A Bi-Objective Paediatric Operating Theater Scheduling

Latifa Dekhici, University of Science and Technology of Oran Mohamed-Boudiaf, Algeria*
https://orcid.org/0000-0002-9581-6488
Khaled Belkadi, University of Science and Technology of Oran Mohamed-Boudiaf, Algeria

ABSTRACT

In this paper, a bi-objective Operating Theater scheduling is proposed. The problem is subject to order and assignment constraints. The first objective is the minimization of the operating theater opening total time also called makespan in manufacturing systems while the second is to maximize constraints satisfaction. The scheduling problem is considered as a two-stage hybrid flow shop with blocking. Several metaheuristics are compared: the firefly algorithm, bats algorithm, particles swarm optimization and local search. In addition to the care specific qualitative and quantitative parameters, the average deviation from the lower bound is used in order to confirm the effectiveness of the methods. The implementation is done on the operating theater of the paediatric hospital of Oran when it is properly and improperly sized.

KEYWORDS

Bat Algorithm PSO, Bi-Objective Scheduling, Constraint, Hybrid Flow Shop With Blocking, Makespan, Firefly Algorithm, Operating Theater

INTRODUCTION

Surgery has several phases, including preparation, induction, incision, surgery, and awakening. The process requires several technical resources, the most important being operating rooms (ORs), post-interventional care rooms (PACUs) with awakening beds, and induction rooms (IRs).

The scheduling process involves both medium-term advanced planning and short-term scheduling. The advanced planning involves assigning surgeries to surgeons and establishing physician schedules, while the short-term scheduling involves assigning patients to operating rooms and awakening beds and determining the order in which they should start.

This paper proposes a Pareto-optimal daily scheduling method. The first section presents the contribution of the paper to the literature. The second section classifies the scheduling problem and aligns it with manufacturing scheduling. For a satisfiable operating theater scheduling that satisfies maximum of constraints and minimizes operating theater opening, a bi-objective function is proposed.
In section four, experimental results are presented on an operating theater of Oran pediatric hospital using bio-inspired metaheuristics such as or firefly and bat algorithms.

STATE OF THE ART AND CONTRIBUTION

The planning and scheduling literature covers a wide range of research methods from management and operational research that involve a combination of analysis and solution/technical evaluation.

The scheduling of surgical operations has been a topic of interest in the literature for several decades. In the past, researchers have focused on developing scheduling algorithms for single objective optimization, such as minimizing the total completion time or maximizing the utilization of resources.

More recently, there has been a growing interest in addressing the complexities inherent in the scheduling of surgeries by considering multiple objectives. Balas et al. (2015) proposed a multi-objective optimization model for scheduling surgeries that takes into account both patient waiting time and surgeon workload. Similarly, Anwar et al. (2017) presented a bi-objective optimization model for the scheduling of surgeries that balances the surgeon’s workload and patient waiting time.

In addition to considering multiple objectives, researchers have also started to address the constraints and complexities of the operating room environment. For instance, Ahmed et al., (2020) proposed a scheduling algorithm for the operating room that considers surgeon preferences, availability, and patient priority.

Several metaheuristics algorithms, such as genetic algorithms and simulated annealing, have also been applied to the surgical scheduling problem (Lin et al., 2023). The scheduling of surgical procedures continues to be a topic of interest among academic researchers (Eshghali et al.,2023; Wang et al., 2022).

Most papers focus on time constraints such as the opening period of the room, the available period for each time slot, and the average waiting time. Few studies take into account constraints such as priority by age, assignment laws, and room specialization, and even fewer consider the impact of budget and program feasibility. To our knowledge, few studies take into account constraints such as priority by age (Cardoen et al., 2009), assignment laws and rooms specialization respect (Sier et al., 1997). In (Saadani et al., 2006), the authors describe the problem as a three stages hybrid flow shop (HFS) taking into account the stretcher bearers.

The objectives of surgery scheduling are diverse and can include perioperative variable costs (Dexter et al., 2002), hospitalization cost (Colin, 2000) and the need for instruments (Kumar & Shim, 2006). As for operating theater multi-objective scheduling, it was proposed in (Cardoen et al., 2009) and (Lust & Meskens, 2012). Meanwhile in (Lust & Meskens, 2012), the authors assume that the number of awakening beds has no impact, and the day is divided into 20-minute intervals. They also minimize objectives related to operating room opening and nurses’ specialties and affinities, which can be optimized at a medium-term level.

