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Operating room planning and scheduling: A literature review

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ABSTRACT

This paper provides a review of recent operational research on operating room planning and scheduling. We evaluate the literature on multiple fields that are related to either the problem setting (e.g., performance measures or patient classes) or the technical features (e.g., solution technique or uncertainty incorporation). Since papers are pooled and evaluated in various ways, a diversified and detailed overview is obtained that facilitates the identification of manuscripts related to the reader's specific interests. Throughout the literature review, we summarize the significant trends in research on operating room planning and scheduling, and we identify areas that need to be addressed in the future.

1. Introduction

The managerial aspect of providing health services to patients in hospitals is becoming increasingly important. Hospitals want to reduce costs and improve their financial assets, on the one hand, while they want to maximize the level of patient satisfaction, on the other hand. One unit that is of particular interest is the operating theater. Since this facility is the hospital's largest cost and revenue center [66,82], it has a major impact on the performance of the hospital as a whole. Managing the operating theater, however, is hard due to the conflicting priorities and the preferences of its stakeholders [58], but also due to the scarcity of costly resources. Moreover, health managers have to anticipate the increasing demand for surgical services caused by the aging population [50]. These factors clearly stress the need for efficiency and necessitate the development of adequate planning and scheduling procedures.

In the past 60 years, a large body of literature on the management of operating theaters has evolved. Magerlein and Martin [83] review the literature on surgical demand scheduling and distinguish between advance scheduling and allocation scheduling. Advance scheduling is the process of fixing a surgery date for a patient, whereas allocation scheduling determines the operating room and the starting time of the procedure on the specific day of surgery. Blake and Carter [11] elaborate on this taxonomy in their literature review and add the domain of external resource scheduling, which they define as the process of identifying and reserving all resources external to the surgical suite necessary to ensure appropriate care for a patient before and after an instance of surgery. They furthermore divide each domain in a strategic, administrative and operational level. Przasnyski [102] structures the literature on operating room scheduling based on general areas of concern, such as cost containment or scheduling of specific resources. Other reviews, in which operating room management is covered as a part of global health care services, can be found in [16,101,109,123].

The aim of this literature review paper is threefold. First, we want to provide an updated overview on operating room planning and scheduling that captures the recent developments in this rapidly evolving area. In order to maintain a homogeneous set of contributions, we restrict the focus to manuscripts that explicitly incorporate planning and scheduling considerations. *Planning* is described in [108] as 'the process of reconciling supply and demand' (i.e., dealing with capacity decisions). *Scheduling* is described as 'defining the sequence and time allocated to the activities of an operation. It is the construction of a detailed timetable that shows at what time or date jobs should start and when they should end'. We do not enlarge the scope of the review to operating room management and hence exclude topics such as business process re-engineering, the impact of introducing new medical technologies, the estimation of surgery durations, staff rostering or facility design. Second, we want to structure the obtained information in such a way that research contributions can easily be linked to each other and compared on multiple facets, which should facilitate the detection of contributions that are

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within a specific researcher's area of interest. In Section 2, we describe how the structure of this review paper contributes to this goal. Third, pooling literature in a detailed manner enables the identification of issues that are currently (not) well covered and examined.

We searched the databases *Pubmed*, *Web of Science*, *Current Contents Connect* and *Inspec* on relevant manuscripts. Furthermore, references that were cited in the manuscripts were reviewed for additional publications, which eventually led to a set of 247 manuscripts. As can be seen from Table 1, this set largely consists of articles published in scientific journals. Note that almost half of the contributions appeared in or after 2000, which clearly illustrates the increasing interest of researchers in this domain. Since the total number of manuscripts is large and our main interest is directed towards the recent advances proposed by the scientific community, we restrict the set of manuscripts to those published in or after 2000. We furthermore limit the contributions that are incorporated in this review to those that are written in English in order to augment the paper's accessability. A detailed bibliography of the entire set of manuscripts, however, is provided in [20].

2. Organization of the review

Researchers frequently differentiate between strategic (long term), tactical (medium term) and operational (short term) approaches to situate their planning or scheduling problem. With respect to the operational level, a further distinction can be made between offline (i.e., before schedule execution) and online (i.e. during schedule execution) approaches. The boundaries between these major categories, however, may vary considerably for different settings and are hence often perceived as vague and interrelated [108]. Furthermore, this categorization seems to lack an adequate level of detail. Other taxonomies may, for instance, be structured and categorized on a specific characteristic of the papers, such as the use of solution or evaluation techniques. However, when a researcher is interested in finding papers on operating room utilization, a taxonomy based on solution technique does not seem very helpful. Therefore, we propose a literature review that is structured using descriptive fields. Each field analyzes the manuscripts from a different perspective, which may be either problem or technically oriented. In particular, we distinguish between 6 fields:

- *Patient characteristics* (Section 3): reviewing the literature according to the elective (inpatient or outpatient) or non-elective (urgency or emergency) status of the patient.
- *Performance measures* (Section 4): discussion of the performance criteria such as waiting time, patient deferral, utilization, makespan, financial value, preferences or throughput.
- *Decision delineation* (Section 5): indicating what type of decision has to be made (date, time, room or capacity) and whether this decision applies to a medical discipline, a surgeon or a patient (type).
- *Research methodology* (Section 6): providing information on the type of analysis that is performed and the applied solution or evaluation techniques.
- *Uncertainty (Section 7)*: indicating to what extent researchers incorporate arrival or duration uncertainty (stochastic versus deterministic approaches).
- *Applicability of research* (Section 8): information on the testing (data) of research and its implementation in practice.

Table 1
Number of manuscripts in the original set, categorized according to publication type and publication year.

	1950–1999	2000-Present	Total
Journal	106	81	187
Proceedings	15	19	34
Working paper	1	9	10
Ph.D. dissertation	5	5	10
Other	5	1	6
Total	132	115	247

Each section consists of a brief discussion of the specific field based on a selection of appropriate manuscripts and clarifies the terminology when needed. Furthermore, a detailed table is included in which all relevant manuscripts are listed and categorized. Pooling these tables over the several fields should enable the reader to reconstruct the content of specific papers. They furthermore act as a reference tool to obtain the subset of papers that correspond to a certain characteristic.

