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Operational strategies to manage non-elective orthopaedic surgical flows. A simulation modelling study

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TITLE PAGE

Title

Operational strategies to manage non-elective orthopaedic surgical flows. A simulation modelling study

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Keywords

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Abstract

Objectives

To apply simulation modelling to evaluate the effects of strategies to plan and schedule operating room (OR) resources aimed at reducing time to surgery for non-elective orthopaedic inpatients.

Methods

We applied Discrete Event Simulation modelling. The model was populated with data from a Swedish university hospital with a strong focus on reducing waiting time to surgery for patients with hip fracture. The system modelled concerned non-elective patients in need of orthopaedic surgical treatment. Both hip-fracture and other non-elective orthopaedic patients were included because they share the same OR resources. The experiment was conducted by simulating three scenarios. These scenarios were developed based on the literature and interaction with staff and managers at the hospital site and they were: 1) baseline; 2) reduced turnover time between surgeries by 20 minutes; 3) one extra OR during day time. The outcome variables were waiting time to surgery and the percentage of patients who waited longer than 24 hours for surgery.

Results

The mean waiting time in hours was significantly reduced from 16.2 hours in scenario 1 (baseline) to 13.3 hours in scenario 2 and 13.6 hours in scenario 3 for hip-fracture surgery and from 26.0 hours in baseline to 18.9 hours in scenario 2 and 18.5 hours in scenario 3 for other non-elective patients. The percentage of patients who were treated within 24 hours significantly increased from 86.4% (baseline) to 96.1% (scenario 2) and 95.1% (scenario 3) for hip-fracture patients and from 60.2% (baseline) to 79.8% (scenario 2) and 79.8% (scenario 3) for patients with other non-elective patients.

Conclusions

Healthcare managers who strive to improve the timelines of non-elective orthopaedic surgeries may benefit from focusing on reducing turnover times. This strategy can yield the same results as an extra OR and does not necessarily require additional costs.

Strengths and limitations of this study

- The simulation experiment was conducted with real world data from a Swedish university hospital.
- This is one of the few studies applying simulation modelling to non-elective patient flows.
- The simulation study has been carried out in collaboration with hospital staff and the model was continuously validated.
- The outcome variables were limited to waiting time and percentage of patients undergoing surgery within 24 hours.
- Unexpected incidents such as patient health status or employee sick leave were not included in the simulation model.

Introduction

The planning and scheduling of activities in the operating room (OR) is a complex task and if done inappropriately it can generate unnecessary costs and delays in patient treatment.[1] The negative consequences of poorly managed OR resources becomes evident for patients with hip fracture. Delay to surgery is associated with post-operative complications, prolonged recovery and length of stay, as well as increased mortality.[2-5] Despite the positive effects of improvement efforts to reduce waiting time to surgery, the management of ORs resources still represents a challenge for the timely delivery of surgical services for this vulnerable patient group.[6, 7]

One of the challenges in the management of OR resources relates to the management of multiple patient groups that compete for the same resources. A major issue is the trade-off between elective and non-elective cases.[8, 9] In orthopaedics, non-elective surgical cases have historically been added to the elective schedules which result into several problems including disruptions to elective cases and after-hour surgery.[10, 11] To overcome these problems, hospitals have introduced dedicated day-time orthopaedic ORs for non-elective orthopaedic patients. The use of dedicated orthopaedic ORs is associated with shorter after-hour surgeries for trauma cases and less disruptions to elective schedules,[8, 12] as well as improved patient care, e.g. decreased rates of perioperative mortality, post-operative complications, and length of stay.[13] The management of non-elective orthopaedic patient flows, is however still a challenge as it is often based on "ad-hoc" strategies,[14] and limited research is applied to non-elective patient flows.[1]

Simulation modelling is one approach that can help to develop effective strategies to plan non-elective surgeries. Stemming from Operations Research, simulation modelling allows for the development and testing of changes before they are implemented in reality.[15, 16] Simulation modelling can also function as a system analysis tool[17] to identify processes in need of improvement in order to reach the goals of the organization. Simulation modelling applied to operating room departments and surgery often focuses on optimising capacity of flows, schedule and utilization.[18-20] However, most research still focuses on elective patients despite the challenge non-elective patients represent when it comes to planning care.[1]

Aim

In this study we applied simulation modelling to evaluate the effects of strategies to plan and schedule OR resources aimed at reducing the time to surgery for non-elective orthopaedic inpatients. We specifically analysed the effects for patients with hip fracture and other non-elective orthopaedic inpatients. These patients often share OR resources with other non-elective orthopaedic patients, and therefore it is of importance to include both patient groups in the analysis.

Method

The applied simulation method was Discrete Event Simulation (DES). DES is often applied to healthcare for patient-flow management, resource allocation, and scheduling,[21] and is the predominant method used in surgical care.[22] DES represents the components of a system and their interactions and looks at specific events in a given process (e.g. surgical procedure) and their chronological sequence.[23]The state of the system observed and simulated is updated as each event takes place making DES a suitable tool to evaluate and improve system performance.[24] The effects of OR planning and scheduling strategies were measured by waiting time to surgery and the percentage of patients operated within 24 hours, a common improvement target for patients with hip fracture.[7] The study has been granted ethical approval by the Regional Ethics Committee in Stockholm (ref no. 2009/1657-31).

Setting

This study was carried out at a Swedish university hospital with a catchment area of approximately 450,000 inhabitants. The 52-bed orthopaedic department has an annual admittance of approximately 3,700 patients, mainly for non-elective care. Patients with hip fractures constitute the major non-elective group with an annual surgical rate of approximately 600 fractures. In Sweden, the National Board of Health and Welfare recommends that patients with hip fracture receive surgical treatment within 24 hours from admission.[25] When this study was conducted, the County Council requirement was that 80% of patients with a hip fracture should be operated within 24 hours from admission. At the hospital, several efforts have been made during the years to reach this goal. Despite the improvement observed, variability in the process still exist.[7] Staff and managers at the hospital expressed that further improvement could be achieved by improving the process at the OR, which became the focus of the simulation model.

There were 12 ORs at the current OR department and five (six on Mondays) were dedicated for orthopaedic surgeries and the remainder were dedicated for general surgical and urological cases. Two ORs were dedicated during day shift to serve non-elective orthopaedic surgeries and one OR during night shift. At weekends there was one OR dedicated during both the day and night shift. In 2014, a total of 10,574 surgeries were performed at the operating department; of these 4,512 were orthopaedic surgeries, 2,230 non-elective and 2,282 elective surgeries. Normally, according to a regional guideline, multi trauma cases were treated at another hospital in the County Council and therefore very few underwent surgery at this hospital.