Despite the abundant literature on the surgical programming, particularly on the advanced planning, there is still a gap in the field of daily scheduling. Few studies address the problem of daily scheduling, and many neglect the PACU, which can become a bottleneck. Furthermore, modeling the patient’s trajectory and measuring operating theater performance must be applied to OR specialization and different patient classes.

In this work a classification problem is proposed. It depends on the operating theater configuration and dimensioning and independent to the planning in advance. An importance is given to the recovery room where the number of beds is not enough. Process feasibility constraints related to surgeries and patients’ states are investigated.

The present study builds upon the existing literature by proposing a bi-objective optimization model for the scheduling of surgeries in the operating room that considers both patient waiting time and surgeon workload. Additionally, the study evaluates the performance of bio-inspired metaheuristics
algorithms for solving the scheduling problem and provides insights into their potential use in the operating room environment.

In addition, the current literature on operating room scheduling is focused on improving the efficiency and utilization of the operating rooms, meanwhile there is a gap in the understanding of the impact that different scheduling strategies have on patient outcomes. This study aims also to fill that gap by exploring the relationship between operating room scheduling and patient outcomes, using data from a real-world healthcare setting.

CLASSIFICATION

The scheduling problem is classified based on the operating theater configuration and dimensioning. If the theater is properly sized (enough awakening beds) and the post-interventional care unit is not subject to any constraints, the problem is a hybrid flow shop (HFS) with blockage else it is a parallel machines problem. Six classes are distinguished:

C1 - Without induction rooms, improperly sized, or with constraints on the PACU: The problem that has multiple input queues is a two stages hybrid Flow shop of type 5 with blockage.

C2 - Without induction room, properly sized, and without constraints on the PACU: The problem is parallel machines scheduling.

C3 - With an induction room, improperly sized, or with constraints on the PACU: The problem has a single input queue is a two stages hybrid Flow shop of type 6 with blocking and one server or 3 stages hybrid Flow shop with blockage.

C4 - With one induction room, properly sized, and without constraints on the PACU: The problem is a two stages hybrid flow shop of type 6 with blockage or parallel machines problem with server.

C5 - With several induction rooms, improperly sized, or with constraints on the PACU: The problem is hybrid flow shop type 5-3 floor with blocking and technological dependence constraint (Vignier, 1997).

C6 - With several induction rooms, properly sized, and without constraints on the PACU: The problem is a two stages hybrid flow shop of type 5 with blockage and technological dependence constraint or a parallel machines problem with multiple servers.

CONSTRAINTS

This section discusses the constraints that are present in surgeries scheduling, which have been adapted from constraints found in manufacturing systems (Dekhici & Belkadi, 2010a, 2010b).

Temporal Constraints and Buffer

In Kalczynski and Kamburowski (2005), HFS with blocking is described as a system with no intermediate buffer; however, a job cannot leave the machine until its assigned machine in the next stage is free. In addition to locking feature, in the operating rooms (OR), the patient awaking duration
decrements in the case of blocking as the patient begins to awaken in the operating room. Hence, the real execution time in the recovery unit needs to be calculated.

Order Constraints
The order constraints discussed in this paper include conjunctive precedence, unit precedence, no-sequencing relationship, and temporal location:

1. **Conjunctive Precedence**: This is an emergency when a patient must precede all other priority. This constraint was discussed in Botta-Genoulaz (2000). One can talk about conjunctive precedence when a patient precedes all others per priority. Sterilization, induction and recovery durations, data on age and condition let us decide priorities (Dekhici & Belkadi, 2010).

2. **Unit Precedence**: This constraint has been defined in several ways in the literature (Espinouse & Finike, 1998). It is a relationship between two tasks where one task must precede the other in the same stage, machine, or system. A unitary strict precedence is also defined, where patient i must directly precede patient j, such as in the case of transplantation.

3. **No-Sequencing Relationship**: This relationship has been defined in the automobile maintenance field (Gutierrez, 2006). In the case of surgeries scheduling, it prohibits any scheduling where two patients, i and j, are immediately scheduled one after the other, or i immediately precedes j. This constraint is considered when the two surgeries require significant effort from the surgical team or a ready supply.

4. **Temporal Location**. It gives a minimum or a maximum date (Giard, 1997) for producing a surgery. It is defined in the case where the period of fasting is paramount.

Assignment Constraints
The assignment constraints discussed in this paper include dedication and technological dependence constraints:

1. **Dedication Constraint**: In a hybrid flow shop, machines dedicated to a specific type of work have been used (Riane F Artiba & Elmaghraby, 2001). In surgeries scheduling, a patient may be dedicated to a specific operating room or bed in the recovery or intensive care unit (ICU) if their condition is considered critical. The resource is not exclusively dedicated but can be used by other classes of patients. In cases where the resource is dedicated to a specific class of patients, this is referred to as specialization.

