochastic model to incorporate the disturbances of manpower demands that occur in actual operations. They deal with the uncertainty by solving a mixed integer linear program and evaluating its performance with a simulation-based method. In fact, in more than 65% of the manuscripts with a stochastic component, a simulation-based method is used.

5. Application area and applicability of research

We distinguish between six application areas: services, transportation, general, manufacturing, retail and military personnel scheduling problems. When no application area is mentioned in the text, we considered the paper to be “general”.

In Table 15 we list the relevant manuscripts classified according to the type of application area. Among the less frequent service application areas, classified as “Other”, we find organizations such as restaurants [87], supermarkets [208], festivals [138], parking lots [244], etc.

Table 15: List of papers per application area.

Services		
	General	17, 29, 35, 58, 75, 90, 92, 94, 127, 139, 157, 159, 161, 162, 169,192, 206, 216, 254, 257, 265, 273, 283, 287, 305
	Nurse	3, 4, 5, 6, 19, 25, 26, 30, 33, 37, 38, 39, 44, 47, 49, 50, 53, 54, 56, 65, 66, 69, 70, 71, 72, 74, 86, 103, 107, 134, 137, 144, 146, 149, 151, 187, 188, 189, 190, 195, 198, 199, 201, 203, 204, 207, 212, 213, 222, 228, 231, 237, 239, 249, 254, 260, 274, 279, 281, 282, 284, 295, 296, 303
	Other health care	7, 45, 46, 60, 61, 62, 79, 89, 120, 121, 122, 124, 140, 163, 165, 191, 226, 227, 236, 263, 278, 285, 294
	Protection/Emergency	116, 130, 139, 171, 259, 277
	Call Centre	14, 19, 20, 21, 22, 23, 24, 52, 76, 80, 81, 108, 119, 139, 153, 156, 164, 193, 235, 245, 246, 289
	Other	87, 138, 152, 158, 174, 176, 180, 186, 208, 242, 244, 255, 297
Transportation		
	General	2, 135, 141, 142, 143, 173, 182, 183, 219, 254
	Airline	19, 64, 77, 88, 110, 179, 196, 202, 248, 253, 254, 262, 267, 298, 299, 300
	Railway	16, 85, 114, 147, 184, 185
	Bus	104, 304
General		10, 13, 34, 36, 40, 41, 43, 57, 63, 67, 82, 83, 95, 96, 97, 98, 105, 106, 109, 112, 113, 115, 126, 131, 136, 155, 166, 167, 168, 177, 181, 197, 209, 211, 214, 215, 223, 238, 240, 243, 247, 254, 256, 261, 264, 272, 288, 290, 291, 301
Manufacturing		9, 11, 15, 18, 27, 28, 40, 41, 51, 91, 93, 128, 146, 154, 178, 194, 210, 221, 251, 252, 254, 258, 266, 302
Retail		84, 170, 220, 230, 306
Military		158, 180, 186, 255

We can compare our results with the annotated library of Ernst et al. [117]. A notable difference is the share of manuscripts applied to transportation systems. Half of the papers in their library are developed for airline, railway, bus or subway systems. The impact of the transportation sector is limited in our findings, but the other application areas share similarities. Nurse rostering is by far the most popular and personnel rostering problems in services receive more attention than those in a production environment.

In addition to the development of a model or a formulation, researchers usually provide a testing phase to illustrate the applicability of their research. The majority of papers favor real-world based data over theoretical data (Table 16). If it is not clear whether the model was actually implemented, we classify those papers into the set with real-world data. When the research was carried out, the authors hardly ever provided details of the process of implementation or the observed results, although these could have been of interest to the reader. The different stakeholders that are involved in personnel scheduling problems need to be kept satisfied during the implementation process. The problems that come in the wake of this implementation can be similar to problems other authors face in their work. Therefore, we encourage the provision of additional information on the behavioral factors that coincide with actual implementation.

Table 16: Applicability of research.