Simulation model

The system modelled used real patient data from 2013 and concerned hip-fracture patients and other non-elective patients arriving for orthopaedic surgery. In the model, we only considered patients who required surgery, and hence, assumed to have already been assessed for surgical needs. However, in reality the time which elapses before surgery actually is scheduled, varies greatly, depending on patient condition, as some patients require other pre-investigations and/or treatments prior to surgery, e.g, stabilization for several days. This variation was not added to the model, as it is was not considered to be a hospital-related delay to surgery. Nonetheless, we did add a short time to each of the modelled patients waiting to undergo surgery as they were not very likely to be scheduled for surgery immediately after being assessed by an orthopaedic surgeon. This time was computed as the mean for the 20 fastest patients in the hip-fracture and other non-elective patient groups respectively, i.e., patients that computed the fastest elapsed time, from the time when the patient was admitted to the hospital to the time the patient entered the OR.

Furthermore, we divided the patients into two separate groups (queues), one queue for hip-fracture surgery and one for the remaining orthopaedic non-elective surgical cases (figure 1). These two patient groups shared the same OR resources. Given the few multi trauma cases, the hip-surgery patient in general was considered to have a higher priority and therefore the hip-surgery queue was given higher priority than the other orthopaedic queue. Both queues were modelled by first-come-first-served processing rule. The number of ORs were dynamically modelled according to the authentic number of ORs open for a specific day in the week. In the same way, we modelled the opening hours of the ORs according to how long the specific OR was open for a specific day in week in reality.

< Insert Figure 1 here >

First, the patients arrived according to an arrival process $\alpha(x)$ and were placed in one of the two queues according to the described rules above (figure 1). The process $\alpha(x)$ was assumed to be Poisson, i.e., having exponential arrival intervals with a calculated arrival mean derived for each hour during the day and night.[26] If one of the operating rooms was available, i.e., not occupied with another surgical procedure or closed, the simulation model searched the queues for a patient ready to undergo surgery according to a prioritization scheme (described in the experiment). If a patient's estimated surgical procedure time exceeded the remaining OR opening hours, the patient was forced to wait (remain in the queue) until the next day, and instead the next patient in line was processed. The estimated surgical procedure time, was based on the mean procedure time for a particular procedure, whereas the simulated surgical procedure time was drawn from a log-normal distribution[27] and was unknown before the simulated surgery started. This means that the opening hours of an OR may be exceeded and over time will be required in order to complete the surgical procedure already underway. After surgery was completed, the patient was sent out of the system.

The data obtained from the hospital was pre-processed by use of Python script language and the simulation model was developed in Java.

Simulation experiment with scenarios

The simulation experiment was set up to evaluate the effects of three scenarios on the mean waiting time and the percentage of patients waiting longer than 24 hours for surgery. These two variables were measured for both hip-fracture patients and other non-elective orthopaedic patients. The experiment was conducted by simulating three scenarios that were developed based on the literature and through interactions with staff and managers at the hospital. The first scenario represented the planning and scheduling of the non-elective orthopaedic cases using current practice (baseline scenario), the second scenario represented current practice but the turnover between surgeries was reduced by 20 minutes and the third scenario represented current practice with the exception of one extra OR in day time (Monday to Friday). Scenario 2 and 3 represent potential areas for improvements discussed at the involved departments, i.e., the operating department, the orthopaedic department and the anaesthesia and intensive care department. Each scenario was simulated 10 times using different random seeds.

Non-elective orthopaedic data from 2013 extracted from the hospital OR-system was used as input to the simulation model. After ocular inspection, incomplete case records were omitted from the data set. In table 1 the various setting parameters used for the simulation are listed. The prioritization parameter at the bottom in the table describes the logical flow of how the priority between hip-fracture patients and other non-elective orthopaedic patients was simulated.

The turnover time including post - and pre-procedure of two subsequent surgical cases was estimated at the included hospital to be 60-90 minutes depending on the surgical cases. A reduction of 20 minutes turnover time altogether was deemed reasonable and well motivated by the staff.

To ensure that the simulation model was a representation of, or as close to, the real orthopaedic surgical system as possible, the model was validated continuously throughout the study. Several meetings with orthopaedic surgeons, anaesthesiologists, OR nurses, OR coordinators and registered nurse anaesthetists were carried out along with intermittent observations at the operating department.

< Insert Table 1 here >

Table 1. Description of parameters used in the simulation model

Parameter	Value in baseline scenario	Distribution type	Data source
OR opening	8.00 am		Personal communication with staff
OR closing (day time)	4.00 pm		Personal communication with staff
OR closing (Friday)	2.00 pm		Personal communication with staff
OR closing (night shift)	9.00 pm		Personal communication with staff
Number of ORs open per week	2 OR day time and 1 OR evening shift. Weekends: 1 OR daytime and 1 OR evening shift		Expert opinion
Patient arrival		Poisson	OR scheduling system
Time from Emergency Department to OR	5 hours for hip-fracture patients and 3.5 hours for other non-elective patients		Patient records
Simulated surgical procedure time	All patient time included. Included surgical preparation as cleaning and anaesthesia, i.e., pre- and post-procedure	Lognormal	OR scheduling system
Planned surgical procedure time	Mean (all patient time included)		OR scheduling system
Turnover time	The turnover time including post- and pre -procedure of two subsequent surgical cases was estimated to be 60-90 minutes		Expert opinion
Prioritization (hip-fracture patients vs other non-elective patients)	a. **If** hip < 24h **and** other < 36h **then** hip priority		
	b. **If** hip < 24h **and** other > 36h **then** other priority		Expert opinion
	c. **If** hip > 24h **and** other > 36h **then** hip priority		
	d. **If** other > 36h **and** postponed **then** other priority		

Statistical analysis

The arrival of patients was modelled by a Poisson process and the uncertainty of surgical duration was modelled by a log-normal distribution. A parametric approach using 95% confidence intervals for waiting time in hours and percentage of cases treated within 24 hours was used to compare the three scenarios. Box-plot was used to graphically represent the data.

Results

The reduction of the turnover time by 20 minutes (scenario 2) and the introduction of an extra OR during day time (scenario 3) contributed to a significant, as indicated by the lack of overlapping between the confidence intervals, reduction in waiting time to surgery for both patient groups, compared to scenario 1 (baseline). For hip-fracture patients, the mean waiting time decreased from 16.2 hours in scenario 1 to 13.3 hours in scenario 2 and 13.6 hours in scenario 3. The corresponding change in mean waiting time for the other non-elective patients was a reduction from 26.3 hours to 18.9 hours and from 26.3 hours to 18.5 hours, in scenario 2 and 3 respectively (table 2).