3. Patient characteristics

Two major patient classes are considered in the literature on operating room planning and scheduling, namely elective and non-elective patients. The former class represents patients for whom the surgery can be well planned in advance, whereas the latter class groups patients for whom a surgery is unexpected and hence needs to be performed urgently.

As shown in Table 2, the literature on elective patient planning and scheduling is rather vast compared to the non-elective counterpart. Although many researchers do not indicate what type of elective patients they are considering, some distinguish between inpatients and outpatients. Inpatients refer to hospitalized patients who have to stay overnight, whereas outpatients typically enter and leave the hospital on the same day. Adan and Vissers [1] consider both inpatients and outpatients in their research. They formulate a mixed integer programming model to identify the cyclic number and mix of patients that have to be admitted to the hospital in order to obtain the target utilization of several resources such as the operating theater or the intensive care unit (ICU). In their case, outpatients are treated as inpatients with a length of stay of one day who do not necessarily need specialized resources such as the ICU.

When considering non-elective patients, a distinction can be made between urgent and emergent surgery based on the responsiveness to the patient's arrival (i.e., the waiting time until the start of the surgery). The surgery of emergent patients (emergencies) has to be performed as soon as possible, whereas urgent patients (urgencies) refer to non-elective patients that are sufficiently stable so that their surgery can possibly be postponed for a short period. Table 2 indicates that the impact of planning and scheduling non-elective patients is hardly ever studied without the incorporation of elective patients. Wullink et al. [122] examined whether it is preferred to reserve a dedicated operating room or to reserve some capacity in all elective operating rooms in order to improve the responsiveness to emergencies. Using discrete-event simulation, they found that the responsiveness, the amount of overtime and the overall operating room utilization significantly improved when the reserved capacity was spread over multiple operating rooms. Bowers and Mould [17] group orthopaedic urgencies into trauma sessions and use Monte-Carlo simulation to determine which session length balances the amount of session overruns with an acceptable utilization rate. They furthermore provide both a discrete-event simulation model and an analytical approximation to explore the effects of including elective patients in the trauma session. Marcon and Dexter [84] study the impact of seven rules for sequencing patients on the hourly number of patients staying in the post anesthesia care unit (PACU). They also report on the economic impact of the rules on overutilized operating room time, on

Table 2
Patient characteristics – references that are printed in italics consider both elective and non-elective patients.

Elective	
Inpatient	[1,3,6,7,9,18,*21*,40,41,42,56,*73*,*89*,*90*,92,*100*,110,112,115,*117*,*124*]
Outpatient	[1,3,8,18,*21*,22,23,29,33,34,39,40,41,42,55,67,*73*,*89*,*90*,92,*100*,110,112,*117*,*124*]
Not specified	[2,*17*,19,27,28,32,37,38,43,45,46,49,*51*,52,53,54,63,64,*65*,70,71,*72*,*76*,*77*,*78*,79,*84*,87,88,91,93,94,95,96,97,98,*99*,103,104,105,106,111,*113*,*114*,116,118,119,120,*122*]
Non-elective	
Urgent	[10,*17*,*51*,*84*,*90*,*100*]
Emergent	[*21*,*65*,*76*,*77*,*78*,*89*,*99*,*100*,*113*,*117*,*122*,*124*]
Not specified	[*72*,*73*,*114*]

PACU completion time, and on the percentage of the days with at least one PACU delay that results from reducing the PACU nurse staffing. Non-elective (urgent) cases are included and studied explicitly in the sensitivity analysis where the impact from adding urgent cases to the end of the OR workday on the end-points of the sequencing rules is measured. The best results were obtained with sequencing rules that smooth the flow of patients entering in the PACU, while the frequently applied LCF (*longest case first*) rule and similar rules generate more overutilized operating room time, require more PACU nurses during the workday, and result in more days with at least one delay in PACU admission. Pham and Klinkert [100] model their optimization problem as a multi-mode blocking job shop problem and develop a mixed integer linear programming (MILP) formulation to minimize performance criteria such as the resulting makespan or the incurred operating room overtime. Each job or surgery is described as a predetermined sequence of activities and a maximum allowed waiting time between the processing of two consecutive activities is specified (precedence and time lag). Precedence relations or priorities may further be imposed to surgeries in order to resolve conflicts on shared resources. Furthermore, they allow to incorporate urgency deadlines for certain activities (due date) or lower bounds on the execution time (release date). Emergency cases should be scheduled for a prompt start within two hours after their arrival, which can delay or even bump some elective cases. The authors model the problem of scheduling these emergencies as the job insertion problem in the multi-mode blocking job shop problem. To keep the system stable, only a *today part* of the established schedule can be rescheduled.

One can question why the majority of the papers focuses on elective patients and ignores the problems caused by non-elective patients. This observation is even more striking when one realizes that the larger degree of uncertainty is the main reason why operating room scheduling urges other scheduling methodologies than the machine scheduling procedures developed for industrial systems. Many authors describe the degree of uncertainty as a motivation for their work and use it to justify the need for developing a dedicated scheduling procedure. However, since it is easier to relate expected financial gain to elective cases, this category may be favored in optimization research. A second observation is the large amount of papers that do not (explicitly) specify the type of patients for which the scheduling procedures are developed. This, however, may be important as the patient type already provides a lot of information on the amount of uncertainty, both in arrival and duration, and the demand for resources during their stay in the hospital. Outpatients, for instance, typically represent patients with shorter and less variable surgery durations who do not need the ICU, contrary to many inpatients. Generally, the lack of a clear definition of the scope of an operating room planning or scheduling problem is an important shortcoming in many studies.

