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OPERATING ROOM PLANNING AND SCHEDULING PROBLEMS: A CLASSIFICATION SCHEME

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ABSTRACT

The increasing interest in the domain of operating room planning and scheduling leads to a proliferation of problem types. The statement and the scope of the particular problems, however, are often unclear. In this paper, we report on a scheme to classify operating room planning and scheduling problems using multiple fields. Each field describes a specific set of characteristics of the particular problem by means of parameters, elements and optional further specifications. We also elaborate on the use of delimiters to separate the entries in the classification notation. Next to the formulation of the scheme, we examine its applicability on a range of problems that are encountered in recent literature. With the development of the classification scheme, we hope to structure and to clarify forthcoming research in this domain.

Keywords: Health care, operating room, classification scheme, planning, scheduling.

1. INTRODUCTION

The increasing interest of researchers in the domain of operating room planning and scheduling induces a steady increase in the number of contributions over time. Figure 1 clearly visualizes this upward trend and even underestimates the number of contributions that appeared from 2000 on, as this set does not cover an entire decade. Not surprisingly, the increase in contributions is accompanied by a

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proliferation of problem types. The statement and the scope of these problems, however, are often unclear. As such, the effort of researchers to verify whether the particular problem is really interesting with respect to their own research purposes, increases. The introduction of an adequate scheme to classify the contributions on operating room planning and scheduling, which constitutes the subject of this paper, may present a first step to structure and to clarify forthcoming research in this domain.

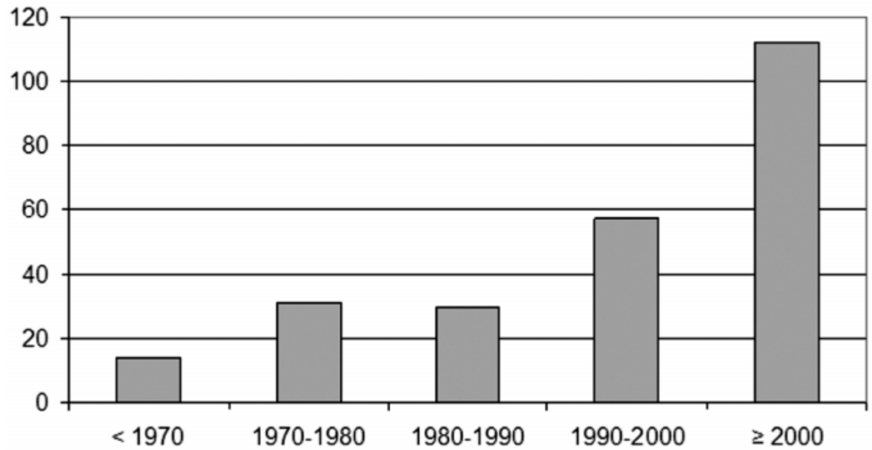

Fig. 1: Number of Research Contributions about Operating Room Planning and Scheduling (up to 2008) Categorized According to the Year of Publication (Cardoen et al., 2010)

One major concern in the development of classification schemes is the trade-off between the amount of information and the simplicity of the notation. Providing a lot of information easily results in an overcomplicated notation. In our opinion, the goal of a classification scheme is to provide as much (meaningful) information as possible while maintaining a simple and brief notation. On the one hand, classification schemes hence have to incorporate a sufficient amount of detail to represent a clarifying framework or taxonomy, while they have to offer a sufficient degree of freedom to the user to specify the problem setting, on the other hand. Therefore, classification schemes should be meaningful, brief and flexible as the acceptance of the scheme by the scientific community is otherwise doubtful. Moreover, classification schemes should exclude ambiguity as it is not allowed to state multiple notations for one particular problem.

Multiple classification approaches, which address various planning and scheduling domains, can be identified in the literature. The classification scheme that was introduced for machine scheduling problems, for instance, is composed of three fields or descriptive areas α, β and γ (Graham et al., 1979; Blazewich et al., 1983; Blazewich et al., 1986). The first field α describes the machine environment (e.g. job shop, flow shop). The second field β comprises the task and resource characteristics (e.g. task processing times, deadlines). The third and final field γ provides information on the performance measures of interest (e.g. makespan). We identified a similar structural approach to classify project scheduling problems. Demeulemeester and Herroelen (2002) generalize the machine scheduling classification scheme and similarly describe three fields. In their scheme, the fields α, β and γ respectively describe the problem's resource characteristics, activity characteristics and performance measures. With respect to operating room planning and scheduling problems, we were unable to identify such a profound and detailed classification attempt in the current body of literature (see Section 2). Since both the machine classification scheme and the project scheduling scheme are successfully structured using fields, we should wonder whether this approach can also be applied to an operating room context. In Section 2, we explore and confirm this idea, starting from a recent literature review on operating room planning and scheduling contributions. In Section 3, we elaborate on each retained field. Similarly to the machine scheduling and project scheduling classification schemes, we specify for each field a number of parameters which can take multiple values. These values will be referred to as elements and provide the actual information. An optional further specification of the elements is provided when applicable. Section 4 clarifies the use of delimiters in the classification notation, whereas Section 5 provides some examples to illustrate the applicability of the scheme. A summary of the paper's classification approach is finally stated in Section 6.