< Insert Table 2 here >

Table 2. Performance of the three simulated scenarios

		Scenario 1 (baseline)	**Scenario 2**	**Scenario 3**
Mean waiting time in hours with 95% confidence interval	Hip-fracture patients	16.2 hours (95% CI, 15.4-17.1)	13.3 hours (95% CI, 13.1-13.5)	13.6 hours (95% CI, 13.4-13.9)
	Other non-elective patients	26.3 hours (95% CI, 24..3-27.6)	18.9 hours (95% CI, 18.1-19.7)	18.5 hours (95% CI, 18.1-19.0)
Percentage of patients treated within 24 hours with 95% confidence interval	Hip-fracture patients	86.4% (95% CI, 83.5-89.3)	96.1% (95% CI, 95.5-96.7)	95.1% (95% CI, 94.0-96.1)
	Other non-elective patients	60.2% (95% CI, 56,9-63.7)	79.8% (95% CI, 77.6-82.1)	79.8% (95% CI, 78.5-81.1)

The level of improvement achieved in scenario 2 and, compared to baseline, were similar for both scenarios. Scenarios 2 and 3 showed better results for all simulation runs compared to

baseline except for one run in scenario 3 (figure 2). Figure 3 shows the same results, viewed as box plot.

< Insert Figure 2 here >

< Insert Figure 3 here >

Significant results were also observed for the percentage of patients who waited longer than 24 hours for surgical treatment, i.e. similar levels of improvement were identified for scenario 2 and 3 compared to baseline (table 2).

The percentage of hip-fracture patients who underwent surgery within 24 hours was simulated at 86.4% in the baseline scenario. In scenario 2 and 3, however, simulated results showed that 96.1% and 95.1%, respectively, of the hip-fracture patients underwent surgery within 24 hours. Furthermore, in the other non-elective patient group a significant increase in percentage of patients who underwent surgery within 24 hours were simulated in scenario 2 (79.8%) and 3 (79.8%) compared to baseline (60.2%) (table 2).

Discussion

In this paper we investigated how different operational strategies influence waiting time to surgery for patients with hip fracture and other non-elective orthopaedic patients. We found that a reduction in turnover time by 20 minutes in an OR can yield the same level of improvement as adding an extra OR during daytime.

This study contributes to the literature on how to improve the planning and scheduling of non-elective patient flows using simulation, a field in which empirical research is limited.[1] The main contribution lies in showing how, in a hospital setting where non-elective orthopaedic surgeries are performed in dedicated ORs, the reduction of the turnover time may have the same effect as adding an extra OR. The latter strategy may yield higher costs as it would require investing in additional human resources, physical space and associated equipment. The experimental results can be explained by the pattern in patient arrival rate. An increase in OR resources during the daytime has limited effect on waiting time since non-elective patients typically arrive 24 hours a day, 7 days a week, although the arrival rate is likely to be less frequent during the night. If health care organizations manage to reduce the turnover time in their ORs, they are also likely to improve the clinical outcomes for patients.[2-5]

Previous studies of elective patient flows suggest several strategies for how to reduce turnover time, for instance through parallel processing.[28, 29] Friedman and colleagues found that turnover time could be reduced through parallel processing in ORs designed for outpatient inguinal hernia repair. Parallel processing was achieved without additional resources by having the operating team of surgeon, nurses, and scrub technicians working on two patients simultaneously. The maintenance of a constant team throughout the entire day also contributed to the observed improvement.[29] Another approach to parallel processing is to start the pre-procedure of the upcoming surgical case before the post-procedure of the current surgical case is closed. However, this approach requires extra resources in terms of surgical teams. Holmgren and Persson present an optimization model that sequence surgical cases in such a way that parallel processes are scheduled for many ORs subject to a limited number of surgical teams.[28] Future studies can investigate how parallel processing, as well as other strategies, can be used to improve the efficiency of non-elective surgical flows.

Strengths and weaknesses of the study

The main strengths of this study are that is was based on real world data from a hospital and the development of the model was grounded on the real needs of hospital staff and managers who had worked for several years to reduce waiting time to surgery for patients with hip fracture.[7] The model itself was developed and validated in collaboration with hospital staff and managers, a process that is of key importance.[30, 31]

The main limitations of the study are twofold. First, the simulation model does not take into account unexpected incidents such as patient health status (not being well enough to undergo a surgical procedure) or sick leave of employees. Hence, the results simulated, both baseline and the comparing scenarios, are somewhat overestimated. We sought to overcome this limitation by considering the relative performance, i.e. the difference in results between scenarios. Second, the outcome variables included were limited to waiting time and percentage of patients undergoing surgery within 24 hours. A more comprehensive evaluation of performance, including measures of cost, utilization rates of the OR, and percentage of cancelled surgeries, can be a way forward to develop better strategies for the management of non-elective patient flows.

Conclusion

We conclude that a reduction of only 20 minutes in OR turnover time yields almost the same effect in patient waiting time as the addition of one extra OR during the daytime. Future research can investigate how this reduction in turnover time can be reached for non-elective patient flows and the health economic effects of this strategy. This study shows that simulation modelling can help understand system performance. We therefore suggest that simulation modelling can become an integral part of health care development to investigate improvement strategies with healthcare managers and professionals.

Contributorship statement

MP, HHF, MU, OGS, AS, PKP, and PM designed the study. MP, MU, PKP, OGS, and PM collected the data. All authors contributed to the development of the model and MP conducted the implementation of the model and result analysis. MP, HHF, MU, and PM drafted the manuscript. OGS, AS, and PKP read and critically revised the manuscript. All authors approved the final manuscript and are accountable for all parts of the work.

Competing Interests

The authors declare that they have no competing interests.

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Data sharing statement

The Excel file with the input and output data from the simulation model (i.e. key activities carried out in the care process and the time when they were carried out) is available upon request by e-mailing marie.persson@bth.se or pamela.mazzocato@ki.se.