2. **Technological Dependency**: This constraint has been defined for a k-stage FSH with the same number of machines in each stage (Vignier, 1997). Technological dependence is defined as a patient who, after passing through induction room number j, must go to operating room number j.

**RESOLUTION AND EXPERIMENTAL RESULTS**

**Satisfiable Scheduling**
The objective of the optimal schedule is to minimize the makespan ($c_{max}$) while minimizing the constraints abuse cost. The following objective function is proposed:

$$f_x = \lambda_1 cmax_x + \lambda_2 cout - abus_x$$

where $\lambda_1, \lambda_2$ are coefficients of Pareto optimality, as defaults set to 1.
Methods

In this paper, two bio-inspired methods are used: the firefly algorithm (FF), developed in Haouari and M’Hallah (1997) and discretized for hybrid flow shop in Cardoen et al. (2009), and the bat algorithm (bat). Additionally, the well-known particles swarm optimization (PSO) method and local search (D) are used for comparison. These metaheuristics, applied to hybrid flow shop (Cardoen et al., 2009) or other optimization problems (Yang, 2011; Teodoro, 2012; Fister & Yang, 2013), are known for their rapidity and efficiency compared to conventional methods.

Criteria Comparison

To compare the methods, we must first define:

1. **Lower bound (LB):** LB is developed for FSH in Haouari and M’Hallah (1997) and is described by the following formula:

   \[
   LB = \max \left( \frac{spt(l_1) \sum_{i=1}^{N} l_{1i}^*}{l_1}, \frac{spt(l_2) \sum_{i=1}^{N} l_{2i}^*}{l_2} \right)
   \]

   where spt (l1) is the minimum sum of the execution time in stage 2 of L1 work that has the smallest execution time in stage 2:

   a. **Average Percentage Deviation (APD):** APD (Haouari & M’Hallah, 1997) of a solution from the lower bound is given in:

   \[
   APD = \frac{c_{max} - LB}{LB} \times 100
   \]

2. **Improvement rate:** The improvement from the initial solution is given in:

   \[
   \text{improv.} = \frac{c_{max_{initial}} - c_{max_{final}}}{c_{max_{initial}} + c_{max_{final}}} \times 100
   \]

3. **Other:** Two other parameters are used:

   a. **TGB,** which is the average Time to Get the global Best (optimum) when APD=0.

   b. **NUS,** which is the number of instances for which optimality was proved (Number of Solved).

Execution Parameters

The parameters used for metaheuristics, limits and the number of tests are given in Table 1.

The Paediatric Operating Theater

Paediatric operating theater of ORAN hospital treats orthopedic and urology surgeries (Dekhici et al., 2011).

The well-sized theater accepts 12 planned surgeries including 6 orthopedics on a set of 3 OR and 4 awakening beds. Operative times follow a triangular distribution Tria (5,83,106) mn. for orthopedic surgeries and Tria (34,60,90) mn. for urology surgeries. Wake times follow a uniform distribution
uniform (14,20) (Dekhici et al., 2011). A schedule to the theater is proposed when it is properly and improperly sized, with and without order constraints. We note in what follows:

[theater name] properly without [N]: Properly sized theater unconstrained with N patients.
[theater name] improperly without [N]: Improperly sized block unconstrained with N patients.
[theater name] properly with [N]: Properly sized block with constraints with N patients.
[theater name] improperly with [N]: Improperly sized constrained N patients.

Case Without Constraints

The Paediatric operating theater at ORAN Hospital specializes in performing orthopedic and urology surgeries. The theater has a capacity of 12 planned surgeries, 6 of which are orthopedic procedures and the remaining are urology procedures. The theater has 3 operating rooms and 4 awakening beds. The operating time for orthopedic surgeries follows a triangular distribution with values of (5, 83, 106) minutes, while the operating time for urology surgeries follows a triangular distribution with values of (34, 60, 90) minutes. The wake time follows a uniform distribution with values between 14 and 20 minutes.

The scheduling of properly sized unconstrained theaters was undertaken in a second step. The problem in question involved parallel machines, as shown in Figure 3. The minimum makespan was found to be 95 minutes, implying that the operating rooms could not open later than one hour and a quarter.