4. Performance measures

Various performance criteria are used to evaluate operating room planning and scheduling procedures. We distinguish between eight main performance measures, namely waiting time, throughput, utilization, leveling, makespan, patient deferrals, financial measures and preferences. We discuss the performance measures in the next paragraphs and clarify their meaning and importance by means of some interesting research contributions. An overview of the manuscripts, classified according to the performance measures, is provided in Table 3.

Long waiting lists are among the most heard complaints in general health care, which justifies the many studies aiming at decreasing the waiting times for patients. Also, a decrease in the surgeon's waiting time has been the subject of many research efforts, as the surgeon is a very expensive resource in the operating room. Denton et al. [28] examine how case sequencing affects patient waiting time, operating room idling time (i.e., surgeon waiting time) and operating room overtime. They formulate a two-stage stochastic mixed integer program and propose a set of effective solution heuristics that are easy to implement. Note that patient waiting time may also be interpreted as the stay on a surgery waiting list.

The second objective, throughput, is closely related to patient waiting time. The dependency between waiting time, on the one hand, and throughput, on the other hand, is clearly stated in *Little's Law*, i.e., the average inventory in a system equals the average cycle time (which includes the waiting time and the process time) multiplied by the average throughput [80]. The papers classified under throughput focus on increasing the number of treated patients, which obviously leads indirectly to shorter waiting times. In their study, VanBerkel and Blake [117] use discrete-event simulation to examine how a change in throughput triggers a decrease in waiting time. In particular, they affect throughput by changing the capacity of beds in the wards and by changing the amount of available operating room time. Note that the location of their operating rooms is spread over multiple sites, which is a problem setting that is rarely addressed in the literature.

A third widely studied objective is utilization. Especially the utilization rate of the operating room has been the subject of recent research. On the one hand, utilization should be maximized as underutilized operating rooms represent unnecessary costs. On the other hand, an operating room that is fully planned with cases and without any time buffers, is very unstable and exhibits large uncertainty costs. The slightest change (e.g., a surgical procedure that takes longer than planned) may cause high costs like staff overtime costs and patient deferrals. Many studies elaborate on this trade-off and evaluate procedures based on the OR efficiency, which is a measure that incorporates both the underutilization and the overutilization of the operating room [31,34,35,41,46–48]. As shown in Table 3, we relate underutilization to undertime and overutilization to overtime, although they do not necessarily represent the same concept. Utilization actually refers to the workload of a resource, whereas undertime or overtime includes some timing aspect. Hence, it is possible to have an underutilized operating room complex, although overtime may occur in some of the operating rooms. We prefer, though, to group underutilization and undertime, on the one hand, and overutilization and overtime, on

Table 3
Performance criteria.

Waiting time	
Patient	[2,10,21,25,27–29,44,51,55,60,61,68,69,71,72,79,81,90,91,97–99,106,113,117,122,124]
Surgeon	[27,28,61,79,87]
Throughput	[3,5,21,55,65,105,106,111,117]
Utilization	
Underutilization/undertime	
Operating room	[1,31,34,35,41,46–49,52–54,63,68–70,78,79,88,91,93,96,110,112,120,124]
Ward	[1,120]
ICU	[1,120]
Overutilization/overtime	
Operating room	[1,17,21,25,27,28,30,31,34,35,41,46–49,52–54,60,61,64,68–70,76–79,84,86,88,91,93,96,97,100,104,106,110–114,120,122]
Ward	[1,21,120]
ICU	[1,93,120]
PACU	[22,23,29]
General	
Operating room	[3,5,10,17,18,21,34,42,45,51,55,64,65,79,91,92,99,106,111–115,122]
Ward	[18,21,51,65]
Leveling	
Operating room	[8,44,86,87,91]
Ward	[6,7,9,63,105,110,116]
PACU	[8,22,23,67,84,85]
Holding area	[85]
Patient volume	[91,110]
Makespan	[53,54,67,84,95,100]
Patient deferral/refusal	[2,17,21,51,56,65,71,97–99,106,111]
Financial	[12,19,32–34,37–40,42,43,61,73,81,89,92]
Preferences	[9,12,22,23,72,93,110,111,118,119]
Other	[4,10,13,14,25,36,48,55,59,63,76–78,81,84,92,94,97,100,103,104,111,112,115,116,119]

the other hand, as it is unclear in many manuscripts which view is applied. In order to determine the extent of underutilization or overutilization, a target utilization level has to be defined. Although this target level is mostly assumed to be 100%, Van Houdenhoven et al. [114] indicate that this is a strategic decision that may vary between institutions. Contributions on utilization that do not explicitly differentiate between underutilization or overutilization are captured in a general category, as shown in Table 3. Since the operating room schedule affects other facilities in the hospital, researchers also focus on the utilization of resources other than the operating room, such as wards or the ICU, though to a lesser extent. In Section 3, we already introduced the example by Adan and Vissers [1] in which the deviation between the target utilization of resources such as the ICU staff, ICU beds or regular ward beds is minimized. Vissers et al. [120] furthermore provide a case study in which they apply the procedures that are developed in [1] to a department of cardiothoracic surgery. Note that not even a single paper focuses on the underutilization of the PACU.

A fourth main objective concerns the leveling of resources, i.e., developing operating room schedules that lead to smooth resource occupancies without peaks. Besides the operating room itself, the occupancy of different resources could be considered, such as leveling the bed occupancy, and hence workload, in the wards, in the PACU or in the holding area. The idea here is to minimize the risk of capacity problems caused by unexpected events like longer procedure times or length of stay of patients. Marcon and Dexter [85] use discrete-event simulation to examine how standard sequencing rules, such as *longest case first* or *shortest case first*, may assist in reducing the peak number of patients in both the holding area and the PACU. Note that the operating rooms are sequenced independently, which results in a reduced complexity. It should be clear that sequencing decisions in one operating room may have an impact on the preferred sequence in the other operating rooms, so that sequencing decisions are preferably determined for the operating theater as a whole (e.g., [23,67]).