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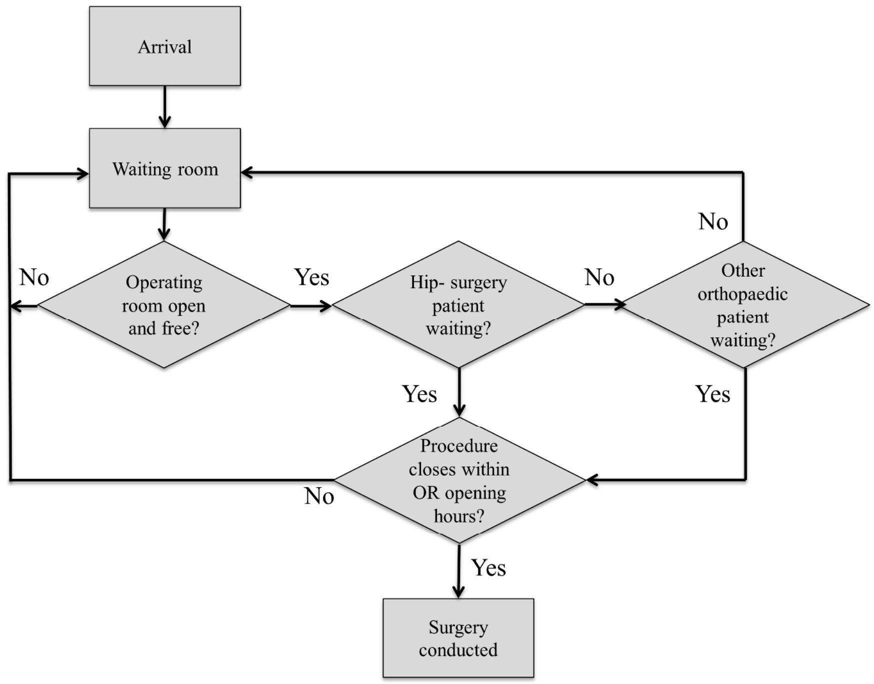

Figure 1. Flow chart of the simulation model

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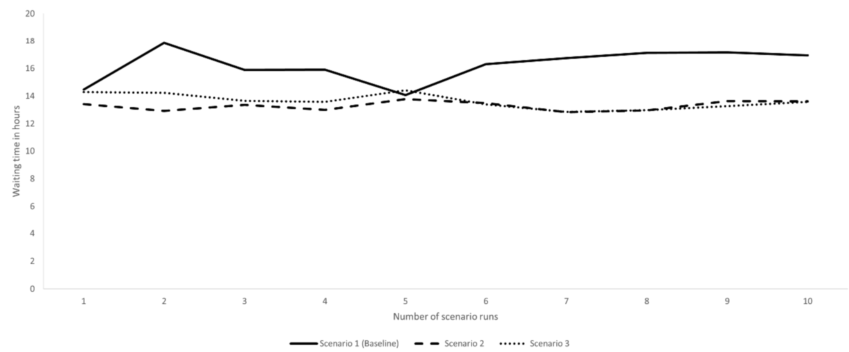

Figure 2. Mean waiting time in hours for hip-fracture patients monitored for each scenario

338x190mm (300 x 300 DPI)

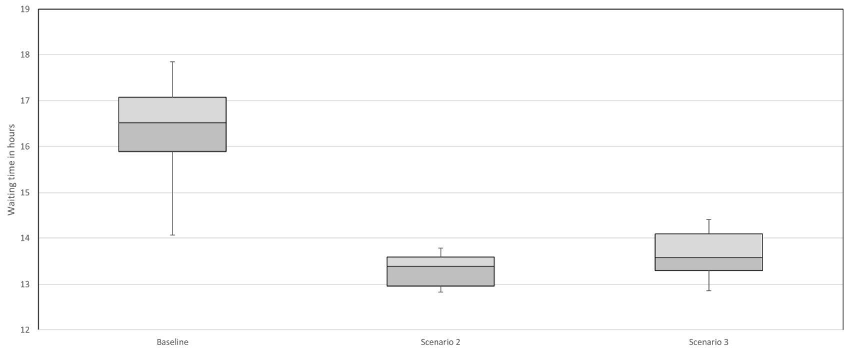

Figure 3. Box plots of the waiting time for hip-fracture patients for each of the three scenarios

338x190mm (300 x 300 DPI)

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TITLE PAGE

Title

Operational strategies to manage non-elective orthopaedic surgical flows. A simulation modelling study

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Abstract

Objectives

To apply simulation modelling to evaluate the effects of strategies to plan and schedule operating room (OR) resources aimed at reducing time to surgery for non-elective orthopaedic inpatients.

Methods

We applied Discrete Event Simulation modelling. The model was populated with real world data from a Swedish university hospital with a strong focus on reducing waiting time to surgery for patients with hip fracture. The system modelled concerned non-elective patients in need of orthopaedic surgical treatment. Both hip-fracture and other non-elective orthopaedic patients were included because they share the same OR resources. The experiment was conducted by simulating three scenarios. These scenarios were developed based on the literature and interaction with staff and managers at the hospital site and they were: 1) baseline; 2) reduced turnover time between surgeries by 20 minutes; 3) one extra OR during day time, Monday to Friday. The outcome variables were waiting time to surgery and the percentage of patients who waited longer than 24 hours for surgery.

Results

The mean waiting time in hours was significantly reduced from 16.2 hours in scenario 1 (baseline) to 13.3 hours in scenario 2 and 13.6 hours in scenario 3 for hip-fracture surgery and from 26.0 hours in baseline to 18.9 hours in scenario 2 and 18.5 hours in scenario 3 for other non-elective patients. The percentage of patients who were treated within 24 hours significantly increased from 86.4% (baseline) to 96.1% (scenario 2) and 95.1% (scenario 3) for hip-fracture patients and from 60.2% (baseline) to 79.8% (scenario 2) and 79.8% (scenario 3) for patients with other non-elective patients.

Conclusions

Healthcare managers who strive to improve the timelines of non-elective orthopaedic surgeries may benefit from focusing on reducing turnover times. This strategy can yield the same results as an extra OR and does not necessarily require additional costs.

Strengths and limitations of this study

- The simulation experiment was conducted with real world data from a Swedish university hospital.
- This is one of the few studies applying simulation modelling to non-elective patient flows.
- The simulation study has been carried out in collaboration with hospital staff and the model was continuously validated.
- The outcome variables were limited to waiting time and percentage of patients undergoing surgery within 24 hours.
- Unexpected incidents such as patient health status or employee sick leave were not included in the simulation model.

Introduction

The planning and scheduling of activities in the operating room (OR) is a complex task and if done inappropriately it can generate unnecessary costs and delays in patient treatment.[1] The negative consequences of poorly managed OR resources become evident for patients with hip fracture. Delay to surgery is associated with post-operative complications, prolonged recovery and length of stay, as well as increased mortality.[2-5] Despite the positive effects of improvement efforts to reduce waiting time to surgery, the management of ORs resources still represents a challenge for the timely delivery of surgical services for this vulnerable patient group.[6, 7] Waiting time to surgery is consequently still one of the most important performance variables for managing non-elective patient flows in order to prevent unnecessary patient suffering.