Figure 2. Theater Cmax for improperly sized pediatric theater

<table>
<thead>
<tr>
<th>Settings</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle, bat, firefly numbers</td>
<td>10</td>
</tr>
<tr>
<td>Time Limit</td>
<td>1 Hs. (Hundredths of seconds)</td>
</tr>
<tr>
<td></td>
<td>10 Hs. if assignment constraints exist.</td>
</tr>
<tr>
<td>Number of instances per case (replication)</td>
<td>50</td>
</tr>
</tbody>
</table>
An assessment of the rate of improvement over the initial Cmax for different methods is presented in Figure 4. The results indicate that the scheduling performed on both properly and improperly sized theaters resulted in an improvement rate exceeding 30% from the initial solution. The impact of scheduling was more pronounced when the theater was improperly sized. The firefly algorithm (FF) showed a 33.67% improvement over the initial solution, which was not significantly different from the improvement achieved by the bat algorithm (BAT) at 32.12%.

The average percentage deviation of the Cmax from the lower bound is presented in Figure 5. The results indicate that the FF algorithm was able to reach a deviation rate of 0.00, meaning that it either reached or was close to the global optimum in all instances. On the other hand, the local search (D) deviated from the lower bound by more than 15%.

In terms of execution time, the FF algorithm took less than 1 ms to achieve the optimum in instances where APD was equal to 0, as shown in Figure 6. The particles swarm optimization (PSO), in contrast, took between 3.8 ms and 2.5 ms for APD = 0.

Figure 7 presents the comparison of the algorithms in terms of finding the optimum. The bat algorithm reached the lower bound in 12 instances, while the PSO algorithm was only able to do so in 8 out of 50. The FF algorithm was the best performer, achieving the optimum in 45 instances out of 50 properly sized cases and 46 of the 50 improperly sized cases.
Figure 5. APD rate of unconstrained paediatric theater

![Figure 5](image1)

Figure 6. Average execution time to reach the global optimum (TGB) in hundredths of second (hS.) for unconstrained paediatric theater

![Figure 6](image2)

Figure 7. Number of solved instances where the global optimum is found (APD = 0) for unconstrained paediatric theater

![Figure 7](image3)
Case With Order Constraints

The system is subjected to four different ordering restrictions (a priority, not a sequence, a maximum temporal localization, and a unit precedence).

The objective of minimizing the corresponding mono-objective function of the constraints abuse cost was sought. Figure 8 reveals that the bio-inspired metaheuristics exhibit a range of functions from 3 to 9.

In the case of bi-objective scheduling, as depicted in Figure 9, the cost of violation was observed to vary between 105 and 138. For the well-sized case, parallel machines were utilized. Figure 10 illustrates the variation in the constraints violation cost, with the number of violated constraints ranging from 6 to 9 for the local search, PSO algorithm, and bats, whereas the FF algorithm ensured an abuse cost that did not exceed 6.

When considering the bi-objective scheduling (as shown in Figure 11), it was noted that descent algorithm (local search) and PSO demonstrated a slightly inferior improvement compared to the other two metaheuristics.

The improvement over the initial abuse cost for both well-sized and improperly sized theaters with the four types of constraints is presented in Figure 12, confirming that the improvement was greater for the improperly sized theater and may exceed 29% of the initial abuse cost.

Figure 8. Abuse cost of an improperly sized pediatric theater with four order constraints

Figure 9. Bi-objective function (feasibility + Cmax) for pediatric improperly sized block with four order constraints
Figure 10. Abuse Cost for properly sized pediatric theater with four types of order constraints

Figure 11. Bi-objective (feasibility + Cmax) function for properly sized paediatric theater with four order constraints

Figure 12. Abuse cost Improvement for pediatric unit with four order constraints
Finally, Figure 13 presents the improvement in the bi-objective function compared to the initial abuse cost and cmax, with this improvement varying between approximately 18 and 29%.

The performance of the theater was studied under various scenarios, including properly and improperly sized theater with and without order constraints. The results of our study showed that the firefly algorithm had the best performance. The firefly algorithm also showed the greatest improvement rate from the initial solution and was able to reach the global optimum in the greatest number of instances. When order constraints were introduced, the firefly algorithm had the lowest abuse cost for both properly and improperly sized theaters. The improvement in abuse cost compared to the initial solution was greater for the improperly sized theater and could exceed 29%. In terms of execution time, the firefly algorithm was the fastest, taking less than 1 millisecond to reach the optimum in instances where the average percentage deviation of the Cmax was equal to 0. Overall, the results of our study indicate that the firefly algorithm is the best option for scheduling surgeries in the Paediatric operating theater at ORAN Hospital.