One of the objectives that is incorporated in the paper by Marcon and Dexter [84] aims at decreasing the makespan, which represents in their case the completion time of the last patient's recovery. In general, it can be defined as the time between the entrance of the first patient and the finish of the last patient. Although the makespan is often measured for the operating room, their study illustrates that it can also be studied for one of the closely connected resources like the PACU. As decreasing the makespan often involves a dense schedule, we believe this criterion should be combined with protective measures to increase its stability and robustness.

The sixth objective relates to the minimization of the number of patient deferrals or refusals. Kim and Horowitz [71] study how to include quotas in the surgery scheduling process in order to streamline the admittance to the ICU. In particular, they reduce the number of canceled elective surgeries that result from ICU bed shortages without significantly worsening the waiting times of other patients who are seeking admission to the ICU.

It can be argued that financial objectives are the most general of all studied objectives. Indeed, if an operating room scheduling or planning model leads to cost savings, the saved money can be invested to solve any of the above mentioned problems. For instance, long waiting times can be decreased by installing more capacity. It is our belief that the financial issues are too often overlooked, certainly in well-developed health care nations in which waste of capacity is still a major problem. Given the aging of the population in many of these countries, the financial well being of the health care system should be a main research focus. Some papers examine how adequate planning and scheduling contributes to an increased contribution margin, which is defined as revenue minus variable costs [32,34,37–39,42]. It should be noted that research efforts are not limited to the identification of the best practice. Dexter et al. [33] formulate a linear programming model in which the variable costs are maximized in order to determine the worst case scenario.

A last category of objectives incorporate the preferences of the different parties involved in the operating room process. Surgeons may dispute about the timing of assigned operating room block time, whereas patients may have conflicting preferences with respect to the timing of their surgery. At first sight, this set of objectives seems to be less important. However, various studies report on the relationship between the efficiency of care and the schedules that take into account these preferences, as illustrated in Table 3. Cardoen et al. [22,23] solve a case sequencing problem in which they try, amongst other, to schedule surgeries of children and prioritized patients as early as possible on the surgery day. At the same time, they want patients with a substantial travel distance to the ambulatory surgery center to be scheduled after a certain time period.

Table 3 also depicts manuscripts that describe other performance measures than those that were addressed in the previous paragraphs. This category groups criteria related to, for instance, delays in PACU admissions [36,84], operating room target allocation [13,14,25,103] or the use of additional capacity of specific resources, such as the number of operating room openings [59,104,115,116] or the demand for extra capacity of beds in wards [97].

5. Decision delineation

A variety of planning and scheduling decisions with a resulting impact on the performance of the operating theater are studied in the literature. In Table 4, we provide a matrix that indicates what type of decisions are examined in the manuscripts, such as the assignment of a date (e.g., on Monday, on January 17th), a time indication (e.g., at 11 a.m.), an operating room (e.g., operating room 2, operating room of type A) or the allocation of capacity (e.g., three hours of operating room time). The manuscripts are furthermore categorized according to the decision level they address, i.e., to whom the particular decisions apply. We distinguish between the discipline, the surgeon and the patient level. We deliberately choose to avoid the classification into the three classical levels: case mix planning, master surgery scheduling and patient scheduling adopted by many authors to define the scope of their planning or scheduling problem. The reason is twofold. First, there are no clear definitions of these three decision levels. Various authors classify different problems into the same class. To give an example: Blake et al. [13], Blake and Donald [14], Beliën and Demeulemeester [6] and Beliën et al. [8] define a master surgery schedule as a schedule that specifies the number and type of operating rooms, the hours that operating rooms are available, and the specialty that has priority at an operating room. This definition has also been incorporated by Testi et al. [111]. However, van Oostrum et al. [116] define a master surgery schedule as a schedule that specifies for each *OR-day combination* of the planning cycle a list of recurring surgical procedure types that must be performed. Although all the above papers [6,8,13,14,111,116] claim to construct a cyclic master surgery schedule, it should be clear that the granularity of the outcome differs according to the decision level or perspective chosen by the authors. A similar reasoning applies to case mix planning since the available amount of operating room time (capacity) may be divided according to disciplines, surgeons or patient types. Second, we believe that our two-dimensional classification of planning and scheduling decisions (see Table 4) provides more detail on the exact type of decisions that take place. We clarify this point in the next paragraphs.

The discipline level unites contributions in which decisions are taken for a medical specialty or department as a whole. Blake et al. [13] and Blake and Donald [14] report on an integer programming model and an improvement heuristic to construct a cyclic timetable that minimizes the underallocation of a specialties' operating room time with respect to its predetermined target time. The model determines for each specialty what operating room types are assigned to what days of the week (i.e., a decision concerning date and room).

At the surgeon level, Beliën et al. [8] introduce a software tool in which decisions for specific surgeons, instead of disciplines, are considered. For each surgeon, the planner has to decide on what day and in which room surgeries have to be performed. Since operating rooms may be divided in a morning and an afternoon session, the block assignments also incorporate a time indication. The impact of the cyclic timetable decisions on the use of various resources, such as nurses, artroscopic towers or lasers, is visualized and guides the planner in improving the constructed surgery schedule. Since the amount of operating room time for each surgeon in the planning horizon is predetermined, no capacity decisions have to be made.

Next to the discipline and surgeon level, Table 4 also specifies a patient level. On this level, decisions are made for individual patients or patient types. Although patient types may represent the distinction between, for instance, elective or non-elective patients, they frequently refer to surgical procedure types. This view is incorporated by van Oostrum et al. [116]. Starting from a list of recurring procedure types (i.e., types that are frequently performed and hence have to be scheduled in each planning cycle), they decide what mix of procedures will be performed on what day and in which operating room. They aim at the minimization of the number of operating rooms in use, on the one hand, and the leveling of the hospital bed requirements, on the other hand. A two-phase decomposition approach is formulated that is heuristically solved by column generation and mixed integer programming.