One of the challenges in the management of OR resources relates to the management of multiple patient groups that compete for the same resources. A major issue is the trade-off between elective and non-elective cases.[8, 9] In orthopaedics, non-elective surgical cases have historically been added to the elective schedules which result into several problems including disruptions to elective cases and after-hour surgery.[10, 11] To overcome these problems, hospitals have introduced dedicated day-time orthopaedic ORs for non-elective orthopaedic patients. The use of dedicated orthopaedic ORs is associated with shorter after-hour surgeries for trauma cases and less disruptions to elective schedules,[8, 12] as well as improved patient care, e.g. decreased rates of perioperative mortality, post-operative complications, and length of stay.[13] The management of non-elective orthopaedic patient flows, is however still a challenge as it is often based on "ad-hoc" strategies,[14] and limited research is applied to non-elective patient flows.[1]

Non-elective patient flows are different from elective flows because patients can arrive at any day and night time, seven days a week and this creates specific planning requriements. In this respect, there are two main approaches to manage health care demand: the unit and the process perspective.[15] The unit perspective aims to maximize resource efficiency within a single unit or department whereas the process perspective focuses more on maximizing the service level for specific patient groups. These two strategies are not in conflict to each other; in fact, it is claimed that a focus on creating efficient processes indirectly also yields a more efficient use of resources.[16] The challenge for health care organizations lies in developing operational strategies that are aligned with the perspective they chose to prioritize. In an OR, the adoption of a unit perspective would mean to focus on how to increase the utilization of OR resources such as surgeons' time and OR-teams; a process perspective instead would emphasize the timeliness of care delivery for specific patient groups.

Simulation modelling is one approach that can help to develop effective operational strategies to plan non-elective surgeries. Stemming from Operations Research, simulation modelling allows for the development and testing of changes before they are implemented in reality.[17, 18] Simulation modelling can also function as a system analysis tool[19] to identify processes in need of improvement in order to reach the goals of the organization. Simulation modelling applied to operating room departments and surgery often focuses on optimising capacity of flows, schedule and utilization.[20-22] However, most research still focuses on elective patients despite the challenge non-elective patients represent when it comes to planning care.[1]

Rationale and aim of the study

In summary, there is a concrete need to develop operational strategies to improve the timeliness of care delivery for patients with hip fracture. Such strategies should be anchored in a process perspective to meet patient demands. Simulation modelling can be a valuable approach to evaluate the effects of strategies that, while they may have been tested for elective patient flows, have not been explored for non-elective ones. Thus, in this study we applied simulation modelling to evaluate the effects of strategies to plan and schedule OR resources aimed at reducing the time to surgery for non-elective orthopaedic inpatients. We specifically analysed the effects for patients with hip fracture and other non-elective orthopaedic inpatients. These patients often share OR resources with other non-elective orthopaedic patients, and therefore it is of importance to include both patient groups in the analysis.

Method

The applied simulation method was Discrete Event Simulation (DES). DES is often applied to healthcare for patient-flow management, resource allocation, and scheduling,[23] and is the predominant method used in surgical care.[24] DES represents the components of a system and their interactions and looks at specific events in a given process (e.g. surgical procedure) and their chronological sequence.[25] The state of the system observed and simulated is updated as each event takes place making DES a suitable tool to evaluate and improve system performance.[26] The effects of OR planning and scheduling strategies were measured by waiting time to surgery and the percentage of patients operated within 24 hours, a common improvement target for patients with hip fracture.[7] The study has been granted ethical approval by the Regional Ethics Committee in Stockholm (ref no. 2009/1657-31).

Setting

This study was carried out at a Swedish university hospital with a catchment area of approximately 450,000 inhabitants. The 52-bed orthopaedic department has an annual admittance of approximately 3,700 patients, mainly for non-elective care. Patients with hip fractures constitute the major non-elective group with an annual surgical rate of approximately 600 fractures. In Sweden, the National Board of Health and Welfare recommends that patients with hip fracture receive surgical treatment within 24 hours from admission.[27] When this study was conducted, the County Council requirement was that 80% of patients with a hip fracture should be operated within 24 hours from admission. At the hospital, several efforts have been made during the years to reach this goal. Despite the improvement observed, variability in the process still exists.[7, 28] Staff and managers at the hospital expressed that further improvement could be achieved by improving the process at the OR, which became the focus of the simulation model.

There were 12 ORs at the current OR department and five (six on Mondays) were dedicated for orthopaedic surgeries and the remainder were dedicated for general surgical and urological cases. Two ORs were dedicated during day shift to serve non-elective orthopaedic surgeries and one OR during night shift. At weekends there was one OR dedicated during both the day and night shift. In 2014, a total of 10,574 surgeries were performed at the operating department; of these

4,512 were orthopaedic surgeries, 2,230 non-elective and 2,282 elective surgeries. Normally, according to a regional guideline, multi trauma cases were treated at another hospital in the County Council and therefore very few underwent surgery at this hospital. Non-elective orthopaedic patient arrives 24 hours a day, seven days a week. The patients arrive at ED and then pass several units preoperatively; different kind of assessments and procedures are carried out in order to prepare the patient for surgery. An anaesthesiologist makes the final decision and decides when the patient is ready for surgery.

Simulation model

The system modelled used real patient data from 2013 and concerned hip-fracture patients and other non-elective patients arriving for orthopaedic surgery. In the model, we only considered patients who required surgery, and hence, assumed to have already been assessed for surgical needs. However, in reality the time which elapses before surgery actually is scheduled, varies greatly, depending on patient condition, as some patients require other pre-investigations and/or treatments prior to surgery, e.g., stabilization for several days. This variation was not added to the model, as it was not considered to be a hospital-related delay to surgery. Nonetheless, we did add a short time to each of the modelled patients waiting to undergo surgery as they were not very likely to be scheduled for surgery immediately after being assessed by an orthopaedic surgeon. This time was computed as the mean for the 20 fastest patients in the hip-fracture and other non-elective patient groups respectively, i.e., patients that computed the fastest elapsed time, from the time when the patient was admitted to the hospital to the time the patient entered the OR.

Furthermore, we divided the patients into two separate groups (queues), one queue for hip-fracture surgery and one for the remaining orthopaedic non-elective surgical cases (figure 1). These two patient groups shared the same OR resources. Given the few multi trauma cases, the hip-surgery patient in general was considered to have a higher priority and therefore the hip-surgery queue was given higher priority than the other orthopaedic queue. Both queues were modelled by first-come-first-served processing rule. The number of ORs were dynamically modelled according to the authentic number of ORs open for a specific day in the week. In the same way, we modelled the opening hours of the ORs according to how long the specific OR was open for a specific day in week in reality.