No testing	57, 96, 288
Theoretical data	6, 9, 10, 11, 13, 38, 45, 46, 47, 49, 61, 63, 75, 86, 91, 92, 94, 95, 97, 98, 105, 106, 107, 114, 124, 126, 128, 135, 144, 145, 152, 153, 155, 156, 158, 161, 163, 164, 166, 167, 168, 174, 180, 186, 189, 193, 197, 198, 199, 202, 203, 206, 209, 215, 216, 223, 228, 229, 240, 243, 251, 252, 257, 261, 266, 272, 273, 278, 283, 285, 289, 290, 297, 301, 302, 303
Real-world data	2, 3, 4, 5, 7, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 33, 34, 35, 36, 37, 38, 39, 40, 41, 43, 44, 45, 46, 47, 49, 50, 51, 52, 53, 54, 56, 58, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 76, 77, 80, 81, 82, 83, 84, 85, 87, 88, 89, 90, 93, 103, 104, 105, 106, 108, 109, 110, 112, 113, 114, 115, 116, 119, 120, 121, 122, 126, 127, 128, 130, 131, 134, 136, 137, 138, 139, 140, 141, 142, 143, 146, 148, 149, 151, 154, 157, 159, 162, 163, 165, 169, 170, 171, 173, 176, 177, 178, 179, 181, 182, 183, 184, 185, 187, 188, 190, 191, 192, 194, 195, 196, 198, 200, 201, 202, 204, 207, 208, 210, 211, 212, 213, 214, 215, 218, 219, 220, 221, 222, 226, 227, 228, 230, 231, 235, 236, 237, 238, 239, 242, 244, 245, 246, 247, 248, 249, 253, 254, 255, 256, 258, 259, 260, 262, 263, 264, 265, 267, 274, 277, 278, 279, 281, 282, 284, 287, 291, 294, 295, 296, 298, 299, 300, 304, 305, 306
Applied in practice	15, 16, 26, 34, 45, 46, 47, 49, 50, 53, 60, 71, 72, 79, 87, 88, 89, 108, 112, 113, 120, 121, 122, 126, 131, 138, 140, 149, 163, 165, 178, 179, 182, 183, 184, 185, 208, 212, 213, 215, 227, 231, 277, 278, 287, 294

We noticed that in many papers the solution approach is only compared (if it is) with a few recent other solution techniques which the researchers had to implement themselves. Preferably, they only consider the problem setting which is the topic of their paper, rather than checking the performance on some benchmark instances. However, many of the considered problem instances look similar. Of course there are differences regarding the constraints and the objectives, but authors really avoid searching for benchmark instances to compare with. There are a few exceptions though. The NRP-competition of the PATAT conference 2010 [150], for example, is an excellent tool to give researchers the opportunity to check the quality of their solution approach concerning a number of different instances. Burke and Curtois [66] compare their solution method to a number of benchmark instances of nurse rostering problems they have collected over the years.

Linked with the previous remark, we want to stress the benefits of a classification notation. De Causmaecker and Vanden Berghe [101] have introduced a classification notation for the nurse rostering problem, which could be extended to the personnel scheduling problem in general. Their classification notation is based on the $\alpha|\beta|\gamma$-notation, which has proven very worthy in the field of resource constrained project scheduling. The widely studied personnel scheduling problem can take advantage of such a classification method, where the constraints, objectives, problem characteristics, etc. are indicated with parameters, allowing researchers to compare their methods with others in a similar problem setting. It can also be suitable to detect some new research areas.

One of the reasons why many research projects do not make it until the implementation in practice is the restrictive problem setting they consider. As we already discussed in Section 2, the personnel scheduling problem is hardly ever integrated with other scheduling problems such as operating room scheduling, machine scheduling, etc. In reality, however, these different scheduling problems interfere with each other on a constant basis. Not only the lack of integration with other scheduling problems undermines the implementation ratio, the low degree of uncertainty incorporation is also one of the main reasons. Most of the researchers do not consider the effect of cancelled tasks, unavailable employees, increased workload, … Researchers should keep in mind that these events have a great impact on the quality of the proposed solutions. Instead of considering these events in the problem setting and trying to cope with them by using stochastic programming, researchers could also study their effects on the robustness of the solutions with a simulation experiment for example. Finally, only a handful of papers cope with these events by personnel (re)scheduling (combined with task assignment), rolling horizon techniques, etc. In the papers of Moz and Pato [212, 213], for example, 68 random test instances are generated to mimic the absence of workers and to test the quality of the solution method, rather than considering distributions to model the absence.