2. TOWARDS THE IDEA OF FIELDS

As suggested in the introduction (see Section 1), only high-level, hierarchical and broadly defined classification attempts are provided in the literature to structure the operating room planning and scheduling approaches. Magerlein and Martin (1978) differentiate between advance scheduling and allocation scheduling to categorize the literature on surgical demand 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. According to these definitions, the scope of their classification is limited to the individual patient, who only represents one particular stakeholder in the surgery process. Many problems can be identified, however, that are not formulated in terms of individual patients (see Blake and Donald (2002) for an example). Moreover, the dichotomy between advance scheduling and allocation scheduling leaves operating room planning problems, in which no timetabling aspect is considered, out of consideration. Blake and Carter (1997) elaborate on the taxonomy of Magerlein and Martin (1978) and add the domain of external resource scheduling, defined as the process of identifying and reserving all resources external to the surgery suite necessary to ensure appropriate care for a patient before and after an instance of surgery. Within each domain, they furthermore distinguish between a strategic, an administrative and an operational level. These levels can be seen as planning and control levels that respectively relate to long-term, medium-term and day-to-day decisions. Van Houdenhoven et al. (2007) also favor this categorization based on the time horizon of the problem setting, but they further differentiate on the operational level between operational offline planning and operational online planning. While the former points at the fact that decisions are taken in advance, the latter deals with process monitoring and reacting to unforeseen events. The boundaries between the strategic, the tactical and the operational level, however, are seemingly hard to define and hence result in unclear or vague statements. Van Houdenhoven et al. (2007), for instance, state that “strategic planning uses patient forecasts and/or historical information, while tactical planning, like operational planning, deals with actual/expected patients”. In our opinion, only operational problems deal with actual, known patients, while the strategic and tactical problems are formulated in terms of expected patients. Especially a differentiation that is solely based on the time horizon of the problem seems to be ambiguous, as researchers may classify problems with a similar horizon in different categories. We may think, for instance, of a problem in which a set of known surgeries are assigned to the days of one particular week (= operational), while one may also conceive a cyclic block schedule that reserves operating room time for surgeons that is repeated every week (= tactical). An alternative categorization of operating room planning and scheduling problems that is frequently applied in the literature hierarchically distinguishes between case mix planning, master surgery scheduling and case scheduling (see Santibanez et al. (2007) for an example). During the case mix planning phase, available operating room time is assigned to surgeons or specialties. Based on these decisions, a master surgery schedule is developed in a second phase. This schedule can be seen as a (cyclic) timetable that defines the number and type of operating rooms available, the hours that rooms will be open, and the surgical groups or surgeons who are to be given priority for the operating room time. Finally, the case scheduling phase deals with the detailed scheduling of each intervention. Again, we notice that multiple definitions exist to describe the above terms, ending up in confusion, van Oostrum et al. (2008), for instance, describe 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. It should be clear that the optimization problem and granularity that stems for this definition differs from the one that is provided by the former definition. Moreover, not only the definitions seem to vary amongst researchers, also differences in terminology seem to appear. Testi et al. (2007), for instance, refer to session planning instead of case mix planning and to elective case scheduling instead of case scheduling. Note that the addition of “elective” in elective case scheduling actually prohibits the categorization of problems in which emergencies are dealt with. Similarly to the strategic, tactical and operational viewpoint, the division into case mix planning, master surgery scheduling and case scheduling is generally linked to a time horizon, respectively a long-term, a medium-term and a short-term horizon. However, no consistency exists on this issue as well: Hughes and Soliman (1985) study a short-term case mix management problem, while Vissers et al. (2005) talk about patient (= case) mix optimization in tactical cardiothoracic surgery planning.