< Insert Figure 1 here >

First, the patients arrived according to an arrival process $\alpha(x)$ and were placed in one of the two queues according to the described rules above (figure 1). The process $\alpha(x)$ was assumed to be Poisson, i.e., having exponential arrival intervals with a calculated arrival mean derived for each hour during the day and night.[29] If one of the operating rooms was available, i.e., not occupied with another surgical procedure or closed, the simulation model searched the queues for a patient ready to undergo surgery according to a prioritization scheme (described in the experiment). If a patient's estimated surgical procedure time exceeded the remaining OR opening hours, the patient was forced to wait (remain in the queue) until the next day, and instead the next patient in line was processed. In the model, a distinction was made between the simulated *planned* surgical procedure time and the simulated *actual* surgical procedure time in order to capture the difference in what is known to the staff before the surgery starts and what really happens in terms of surgery duration. The simulation of the *planned* surgical procedure time, was based on the mean procedure time for a particular procedure, whereas the simulation of the *actual* surgical procedure time was drawn from a log-normal distribution with specified mean and variance[30] and was unknown before the simulated surgery started. This means that the opening hours of an OR may be exceeded and over time will be required in order to complete the surgical procedure already underway. After surgery was completed, the patient was sent out of the system.

The data obtained from the hospital was pre-processed by use of Python script language and the simulation model was developed in Java.

Simulation experiment with scenarios

The simulation experiment was set up to evaluate the effects of three scenarios on the mean waiting time and the percentage of patients waiting longer than 24 hours for surgery. These two variables were measured for both hip-fracture patients and other non-elective orthopaedic patients. The experiment was conducted by simulating three scenarios that were developed based on the literature and through interactions with staff and managers at the hospital. The first scenario represented the planning and scheduling of the non-elective orthopaedic cases using current practice (baseline scenario), the second scenario represented current practice but the turnover between surgeries was reduced by 20 minutes and the third scenario represented current practice with the exception of one extra OR in day time (Monday to Friday). Scenario 2 and 3 represent potential areas for improvements discussed at the involved departments, i.e., the operating department, the orthopaedic department and the anaesthesia and intensive care department. Each scenario was simulated 10 times using different random seeds.

Non-elective orthopaedic data from 2013 extracted from the hospital OR-system was used as input to the simulation model. After ocular inspection, incomplete case records were omitted from the data set. In table 1 the various setting parameters used for the simulation are listed. The prioritization parameter at the bottom in the table describes the logical flow of how the priority between hip-fracture patients and other non-elective orthopaedic patients was simulated.

The turnover time including post - and pre-procedure of two subsequent surgical cases was estimated at the included hospital to be 60-90 minutes depending on the surgical cases. A reduction of 20 minutes turnover time altogether was deemed reasonable and well motivated by the staff.

To ensure that the simulation model was a representation of, or as close to, the real orthopaedic surgical system as possible, the model was validated continuously throughout the study, i.e. the baseline scenario was validated. Several meetings with orthopaedic surgeons, anaesthesiologists, OR nurses, OR coordinators and registered nurse anaesthetists were carried out along with intermittent observations at the operating department. When comparing baseline scenario with real world data, the simulated data showed slightly better results in terms of waiting time to surgery. This difference can be explained by design decisions in the simulation model that were taken due to limited data availability. For instance, we lacked data that could explain the variation in time from arrival at the Emergency Department to the time the patients are declared ready for surgery. This variation could be due to the need for pre-operative investigations for patients which could delay the surgery. Since this delay was not dimmed relevant for this study, we decided to build the simulation model based on the mean of the 20 fastest patients; the mean time between arrival at the Emergency Department and surgery start for these patients was 5 hours.

< Insert Table 1 here >

Table 1. Description of parameters used in the simulation model

Parameter	Value in baseline scenario	Distribution type	Data source
OR opening	8.00 am		Personal communication with staff
OR closing (day time)	4.00 pm		Personal communication with staff
OR closing (Friday)	2.00 pm		Personal communication with staff
OR closing (night shift)	9.00 pm		Personal communication with staff
Number of ORs open per week	2 OR day time and 1 OR evening shift. Weekends: 1 OR daytime and 1 OR evening shift		Expert opinion
Patient arrival		Poisson	OR scheduling system
Time from Emergency Department to OR	5 hours for hip-fracture patients and 3.5 hours for other non-elective patients		Patient records
Simulated actual surgical procedure time	All patient time included. Included surgical preparation as cleaning and anaesthesia, i.e., pre- and post-procedure	Lognormal	OR scheduling system
Simulated planned surgical procedure time	Mean (all patient time included)		OR scheduling system
Turnover time	The turnover time including post- and pre - procedure of two subsequent surgical cases was estimated to be 60-90 minutes		Expert opinion
Prioritization (hip-fracture patients vs other non-elective patients)	a. **If** hip < 24h **and** other < 36h **then** hip priority		Expert opinion
	b. **If** hip < 24h **and** other > 36h **then** other priority		
	c. **If** hip > 24h **and** other > 36h **then** hip priority		
	d. **If** other > 36h **and** postponed **then** other priority		

Statistical analysis

The arrival of patients was modelled by a Poisson process and the uncertainty of surgical duration was modelled by a log-normal distribution. A parametric approach using 95% confidence intervals for waiting time in hours and percentage of cases treated within 24 hours was used to compare the three scenarios. Box-plot was used to graphically represent the data.

Results

The reduction of the turnover time by 20 minutes (scenario 2) and the introduction of an extra OR during day time (scenario 3) contributed to a significant, as indicated by the lack of overlapping between the confidence intervals, reduction in waiting time to surgery for both patient groups, compared to scenario 1 (baseline). For hip-fracture patients, the mean waiting time decreased from 16.2 hours in scenario 1 to 13.3 hours in scenario 2 and 13.6 hours in scenario 3. The corresponding change in mean waiting time for the other non-elective patients was a reduction from 26.3 hours to 18.9 hours and from 26.3 hours to 18.5 hours, in scenario 2 and 3 respectively (table 2).