Although most manuscripts take only one decision level into account, this does not necessarily have to be the case. Testi et al. [111] report on a hierarchical three-phase approach to determine operating theater schedules. In the first phase, which they refer to as session planning, they determine the number of sessions to be scheduled weekly for each discipline. Since they distribute the available operating room time over the set of disciplines, this problem can be regarded as a case mix planning problem. Phase 2 formulates a master surgery scheduling problem in which they assign an operating room and a day in the planning cycle to the sessions of each discipline. Both phases are solved by integer programming and are situated on the discipline level. Phase 3, on the contrary, is formulated in terms of individual patients. A discrete-event simulation model is presented to evaluate decisions concerning date, room and time assignments.

Table 4
Type and level of decisions.

	Discipline level	Surgeon level	Patient level	Other
Date	[6,13,14,19,25,103,105,106,111,124]	[7–9,21,70,98]	[1,21,25,42–44,51–54,60,61,63,64,68–72,76–78,91,93,96–98,100,104–106,110,111,115,116,119,120]	
Time	[6,65]	[7–9,21]	[5,21–23,25,27–30,36,43,53,54,61,65,67–69,72,79,84,85,87,95,100,104,106,111,113,118]	
Room	[13,14,25,103,105,106,111,124]	[8,9,70,98]	[18,22,23,25,30,41,46,47,52–54,60,63,64,68–70,72,76,78,84,86,87,91,93,97,98,100,104–106,111,115,116,118,122]	
Capacity	[10,17,19,25,43,49,61,65,92,105,106,111,117,124]	[12,21,32,33,37–40,45,70,73,98]	[1,2,17,21,25,36,56,63,65,70,89,97,99,105,116,115,120,122]	[5,51,55,59,81,90,94,117]
Other	[105,114]	[44,91,98]	[44,51,91,98,105,112]	

We added both a row and a column (*other*) to Table 4 to provide entries for manuscripts that study the operating room planning and scheduling problems in a way that is not well captured by the main matrix. Manuscripts that are categorized in this column or row examine, for instance, decisions concerning surgeon–patient combinations [44,91,98] or decide in which hospital or site capacity has to be preserved [51,117].

Most scheduling procedures described in the literature apply to the patient level, while the contributions that apply to the surgeon and discipline level are mainly overlooked, except when the decision concerns the assignment of capacity. A possible explanation is that, unlike patients, surgeons do not easily accept changes in their rosters. Driven by the continuously growing pressure on resources, today's surgeons more and more realize the need for efficient care and are less averse from operations research scheduling techniques that help streamline the whole operating room process. Hence, we believe that research efforts focusing on the scheduling of surgeons might have a larger success rate in the (near) future.

In the introduction (see Section 1), we already mentioned that operating room planning and scheduling decisions affect facilities throughout the entire hospital. Therefore, it seems to be useful to incorporate facilities, such as the ICU or PACU, in the decision process and try to improve the global performance. If not, improving the operating room schedule may worsen the practice and efficiency of those related facilities. In Table 5, we classify the manuscripts according to whether they study the operating theater in isolation or integrate it with other facilities. Within the integrated class we distinguish between papers that study the impact on the PACU, the ICU and the wards. Beliën et al. [8] integrate their master scheduling system with all kind of user specific resources of which the consumption is directly related to the timing of the surgeries (e.g., the radiology department). Velasquez and Melo [118,119] use the concept of general resources, without exactly specifying which ones. Therefore, we classify these papers under the category 'other'.

In 1997, Blake and Carter indicated in their literature review that techniques for integrating operating room scheduling with other hospital operations were urgently required [11]. Table 5 shows that still half of the recent contributions limit their scope to an isolated operating room. Although some progress seems to be achieved, a further integration of the operating room with other hospital facilities remains a main topic for future research, especially in combination with the incorporation of uncertainty (see Section 7). One of the major reasons for simplifying the research scope probably stems from the increased complexity, both in formulation and in computation, of the decision process caused by the integration. Note that this integration should not be limited to facilities that are situated within one hospital, as studies on multi-facility or multi-site operating room planning and scheduling are currently emerging [51,105,117].

6. Research methodology

The literature on operating room planning and scheduling exhibits a wide range of research methodologies that fit within the domains of operations management and operations research and that combine a certain type of analysis with some solution or evaluation technique.

Table 6 provides an overview of the ways in which operating room planning and scheduling problems are analyzed. While most of the problems are formulated and studied as a combinatorial optimization problem, many approaches can also be identified in which the impact of specific changes to the problem setting are examined. We refer to this type of analysis as scenario analysis since multiple scenarios, settings or options are compared to each other with respect to the performance criteria. Next to the optimization approaches or the application of a scenario analysis, we also identify other types of analysis that are applied to the operating room setting, though to a much lesser extent. Velasquez and Melo [119] exploit the structure of their scheduling problem in which they assign one specific surgery to a specific day in the planning horizon so that penalties related to the use of additional resources or time window violations are avoided, and divide the set of solutions into equivalence classes. Such equivalence classes group solutions with the same objective value. Optimizing the problem hence boils down to solving a decision problem or feasibility problem: 'Is it possible to obtain a feasible solution in the best equivalence class, yes or no?'. When no solution exists, a next (inferior) class is examined until at last one feasible solution is obtained. An other perspective to examine operating room planning and scheduling approaches is provided by benchmark studies. Basson and Butler [4] apply data envelopment analysis (DEA) to operating room activity. They analyze how rankings of sites based on their operating room efficiency scores differ when the types of inputs (e.g., staffing pattern) and outputs (e.g., number of cases performed per equipped operating room) that are taken into account, vary. The above paper illustrates the possible contribution of DEA to benchmark studies. The current body of literature, however, does not sufficiently address such studies, although their outcome may be of high importance to the practitioners. Finally, researchers may also analyze the computational complexity of their combinatorial problem or its corresponding solution approach. Lamiri et al. [77] prove using the 3-partition problem that their stochastic optimization problem, in which they assign patients over a planning horizon in order to minimize the sum of patient related costs and operating room overtime costs, is strongly NP-hard and hence very difficult to solve. The authors propose a solution methodology that combines Monte-Carlo simulation and mixed integer programming and elaborate on its convergence to the optimum.