In order to overcome the existing ambiguities and to provide an alternative to the current classification attempts, we favor the use of descriptive fields. The literature review of Cardoen et al. (2010) provides a head start for the development of an operating room planning and scheduling classification scheme as it is already structured using descriptive fields. The review studies the literature from six different perspectives, namely the patient characteristics, performance measures, decision delineation, research methodology, uncertainty incorporation and the applicability of the research. Building a scheme that consists of six fields, however, violates the requirement to be brief. Therefore, we need to retain only that information that is highly relevant for a clear problem description. Therefore, the main guideline to decide whether a field should take part in the classification scheme, is to identify if it provides information on the problem statement instead of the problem analysis, evaluation or solution. In other words, it does not matter for a correct understanding of the operating room planning or scheduling problem whether real or theoretical data is used to validate the algorithmic solution quality, whether the algorithm is based on dynamic or linear programming, whether the problem is solved to optimality or analyzed by what-if scenarios. As a consequence, including the fields concerning the research methodology or the applicability of the research will not improve the comprehension of the problem statement so that we may exclude these two fields from the classification scheme. This implies that four major fields suffice to provide a problem-based operating room planning and scheduling classification scheme. In particular, we should incorporate information on the patient characteristics, the decision delineation, the uncertainty and the performance measures, as discussed in Section 3.

Although the removed fields do not directly address the statement of the planning or scheduling problem, this does not imply that they are not valuable to the researcher. Moreover, since the specification of the operating room planning or scheduling problem is actually a main characteristic of a paper, one may argue why the scope of the classification scheme is not enlarged from problem classification to paper classification. As long as a single problem is addressed in a paper, this reasoning seems to be valid. However, how should we classify a single paper in which multiple problems are formulated, each solved or analyzed with other techniques and other types of data? In our opinion, classifying problems instead of papers is much more transparent and hence preferred to structure future research.

3. FIELDS, PARAMETERS AND ELEMENTS

Comparably to the machine scheduling and project scheduling domain, we refer to the four fields using Greek symbols. The first field, α, deals with the class of patients that is addressed in the planning or scheduling problem. The second field, β, indicates what type of decision is addressed and to whom it applies. Furthermore, it provides information on the degree of operating room integration with other facilities in the hospital. The third field, γ, indicates to what extent uncertainty is explicitly dealt with in the problem setting. The fourth field, δ, finally represents the performance measures of interest. In the next subsections, we discuss each field in more detail. For each element or further specification, we add in brackets the abbreviation that will be used in the classification notation.

3.1 Field α: Patient Characteristics

The first field, α, provides information on the types or classes of patients that are addressed in the problem. In particular, the field comprises only one parameter

($\alpha = \{\alpha_1\}$) with two elements, i.e. the parameter can take two different values, to delineate the patient characteristics.

- α_1: Patient class: Patients can be treated as elective patients (el) or non-elective patients (nel). The former category represents patients for whom the surgery can be planned in advance, whereas the latter class groups patients for whom a surgery is unexpected and hence needs to be performed urgently. It should be noted that multiple patient types can be addressed in a single planning or scheduling problem.

3.2 Field β: Delineation of the Decision

The introduction of the second field, β, enables researchers to indicate the kind of decisions that have to be taken in their operating room planning and scheduling problem. The field consists of three parameters ($\beta = \{\beta_1, \beta_2, \beta_3\}$). It deals with the following questions: who or what is the subject of the decision (β_1), what type of decision is addressed (β_2) and to what extent is the operating room studied in an integrated way (β_3)?

- β_1: Subject of decision: This parameter indicates to whom the particular decisions apply. We distinguish between four elements: medical disciplines (disc), surgeons (surg), patients or patient types (pat) and other subjects (other), such as hospitals. Patient types typically refer to surgical procedure types, such as a total hip replacement. It should be noted that multiple subjects or levels can be addressed in a single problem.
- β_2: Type of decision: What decision has to be made? We distinguish between five elements: decisions related to the assignment of a date (date, e.g. on Tuesday, on February 12), a time indication (time, e.g. at 10 a.m.), an operating room (room, e.g. operating room 1, operating room of type B), capacity (cap, e.g. three hours of operating room time), or other decisions (other). An example of some other decision can be found in the assignment of patients to surgeons. It should be noted that multiple decision types can be addressed in a single problem.
- β_3: Degree of integration: Does the problem integrate the operating room with other facilities or units in the hospital? We introduce two elements: either the problem studies the operating room in an isolated way (iso), or it integrates the operating room with upstream and/or downstream facilities (int). When integration occurs, we allow for an optional further specification of the linked facilities. We differentiate between the postanesthesia care unit (PACU), the intensive care unit (ICU), the hospital wards (ward) or other facilities (other).