< Insert Table 2 here >

Table 2. Performance of the three simulated scenarios

		Scenario 1 (baseline)	**Scenario 2**	**Scenario 3**
Mean waiting time in hours with 95% confidence interval	Hip-fracture patients	16.2 hours (95% CI, 15.4-17.1)	13.3 hours (95% CI, 13.1-13.5)	13.6 hours (95% CI, 13.4-13.9)
	Other non-elective patients	26.3 hours (95% CI, 24..3-27.6)	18.9 hours (95% CI, 18.1-19.7)	18.5 hours (95% CI, 18.1-19.0)
Percentage of patients treated within 24 hours with 95% confidence interval	Hip-fracture patients	86.4% (95% CI, 83.5-89.3)	96.1% (95% CI, 95.5-96.7)	95.1% (95% CI, 94.0-96.1)
	Other non-elective patients	60.2% (95% CI, 56,9-63.7)	79.8% (95% CI, 77.6-82.1)	79.8% (95% CI, 78.5-81.1)

The level of improvement achieved in scenario 2 and, compared to baseline, were similar for both scenarios. Scenarios 2 and 3 showed better results for all simulation runs compared to

baseline except for one run in scenario 3 (figure 2). Figure 3 shows the same results, viewed as box plot.

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Significant results were also observed for the percentage of patients who waited longer than 24 hours for surgical treatment, i.e. similar levels of improvement were identified for scenario 2 and 3 compared to baseline (table 2).

The percentage of hip-fracture patients who underwent surgery within 24 hours was simulated at 86.4% in the baseline scenario. In scenario 2 and 3, however, simulated results showed that 96.1% and 95.1%, respectively, of the hip-fracture patients underwent surgery within 24 hours. Furthermore, in the other non-elective patient group a significant increase in percentage of patients who underwent surgery within 24 hours were simulated in scenario 2 (79.8%) and 3 (79.8%) compared to baseline (60.2%) (table 2).

Discussion

In this paper we investigated how different operational strategies influence waiting time to surgery for patients with hip fracture and other non-elective orthopaedic patients. We found that a reduction in turnover time by 20 minutes in an OR can yield the same level of improvement as adding an extra OR during daytime.

This study contributes to the literature on how to improve the planning and scheduling of non-elective patient flows using simulation, a field in which empirical research is limited.[1] The main contribution lies in showing how, in a hospital setting where non-elective orthopaedic surgeries are performed in dedicated ORs, the reduction of the turnover time may have the same effect as adding an extra OR. The latter strategy may yield higher costs as it would require investing in additional human resources, physical space and associated equipment. The experimental results can be explained by the pattern in patient arrival rate. An increase in OR resources during the daytime has limited effect on waiting time since non-elective patients typically arrive 24 hours a day, 7 days a week, although the arrival rate is likely to be less frequent during the night. The benefits of reduced turnover time [31, 32] for elective patients have been described earlier; this study clearly shows that such strategy is valuable to improve process efficiency while ensuring efficient resource utilization at the OR also in the context of non-elective patient flows. If health care organizations manage to reduce the turnover time in their ORs, they are also likely to improve the clinical outcomes for patients.[2-5]

Previous studies of elective patient flows suggest several strategies for how to reduce turnover time, for instance through parallel processing.[31, 32] Friedman and colleagues found that turnover time could be reduced through parallel processing in ORs designed for outpatient inguinal hernia repair. Parallel processing was achieved without additional resources by having the operating team of surgeon, nurses, and scrub technicians working on two patients simultaneously. The maintenance of a constant team throughout the entire day also contributed to the observed improvement.[32] Another approach to parallel processing is to start the pre-procedure of the upcoming surgical case before the post-procedure of the current surgical case is closed. However, this approach requires extra resources in terms of surgical teams. Holmgren and Persson present an optimization model that sequences surgical cases in such a way that parallel processes are scheduled for many ORs subject to a limited number of surgical teams.[31] Future studies can investigate how parallel processing, as well as other strategies, can be used to improve the efficiency of non-elective surgical flows.

Like in our study, the specific operational strategies adopted should be tailored to the specific context of application and developed in collaboration with managers and professionals. While the results obtained in this study may be influenced by the setting of application, this study clearly shows the value of using simulation modelling when analysing management strategies that involve stochastic processes, such as patient arrival, case-mix, and procedure duration. In the case organization, the results of this analysis were the starting point for two new research and development projects that aim to investigate how parallel processing can be implemented to increase patient throughput in the OR and how 6-hours workday in the OR can be implemented.

Strengths and weaknesses of the study

The main strengths of this study are that it was based on real world data from a hospital and the development of the model was grounded on the real needs of hospital staff and managers who had worked for several years to reduce waiting time to surgery for patients with hip fracture.[7] The model itself was developed and validated in collaboration with hospital staff and managers, a process that is of key importance.[33, 34]

The main limitations of the study are twofold. First, the simulation model does not take into account unexpected incidents such as sudden change in patient health status (i.e., not being well enough to undergo a surgical procedure) or sick leave of employees. While one may expect these variables to influence the waiting time to surgery, we sought to overcome this limitation by considering the relative performance, i.e. the difference in results between scenarios. In other words, we would expect a sudden change in patient health status and staff sick leave to have a similar effect on all scenarios and hence not crucial to this study. Second, the outcome variables included were limited to waiting time and percentage of patients undergoing surgery within 24 hours. A more comprehensive evaluation of performance, including measures of cost, utilization rates of the OR, and percentage of cancelled surgeries, can be a way forward to develop better strategies for the management of non-elective patient flows.

Conclusion

We conclude that a reduction of only 20 minutes in OR turnover time yields almost the same effect in patient waiting time as the addition of one extra OR during the daytime. Future research can investigate how this reduction in turnover time can be reached for non-elective patient flows such as scheduling, and also the health economic effects of this strategy. This study shows that simulation modelling can help understand system performance. We therefore suggest that simulation modelling can become an integral part of health care development to investigate improvement strategies with healthcare managers and professionals.

Contributorship statement

MP, HHF, MU, OGS, AS, PKP, and PM designed the study. MP, MU, PKP, OGS, and PM collected the data. All authors contributed to the development of the model and MP conducted the implementation of the model and result analysis. MP, HHF, MU, and PM drafted the manuscript. OGS, AS, and PKP read and critically revised the manuscript. All authors approved the final manuscript and are accountable for all parts of the work.

Competing Interests

The authors declare that they have no competing interests.

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Data sharing statement

The Excel file with the input and output data from the simulation model (i.e. key activities carried out in the care process and the time when they were carried out) is available upon request by e-mailing marie.persson@bth.se or pamela.mazzocato@ki.se.