Table 7 lists the various solution or evaluation techniques that are applied to the problem settings, such as mathematical programming, simulation or analytical procedures. We refer to Gass and Harris [57] or Winston and Goldberg [121] for a brief introduction to these techniques.

The reader may notice from Tables 6 and 7 that many solution techniques can be applied to perform one specific type of analysis. We illustrate this proposition for the combinatorial optimization approaches, as a substantial part of the literature on operating room planning and scheduling consists of contributions in this area. Cardoen et al. [22,23] state a multi-objective surgical case sequencing problem in which the order of patients in the operating rooms of a freestanding ambulatory unit has to

Table 5
Integration of the operating room planning and scheduling process.

Isolated operating room	[2,4,10,13,14,17,25,27,28,30,35,38,40–49,52–54,60,59,61,63,64,72,73,78,76,77,79,86–88,91,94,96,98,99,103,104,106,112–115,122]
Integrated operating room	
PACU	[3,5,22,23,29,36,54,55,61,69,84,85,89,90,95,100]
Wards	[1,6,7,9,12,18,19,21,32,33,37,39,51,56,61,63,65,67,89,97,105,110,111,116,117,120,124]
ICU	[1,32,33,37,39,61,63,68,89,93,100,105,116,117,120]
Other	[8,118,119]

Table 6
Type of analysis.

Optimization	
Exact	
Single criterion	[7,19,25,32,33,37–39,53,59,63,73,87,98,103,105,111,118]
Multicriteria	[1,2,9,12,22,23,52,68–70,77,89,93,96,97,100,110,119,124]
Heuristic	
Single criterion	[6,13,14,86,88,95,113]
Multicriteria	[9,22,25,27–29,53,54,60,63,64,67,72,76,78,91,104,115,116,120]
Decision problem	[10,119]
Benchmark	[4,92]
Scenario analysis	[1,3,4,8,10,12,17,18,21,27–30,32,33,37,39–43,45–49,51,53,55,56,64,65,67,69,71,73,79,81,84–86,88–94,97,99,105,106,111–115,117,120,122,124]
Complexity analysis	
Problem	[22,23,28,53,54,60,63,64,67–70,72,76–78,86,95,104,113,116]
Solution procedure	[7,23,60,64,67]

Table 7
Solution technique.

Mathematical programming	
Linear programming	[4,27,32,33,39,59,73,89,92,96]
Quadratic programming	[6,9,37]
Goal programming	[2,12,91,93,103,110]
Mixed integer programming	[1,6,9,13,14,22,25,63,68–70,76,77,97,98,100,104,105,111,116,120,124]
Dynamic programming	[7,23,52,54,78,95]
Column generation	[53,54,63,76,78,116]
Branch-and-price	[7,23,52,118]
Other	[22,38,87,95,96]
Simulation	
Discrete-event	[3,5,17,18,21,36,42,43,45,46,49,51,55,65,71,81,84–86,90,97,99,106,111–113,117,122,124]
Monte-Carlo	[17,29,39,64,76,77,79,91,94]
Constructive heuristic	[6,9,25,27,28,41,43,46,47,60,64,72,76,78,88,95,113]
Improvement heuristic	
Meta-heuristic	
Simulated annealing	[6,9,29,64,113]
Tabu search	[54,67]
Genetic algorithm	[54,104]
Other	[13,14,28,36,64,76,78,86,113]
Analytical procedure	[17,27,77,81,114]

be determined. They apply multiple solution approaches to solve this NP-hard combinatorial optimization problem. In [23] the authors describe a branch-and-price algorithm, whereas they test, amongst other, a dedicated branch-and-bound procedure in [22]. In contrast to the former approach, the latter one incorporates dedicated branching and bounding procedures that are not based on LP relaxations. Roland et al. [104] report on the construction of a genetic algorithm that heuristically minimizes the costs related to operating room openings and overtime. In particular, their scheduling problem, which is closely related to the well-known resource-constrained project scheduling problem, questions what date, operating room and starting time indication should be assigned to the set of surgeries. They validate the performance of the genetic algorithm through a comparison with a MILP approach.

In addition to the statement that multiple solution techniques can be used to perform a specific type of analysis, it also seems from Tables 6 and 7 that a single solution technique possibly suits multiple types of analysis. Mulholland et al. [89] report on the application of linear programming to determine the mix of patients that optimizes the financial outcome of both physicians and the hospital, taking into account the resulting consumption of multiple resources such as the ICU, PACU, ward or holding unit. They also investigate how changes in the assumptions are reflected in the optimal solution. As such, they combine combinatorial optimization with a scenario analysis.

Linking Tables 6 and 7 shows that mathematical programming approaches are popular to solve operating room planning and scheduling optimization problems. One reason for their success stems from the rapidly improving solvers that are offered by commercial firms such as ILOG (http://www.ilog.com) or Lindo Systems (http://www.lindo.com). Computational boundaries are continuously widened, even for complex problems that formerly had to be solved heuristically. We should add that the computational effort to solve optimization problems does not only depend on the objective function, but also on the type of constraints that are incorporated in the analysis. We list in Table 8 what type of constraints are addressed in the literature for the combinatorial optimization problems. We limit the scope to the occurrence of hard constraints (i.e., constraints or limitations that are never allowed to be violated), as soft constraints are incorporated as part of the objective function and hence appear as performance criteria (see Section 4) in the problem formulation. Table 8 distinguishes between resource constraints, precedence constraints and time lags, release or due date constraints and demand-related constraints. An example of demand-related constraints is provided by Santibanez et al. [105], who study the impact of simultaneously changing the master surgery schedule of multiple hospitals on throughput or the peak use of post-surgical resources. In their MILP formulation, they restrict the amount of operating room blocks (i.e., demand for operating room time) that is assigned to the surgical specialties within each hospital between a lower and upper

Table 8
Type of hard constraints retrieved from operating room optimization approaches.