3.3 Field γ: Uncertainty Incorporation

Field γ consists of a single parameter ($\gamma = \{\gamma_1\}$) and indicates the extent of stochasticity that is explicitly dealt with in the problem setting.

- γ_1: Extent of stochasticity: To what extent does the problem explicitly incorporate uncertainty in its description? We identify two elements: the problem can either be deterministic (det) in nature, or stochastic (stoch). We allow for an optional further specification of stochasticity in arrival uncertainty (arr), duration uncertainty (dur) or other kinds of uncertainty (other), such as resource uncertainty or uncertainty in the estimated contribution margins (see Dexter and Ledolter (2003) for an example).

3.4 Field δ: Performance Measures

The fourth and final field (δ) that is required to classify operating room planning and scheduling problems relates to the performance measures or the objectives that are addressed. In particular, two parameters are identified ($\delta = \{\delta_1, \delta_2\}$): the first parameter ($\delta_1$) is related to the question whether the problem addresses multiple objectives, whereas the second parameter (δ_2) lists the types of performance criteria that are incorporated.

- δ_1: Objective scope: Does the problem incorporate a single criterion (single) or multiple criteria (multi) to evaluate solutions to the operating room planning or scheduling problem?
- δ_2: Performance measures: What kind of performance measures are stated or evaluated in the problem? We distinguish between performance criteria that relate to waiting time (wait), throughput (through), utilization (util), overtime (otime), undertime (utime), leveling (level), makespan (C_{max}), deferrals or refusals (defer), financial issues (fin), preferences (pref) or other criteria (other), such as the minimization of the number of operating room openings (see Guinet (2001) for an example). We allow for an optional further specification of utilization as frequently a distinction is observed between overutilization (over) or underutilization (under). Note that the concepts of overutilization and underutilization are different to the concepts of overtime and undertime: one can have an underutilized operating room complex, although overtime may occur in one particular room. Utilization therefore refers to the workload of a resource, whereas overtime and undertime include some timing aspect. Preferences may relate to, e.g., the scheduling of children or prioritized patients as early as possible on the surgery day (see Cardoen et al. (2009) for an example). It should be noted that multiple criteria can be addressed in a single problem.

One may question whether δ_1 is redundant, as the number of elements specified for δ_2 may predict the outcome for δ_1. However, multiple criteria may be addressed under a single type of performance measure. In other words, there is no guarantee that the occurrence of a single type of performance measure also implies that a single objective is used to evaluate procedures or systems. Think, for instance, of a setting in which δ_1 = multi and δ_2 = level. This statement would apply when the problem at hand deals with the leveling of the beds in the PACU and the leveling of the workload in the operating room.

4. DELIMITERS

In order to structure the notation of problems using the classification scheme, a set of delimiters has to be introduced. This is necessary to keep track of the field, parameter, element and further specification hierarchy. An overview of the delimiters is depicted in Table 1. In the next paragraphs, we clarify their use by introducing the delimiters step by step.

Table 1
Summary of the Use of Delimiters in the Classification Scheme

Delimiter	Function	Example
$\vert$	Field delimiter	$\alpha \vert \beta \vert \gamma \vert \delta$
;	Parameter delimiter	$\alpha \vert \beta \vert \gamma \vert \delta_1; \delta_2$
,	Element delimiter	$\alpha \vert \beta \vert \gamma \vert \delta_1$; wait, util
()	Delimiter for further specification of an element	$\alpha \vert \beta \vert \gamma \vert \delta_1$; wait, util (over)
-	Delimiting multiple statements within a further specification	$\alpha \vert \beta \vert \gamma \vert \delta_1$; wait, util (under – over)
{ }	Delimiting a group of coherent statements	$\alpha \vert \{\beta_1; \beta_2; \beta_3\} \{\beta_1; \beta_2; \beta_3\} \vert \gamma \vert \delta$

First, we have to separate the fields from each other. As mentioned in Section 3, the four fields are referred to as α, β, γ and δ. As indicated in Table 1, we separate these fields using a "|" symbol: $\alpha|\beta|\gamma|\delta$.

Second, we can replace the general representation of the fields by their constituting parameters. Since multiple parameters have to be specified for fields β and δ, we also need a delimiter here. Table 1 shows to delimit these parameters using a ";" symbol: $\alpha_1|\beta_1; \beta_2; \beta_3|\gamma_1|\delta_1; \delta_2$.