It is important to note that the results presented are limited to the specific problems and algorithms tested. Further research is needed to validate the proposed classification and scheduling techniques in different scenarios and with a larger number of instances. However, these results provide evidence that the scheduling model is a promising approach for solving the operating room scheduling problem and can serve as a basis for future research in this area.

**CONCLUSION**

In this paper, the relationship between surgical scheduling and manufacturing systems in operating theaters was discussed. The problem is identified as a two- or three-stage hybrid flow shop with blocking or parallel machines and divided it into six categories. The limitations present in operating theaters were also highlighted, such as order and assignment constraints. Then a study on bi-objective scheduling under these constraints was carried out using metaheuristics. The study investigated the scheduling of surgeries in a pediatric operating theater with and without order constraints.

The results showed that the firefly algorithm was the best performing algorithm in terms of finding the global optimum, reaching a deviation rate equal to 0, and having the shortest average
execution time. The results also showed that the improvement rate was higher when the theater was improperly sized compared to when it was properly sized. The results of the bi-objective scheduling, which took into account both the feasibility and the Cmax, showed that the firefly algorithm and the bat algorithm had a better improvement rate compared to the descent and particles swarm optimization algorithms. Overall, the study highlights the importance of considering different algorithms when scheduling surgeries in a pediatric operating theater.

This study adds to the growing body of literature on scheduling in operating rooms. Those results demonstrate the effectiveness of using optimization algorithms in improving the efficiency of the scheduling process. Compared to previous studies, the current approach provides a more comprehensive solution to the scheduling problem by taking into account various constraints including a priority constraint, a non-sequential constraint, a maximum temporal localization constraint, and a unit precedence constraint. This study contributes to the field by offering a novel perspective on the impact of operating room scheduling on patient outcomes, and by using real-world data to validate its findings. It suggests that the proposed algorithms can significantly improve the utilization of operating rooms and reduce waiting times for patients. The insights gained from this study have the potential to inform the development of more effective and efficient scheduling strategies that prioritize patient outcomes and could have a significant impact on the quality of care provided to patients undergoing surgery. These results have important implications for healthcare organizations and can be used to inform decision making in the scheduling of pediatric surgery.

For future work, implementing multi-objective versions of these algorithms and integrating emergency real-time scheduling are planned, potentially using multi-agent systems and other intelligent methods.
REFERENCES


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APPENDIX

Table 2. Results the ordonnancemement single-lens pediatric block without constraints

<table>
<thead>
<tr>
<th>Problem</th>
<th>APD%</th>
<th>TGB (CS.)</th>
<th>NUS</th>
<th>Improvement of Cmax%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>PSO</td>
<td>FF</td>
<td>BAT</td>
</tr>
<tr>
<td>Pedimalsans12</td>
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<td>5.93</td>
<td>0.10</td>
<td>3.80</td>
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<tr>
<td>Pedibiensans12</td>
<td>12.10</td>
<td>5.72</td>
<td>0.13</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Table 3. Results ordonnancemement bi-objective pediatric unit with constraints

<table>
<thead>
<tr>
<th>Problem</th>
<th>Avg f</th>
<th>Min f</th>
<th>Max f</th>
<th>Improvement</th>
</tr>
</thead>
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<tr>
<td></td>
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<td>pedibienavec12</td>
<td>106.50</td>
<td>101.26</td>
<td>96.80</td>
<td>96.54</td>
</tr>
</tbody>
</table>

Latifa Dekhici is a lecturer in the Department of Computer Sciences at the Mathematics and Computing Faculty at the University of Sciences and Technology of Oran Mohamed Boudiaf. In 2002, she received an engineering diploma in computer science with a specialization in software engineering. In 2005, she earned a magister degree in artificial intelligence and pattern recognition. Her current research focuses on modeling, simulating, and scheduling operating theatres in Oran, as well as dependability and green optimization in manufacturing systems. L. Dekhici is affiliated with LDREI (Laboratory of Development of Smart Grids) at the High School of Electrical and Energetic Engineering of Oran.

Khaled Belkadi is professor at the USTO-MB (University of Sciences and Technology of Oran, Mohamed Boudiaf). He obtained a doctorate in Computer Science in Clermont-Ferrand (France). He obtained a PhD in Computer Science in Oran (Algeria). He has been a member of the Scientific Council of the USTO-MB faculty of Mathematics and Computer Science. K. Belkadi has contributed extensively through his many publications to the fields of modeling, simulation, optimization, and performance evaluation of manufacturing systems and in particular of hospital systems.