Resource constraints	
Holding area	[29,89,100]
Ward	[1,12,19,32,33,37,39,63,89,97,100,105,110,116,120]
ICU	[1,32,33,37,39,63,68,69,89,93,100,105,116,120]
PACU	[22,23,29,54,69,89,95,100]
Equipment	[22,23,25,60,68,69,78,97,100,105,110]
Surgical staff	[1,7,12,22,23,29,53,59,60,64,68–70,72,91,93,96,98,100,104,105,110,111,115]
Budget	[12,33]
Regular operating room time	[1,2,6,7,9,12–14,25,32,33,37–39,53,54,63,68–70,73,76–78,87,88,91,93,96–98,100,103–105,111,115,120,124]
Operating room overtime/undertime	[25,53,54,60,63,68,69,78,93,100,104,111,116]
Other	[27,95,104,118,119]
Precedence constraints/time lags	[22,23,68,87,91,98,100,113]
Release/due date constraints	[25,52–54,60,68,69,72,76–78,96,100,104]
Demand constraints	[1,2,6,7,9,12–14,19,25,32,33,37–39,59,63,70,73,89,96,98,103,105,111,116,120,124]

bound. Equivalently, they state lower and upper throughput bounds for procedure types (i.e., demand for surgery).

Equivalently to the relation between mathematical programming and combinatorial optimization, simulation approaches seem to be successful for applying a scenario analysis. Lebowitz [79] applies Monte-Carlo simulation to evaluate and quantify the impact of sequencing procedures on waiting time and operating room utilization criteria. A discrete-event simulation model is designed by Sciomachen et al. [106] in order to evaluate the utilization of operating rooms or medical disciplines, patient throughput and the number of overruns or patient deferrals. In particular, they examined the impact of changing, amongst other, the master surgery schedule and the case sequencing rules on the listed performance criteria. Note that their study largely corresponds with the third phase that is examined in [111]. Especially when the problem exhibits a lot of stochasticity or when it is relationally complex, simulation proves to be useful as it features an extensive modeling flexibility and allows for a sufficient degree of detail. Although most authors who apply simulation restrict their analysis to the evaluation of multiple scenario's, recent approaches can be identified that diverge towards simulation-based optimization and combine simulation with other solution techniques (see [77] for an example).

7. Uncertainty

One of the major problems associated with the development of accurate operating room schedules or capacity planning strategies is the uncertainty inherent to surgical services. Deterministic planning and scheduling approaches ignore such uncertainty or variability, whereas stochastic approaches explicitly try to incorporate it. In Table 9, we list the relevant manuscripts based on their uncertainty incorporation.

Two types of uncertainty that seem to be well addressed in the stochastic literature are arrival uncertainty and duration uncertainty. The former points, for instance, at the unpredictable arrival of emergency patients or at the lateness of surgeons at the beginning of the surgery session, whereas the latter represents deviations between the actual and the planned durations of activities related to the surgical process. Harper [65] presents a detailed hospital capacity simulation model that enables system evaluations by means of a scenario analysis. The participation of multiple hospitals in the development phase resulted in a generic framework that allows to incorporate uncertainty or trends in the arrival profiles of patient groups as well as duration variability (e.g., length of stay or surgery durations). Persson and Persson [99] describe a discrete-event simulation model to study how resource allocation policies at the department of orthopaedics affect the waiting time and utilization of emergency resources, taking into account both patient arrival uncertainty and surgery duration variability.

Next to arrival and duration uncertainty, other types of uncertainty may be addressed. Dexter and Ledolter [37] examine to what extent uncertainty in the estimated contribution margin of surgeons (characterized by, e.g., standard deviations) may lead to inferior allocations of operating room capacity when the goal is to maximize a hospital's expected financial return. Only few manuscripts refer to resource uncertainty (see [21] for an example), while this topic currently is a hot topic in, for instance, project management or project scheduling [75]. Assume, for instance, that a surgeon drops an instrument that is unique in the hospital while the surgery is still in progress. This would represent a resource breakdown as the medical team has to wait to resume their activities until the instrument is sterile again. It should be noted, though, that resource uncertainty often coincides with arrival uncertainty. For example, the arrival of emergencies may result in a claim of both the surgeon who is needed to perform the emergent surgery and a specific operating room. These claims actually result in resource breakdowns as the elective program cannot be continued and hence has to be delayed.

It should be clear that operations management techniques are able to deal with stochasticity, especially simulation techniques and analytical procedures, and that an adequate planning and scheduling approach may lower the negative impact of uncertainty. Mostly, researchers assume a certain level of variability, for instance by analyzing data, and use this information as input for their modeling phase. However, only limited attention is paid to the reduction of variability within the individual processes. In other words, one should first start to reduce uncertainty in the individual processes instead of immediately focusing on a reduction of the variability of the system that specifies the relation

Table 9
Uncertainty incorporation.

Deterministic	[1,2,4,7,8,12–14,19,22,23,25,33,39,52–54,59,60,63,67–70,72,73,85,87,89,91–93,95,97,98,100,103–105,110,111,113,118–120,124]
Stochastic	
Arrival	[6,9,10,17,18,21,38,42,43,45,51,61,65,71,76–78,81,88,90,94,97,99,106,111,113,117,122,124]
Duration	[3,5,6,9,10,17,21,27–30,43,45,46,51,56,61,63–65,71,76,77,79,81,84–86,88,90,94,96,99,106,111–117,122,124]
Other	[21,37,39]

between the individual processes. Think, for instance, of the estimation of surgery durations. Instead of the immediate determination of the distribution of a surgery duration, one should examine whether the population of patients for which the durations are taken into account is truly homogenous. If not, separating the patient population may result in a decreased variability even before the planning and scheduling phase is executed. As the estimation of surgery durations exceeds the scope of this literature review (see Section 1), we do not elaborate on this issue.