Third, we have to substitute the parameters by the corresponding element or value that describes the operating room planning and scheduling problem. As mentioned in the introduction, the elements actually provide the real information. Again, multiple elements may be specified for one specific parameter, which also urges the use of a delimiter, namely a "," symbol, in this step. Note that for each parameter at least one element has to be chosen. We illustrate the application of the delimiter for field α: el, nel$|\beta_1; \beta_2; \beta_3|\gamma_1|\delta_1; \delta_2$. This example would imply that the planning or scheduling problem deals with both elective and non-elective patients.

In Section 3, we stated that multiple elements may be optionally further specified so that they also have to be integrated in the classification notation. Each further specification of an element will appear in brackets, as shown in Table 1. Similarly to the previous paragraph, though, multiple specifications may be introduced in the notation for a single element. Therefore, we introduce a "–" as delimiting symbol. We illustrate this structuring approach for field γ: $\alpha_1|\beta_1; \beta_2; \beta_3|$stoch (arr – dur)$|\delta_1; \delta_2$. This notation indicates that the problem at hand explicitly deals with uncertainty, in particular both arrival uncertainty and duration uncertainty.

It may occur that multiple subjects are addressed in the same operating room planning or scheduling problem. Think, for example, of the case in which patients have to be assigned to surgeons and a surgery date has to be assigned to the patients. When these decisions are dealt with in a sequential way, the classification scheme, as it is explained up to now, can be applied and would result in two problems that are consecutively solved, namely α|surg; other; β_3 |γ|δ and α|pat; date; β_3|γ|δ. However, when both decisions are studied simultaneously, the single problem statement would equal α|surg, pat; other, date; β_3|γ|δ. As such, we cannot identify the precise relation between the elements of parameter β_1 and β_2. Therefore, we introduce a final delimiter "{}" to group statements that belong together. We only apply the delimiter when ambiguity may occur. With respect to the example, we hence adapt the statement as follows: α|{surg; other; β_3} {pat; date; β_3}|γ|δ.

5. EXAMPLES

In this section, we illustrate the applicability of the operating room planning and scheduling classification scheme to various problems that are already studied in the literature. We refer to the literature review of Cardoen et al. (2010) for an analysis of the papers that we classify in this section. Figure 2 may assist in the correct determination of a problem's classification notation, as it recapitulates the fields, parameters, elements and further specifications that were introduced throughout this paper. Note that the abbreviations of the elements are quite descriptive instead of mathematical, which should be beneficial for an easy comprehension of the classification notation. This comprehension should be furthermore improved by the absence of blank entries in the scheme (i.e. for each parameter, at least one element has to be specified). Although we believe that this policy increases the clarity of the scheme, it may lengthen the problem's notation.

The problem that is studied by Adan and Vissers (2002) is classified as el|pat; date, cap; int (ICU – ward)|det|multi; util (over – under). From this notation, a lot of information can be deduced. The problem is oriented towards elective surgery. It is formulated in terms of patients or patient types for whom capacity has to be determined and a day or date has to be assigned. These decisions seem to have consequences for other facilities, in particular the wards and the ICU, as the operating room is studied in an integrated way. The problem does not explicitly incorporate uncertainty and is hence deterministic in nature. Multiple objectives are taken into account that are related to the utilization of resources. In the evaluation of the utilization levels, the authors even seem to make a differentiation between overutilization and underutilization.

Dexter et al. (2002) examine the following problem: el|surg; cap; int (ICU – ward)|det|single; fin. In particular, they studied the financial implications of changing the assignment of operating room capacity, which is reserved for elective surgery, to surgeons. They apply a deterministic view but link the operating room to the ICU and the hospital wards.