The lack of implementation is not always due to the researchers or the problem setting under consideration. It can be very hard to integrate the proposed algorithm into the software system(s) of the company. This can be restrictive for both the researchers and the company. From the viewpoint of the researchers, it is important to define the proposed algorithm as clearly as possible, so that the company's IT-department is able to integrate all the necessary steps into the software. The shift towards a multi-objective and over-constrained problem setting probably leads to an increased use of self-created hybrid heuristics in comparison to the use of commercial optimization software.

6. Conclusion

In this paper, we have reviewed the literature on personnel scheduling problems. We identified different perspectives from which to classify the existing literature. Each classification choice is exemplified through the citation of key references, tables in which all the references are listed. The main contribution of this review is to facilitate the tracing of published work in relevant fields of interest, as well as identifying trends and indicating areas for future research.

In reviewing the literature, we came up with a number of recommendations for future research. The current literature is mainly focused on the staffing and/or scheduling of workers considering fixed inputs. We advise researchers to integrate multiple decisions into the personnel scheduling problem such as demand forecasting, hiring and firing, machine scheduling, considering multiple locations, etc. Hence, these variables can be controlled for operational advantage. Many characteristics of the personnel scheduling problem are often neglected. This puts a limit on the applicability chances of the solution method, since in real-life problems, these characteristics do appear. Therefore, it would be useful to integrate as many aspects as possible, such as break placement, different skills, flexible worker contracts, … The last decades, companies more and more consider employee preferences (such as requests for specific working days or shifts, assignments to a specific location or working partner, preferred durations or start times) in order to satisfy the workforce and to allow them to flexibly manage their personal lives. The first signs of this increase in flexibility have been remarked in the literature on personnel scheduling, but there are still some great opportunities in finding algorithms that efficiently cope with those preferences.

We have shown that personnel scheduling problems come in many variations regarding the hard and soft constraints. The effect of those constraints on the complexity, however, has barely been studied. A more dedicated theoretic study would help researchers understand the effect of the different constraints and would offer them the possibility to develop well-suited algorithms.

Most papers appear to feature a deterministic approach, while real-world personnel scheduling problems have to deal with a variety of uncertainty sources. In situations where uncertainty has a strong effect on the personnel schedule, such as volatile demand or last-minute changes, it could prove very beneficial to incorporate this uncertainty in the decision-making process. Instead of integrating this uncertainty, researchers could also test the robustness of their solutions, for instance by simulating the stochastic behavior of demand, worker availabilities, etc. In the literature, however, we hardly ever encountered this type of analysis. A shift of the behavior of the research community regarding this anomaly, could contribute to the implementation of the solution algorithm. One could offer the company the results of the solution algorithm with respect to the uncertain events, compared with the current approach in the company. Typically, this will be a great improvement. Another interesting option are algorithms which allow for rescheduling based on new information and information forecasts.

We have seen that most of the papers consider real-life data, but that the algorithms do not make it to implementation. As already discussed, the lack of integration regarding personnel or problem characteristics, machine scheduling decisions, etc., all hinder a proper implementation of the solution algorithm. Moreover, it can be hard to implement the algorithm if it is programmed in commercial software that is not available for the company or if the company's software system does not allow to make suitable changes.

With respect to the solution method considered, we observe that the literature is heavily skewed towards mathematical programming approaches and metaheuristics. Decomposition algorithms and hybrid techniques receive more and more attention from the researchers, trying to deal with the heavily constrained personnel scheduling problem. We notice that in many papers the quality of the solution method is not compared to others or only to some basic tabu search or simulated annealing algorithms. It could be useful to apply the solution technique to some well-known problem settings to get a better grasp of the quality of the algorithm.

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