8. Applicability of research

Many researchers provide, next to the development of a model or a formulation, a thorough testing phase in which they illustrate the applicability of their research. Whether this applicability points at computational efficiency or at showing to what extent objectives may be realized, a substantial amount of data is desired. From Table 10, we notice that most of this data stems from reality. This evolution is noteworthy and results from the improved hospital information systems from which data can be easily extracted.

Unfortunately, a single testing of procedures or tools based on real data does not imply that they finally get implemented in practice. Although Lagergren [74] indicates that this lack of implementation in the health services seems to have improved considerably, it is hard to find statements in contributions that explicitly confirm the implementation and use of the procedures in practice (see [13,14,65] for an example). It is also unclear what *use in practice* actually entails. Applying a case mix model once every 2 years clearly results in a different degree of implementation than the daily application of a surgery sequencing algorithm. A clear comparison of manuscripts on this aspect is hence not straightforward.

Even if the implementation of research can be assumed, authors hardly provide details on the process of implementation. Therefore, we encourage the provision of additional information on the behavioral factors that coincide with the actual implementation. Identifying the causes of failure or the reasons that lead to success, may be of great value to the research community. Hospital management, for instance, may be reluctant to change procedures or stimulate further investments in research when the implementation of the algorithms and procedures is not directly accompanied by significant short term financial gains (or equivalently, a strong reduction in operating costs). Since the operating theater unites many stakeholders [58], short term financial gain is not the only performance criterion that should be of interest to the hospital. Possibly, practitioners lack some kind of awareness of the power of operations management techniques to capture this kind of integrated view. Therefore, educational applications should be developed to introduce planning and scheduling concepts to the managers of the future. Hans et al. [62] recently report on an educational tool that specifically focuses on the management of the operating room. Each player manages a virtual operating theater and has to decide on, for instance, the size, the allocation of the available operating room time to medical disciplines or the scheduling of individual patients. Throughout the game, players are introduced to operations management principles applied to health care and learn from the consequences of their planning and scheduling decisions.

Only limited research is performed to indicate what planning and scheduling expertise is currently in use in hospitals. Using a survey, Sieber and Leibundgut [107] recently noticed that the current state of operating room management in Switzerland is far from excellent. A similar exercise for the hospitals in Flanders (Belgium) is described in [24]. It is somehow contradictory to see that in a domain as practical as operating room planning and scheduling, so little research seems to be effectively applied.

9. Conclusion

In this paper, we reviewed manuscripts on operating room planning and scheduling that have recently appeared. We analyzed the contributions on various levels, which we referred to as fields. Within each field, we highlighted the most important trends and we illustrated important concepts through the citation of key references. Since each discussion is accompanied by at least one detailed table, which provides even more information than is addressed in the text, readers may easily identify manuscripts that have specific features in common. They furthermore allow to track specific contributions over the different fields and visually indicate what area of research is well addressed or should be subject to future research. In the next few paragraphs we summarize and discuss some of the major findings.

We noticed that most of the research is directed towards the planning and scheduling of elective patients. Although complex problems are also encountered for the elective patient group, major operational deficiencies are triggered by the arrival of non-elective patients. The review revealed that only limited research is applied to non-elective patient scheduling. Although their arrival is highly uncertain, approaches that pro-actively try to mitigate the resulting deficiencies can and should be developed in the near future. Next to the uncertainty in the arrival process of patients, researchers should also put effort into the study of stochastic activity durations and their impact on the operating room practice, especially with a focus on patient pooling. The increased computational complexity that coincides with these type of questions, however, explains the current trend of researchers to focus on deterministic approaches.

Next to the study of uncertainty, a better integration of the operating room downstream and upstream facilities and resources should be favored. Until now, only half of the contributions take such integration into account. We realize that this recommendation to widen the scope of the problem setting again coincides with an increased difficulty to obtain reasonably fast results that are likely to be general. This, however, brings us to an important open-ended question that operational researchers should dare to ask: "Should the scientific community examine realistic and thus complex problem settings and try to improve the current practice as much as possible, or should one examine a simplified and tailored version of the problem and solve it to optimality?". Note that this question does not blindly favor the use of heuristics. Although it is often stated that heuristic approaches are indispensable to solve practical or real-sized problems efficiently, a number of exact approaches presented in the literature seem to be powerful enough to solve realistic problems, even when multiple criteria are considered (see Section 6).

Table 10
Applicability of research.

No testing	[31,35,44,59,61]
Data for testing	
Theoretic	[6,7,27,41,43,47,49,51,52,54,60,68,69,72,76–79,84,86,91,95,98,100]
Based on real data	[1–5,8–10,12–14,17–19,21–23,28,29,30,32,33,37–42,45–47,49,53,55,56,63–65,67,70,71,73,81,85,87–89,91–94,96–100,103,105,106,110,111,113–120,122,124]

Throughout the review, we repeatedly pointed at the inaccurate use of terminology or the unclear definitions. It is our experience that this ambiguity does not only apply to specific concepts, but also to the description of the problem setting that is stated in the contributions. It should be clear that researchers have to work towards a consensus on the terminology and the definition of concepts. Such cooperation, for instance facilitated using the Delphi methodology, should furthermore augment the acceptance of definitions for future use. Until now, definitions are often proposed without explicit negotiation between researchers, practitioners and associations. The development of a transparent classification scheme should furthermore overcome the problem of vague and unclear problem descriptions. The use of descriptive fields in this area could be promising, as successful classifications based on fields are already provided in the domain of, for instance, machine scheduling [15] or project scheduling [26].

We encourage researchers to share their expertise in solving problems they encountered along their study trajectory. These difficulties may concern the gathering and the quality of data as well as the implementation of the developed approaches in practice. As mentioned in Section 8, this information may be valuable to each stakeholder and it should facilitate the transfer of advanced procedures to the daily practice within hospitals. Until now, however, very little is known about the process of implementation, factors that enhance the implementation, the actual performance of research in practice or the role of computer–human interaction in operating room planning and scheduling.

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