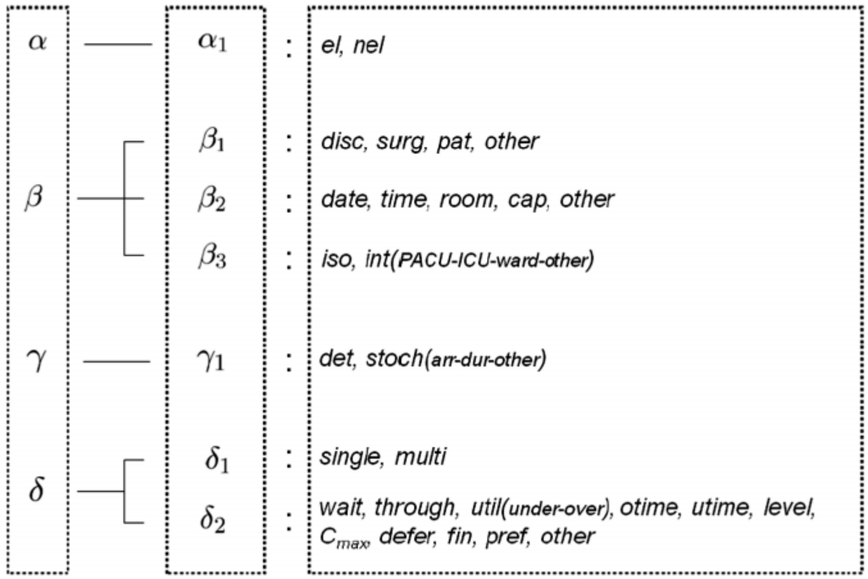

Fig. 2: Overview of the Fields, Parameters, Elements and Further Specifications that Constitute a Classification Scheme for Operating Room Planning and Scheduling Problems

The operating room scheduling problem that is presented by Beliën and Demeulemeester (2007) is summarized by the classification scheme as follows: el|disc; date, time; int (ward)|stoch (arr – dur)|single; level. The authors study the impact of changing the date and the time of operating room inpatient sessions, assigned to medical disciplines, on the demand of a single resource which they try to level. The changes in the operating room schedule seem to have repercussions on the hospital wards and this relation is incorporated in the model. Both arrival uncertainty and duration uncertainty is embedded in the model.

The classification notation of the problem that is addressed by Van Houdenhoven et al. (2007) can be written as follows: el|pat; date, room, cap; iso|stoch (dur)|multi; util, other. Based on this classification, we may assume that this research deals with the assignment of a date, a room and capacity to elective patients. The authors incorporate duration stochasticity. Since their focus is restricted to an isolated set of operating rooms, these durations denote the surgery durations. The various assignments are compared with respect to the operating room utilization and some other criterion, namely the number of freed operating rooms.

Jebali et al. (2006) distinguish between the assignment of surgeries to the operating rooms and the sequencing of these surgeries within each operating room. In the assignment step (el|pat; date, room; int (ICU)|det|multi; otime, utime, wait), they try to minimize operating room overtime, undertime and patient waiting time (between surgery and hospitalization day), whereas the objective in the sequencing step is limited to overtime minimization. They examine the sequencing step both with (el|pat; date, time, room; int (PACU)|det|single; otime) and without (el|pat; time; int (PACU)|det|single; otime) reconsidering the assignments made in the first step. The objective functions are formulated in terms of costs and are optimized using a mixed integer linear programming approach.

A different two-stage approach can be identified in Marcon et al. (2003). In order to master the risk of no realization of surgeries, they make a distinction between a static and a dynamic phase. During the static phase, a multiple knapsack problem is solved in order to get to a fixed schedule. The risk of no realization is captured either by leveling the workload of the operating rooms (el|pat; room; iso|stoch (dur)|single; level) or by avoiding operating room overtime (el|pat; room; iso|stoch (dur)|single; otime). They state, however, that the execution of this schedule during the surgery day will be influenced by unforeseen events. The monitoring and rescheduling due to these events is done in the dynamic phase. Both integer programming and simulation are used to evaluate their procedure.

6. CONCLUSION

In this paper, we introduced a scheme to classify the research on operating room planning and scheduling approaches on the basis of descriptive fields. In particular, we restricted the focus to the classification of operating room planning and scheduling problems. From the original six fields that were discussed by Cardoen et al. (2010), four were retained for the classification scheme (α, β, γ and δ). In short, the classification scheme allows to provide information on the patient characteristics (α), on the type and the subject of the decision that needs to be addressed in the problem and the according degree of operating room integration (β), on the explicit incorporation of uncertainty (γ) and on the particular set of performance criteria (δ). Each field is further detailed using parameters, elements and optional further specifications. By means of some examples, we illustrated that this classification approach satisfies important goals, namely clarity, brevity, exibility and unambiguity. As such, we hope to structure forthcoming research in the domain of operating room planning and scheduling. A major improvement would already be achieved if authors agree to think about the fit between their research and the information provided by the fields while writing down their problem description. This would improve the comprehensibility of the problems and decrease the effort of researchers to identify the operating room planning and scheduling problems that correspond to their research interests.

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