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Figure legends

Figure 1. Flow chart of the simulation model
Figure 2. Mean waiting time in hours for hip-fracture patients monitored for each scenario
Figure 3. Box plots of the waiting time for hip-fracture patients for each of the three scenarios

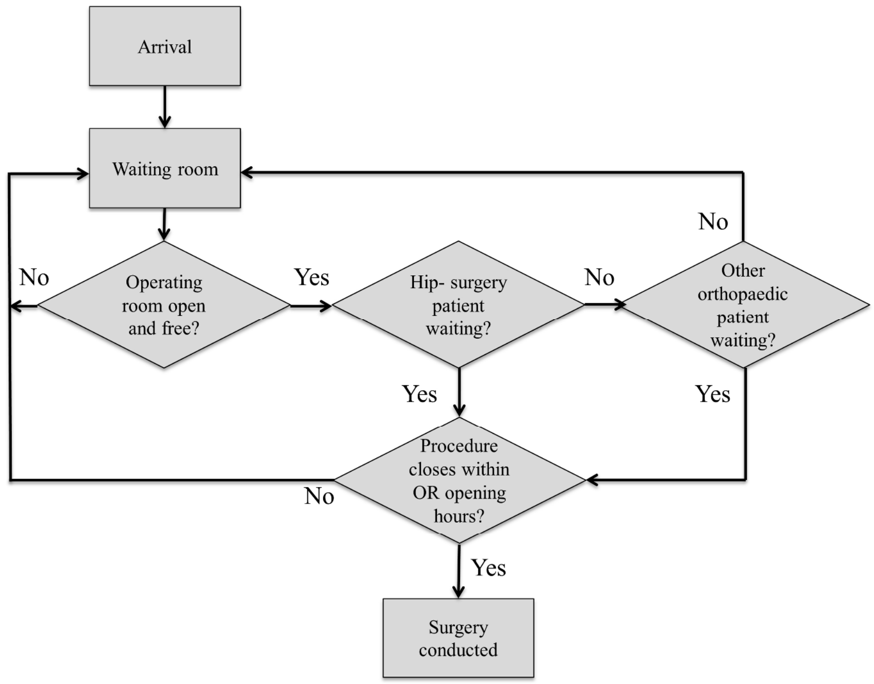

Figure 1. Flow chart of the simulation model

254x190mm (300 x 300 DPI)

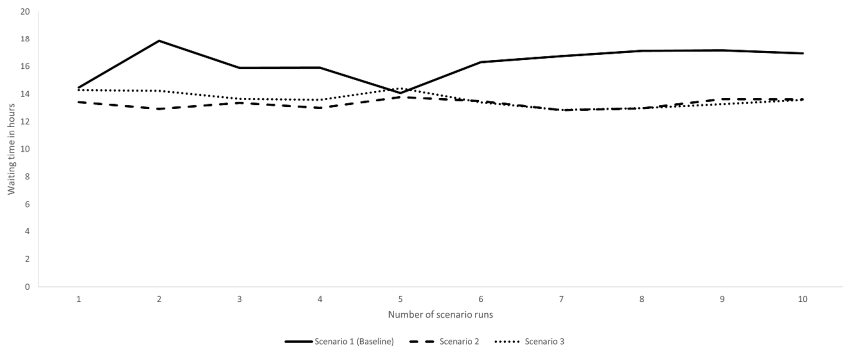

Figure 2. Mean waiting time in hours for hip-fracture patients monitored for each scenario

338x190mm (300 x 300 DPI)

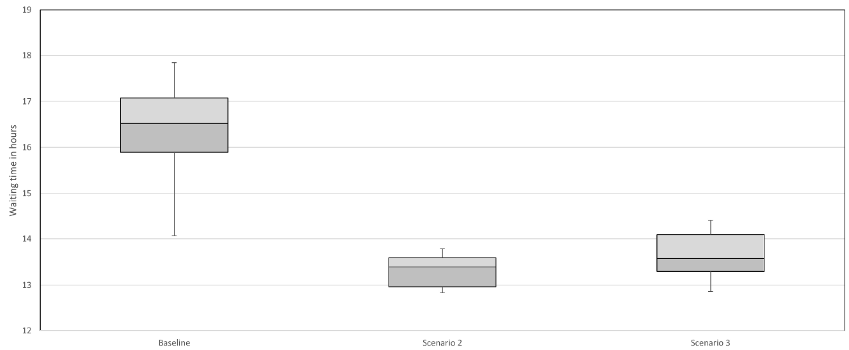

Figure 3. Box plots of the waiting time for hip-fracture patients for each of the three scenarios

338x190mm (300 x 300 DPI)

Requirements in publications of simulation modelling research based on (Fone, Hollinghurst et al. 2003)

Minimum Quality Requirements	**How and where we addressed it in the manuscript**
Clarity of aims and objectives	Stated in the "aim section": "we applied simulation modelling to evaluate the effects of strategies to plan and schedule OR resources aimed at reducing the time to surgery for non-elective orthopaedic inpatients. We specifically analysed the effects for patients with hip fracture and other non-elective orthopaedic inpatients."
Intervention(s)/changes under test adequately defined	Three changes are described in the section "simulation experiment with scenarios."
Outcome measures defined and appropriate	The two outcome variables are described in the methods sections: waiting time to surgery and the percentage of patients operated within 24 hours.
Model adequately described	The Discrete Event Simulation (DES) is described in the methods section.
Parameters specified	Summarized in table 1.
Quality of data sources	Data sources are outlined in table 1.
Explicitness and appropriateness assumptions	All the relevant assumptions are described under the heading "simulation model", including assumption distribution.
Validation of model	Validation was carried out as described in the last paragraph in the section "validation experiment with scenarios."
Presentation of appropriate results with estimation of precision	The results and CI of the experiments are presented in the results section.
Results interpreted and discussed in the context	The results are interpreted in the discussion section.

Reference

Fone, D., S. Hollinghurst, M. Temple, A. Round, N. Lester, A. Weightman, K. Roberts, E. Coyle, G. Bevan and S. Palmer (2003). "Systematic review of the use and value of computer simulation modelling in population health and health care delivery." Journal of Public Health **25**(4): 325-335.

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Operational strategies to manage non-elective orthopaedic surgical flows. A simulation modelling study

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TITLE PAGE

Title

Operational strategies to manage non-elective orthopaedic surgical flows. A simulation modelling study

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Keywords

Quality improvement, simulation modelling, operating room, efficiency, orthopaedic surgery

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Abstract

Objectives

To explore the value of simulation modelling to evaluate the effects of strategies to plan and schedule operating room (OR) resources aimed at reducing time to surgery for non-elective orthopaedic inpatients at a Swedish hospital.

Methods

We applied Discrete Event Simulation modelling. The model was populated with real world data from a university hospital with a strong focus on reducing waiting time to surgery for patients with hip fracture. The system modelled concerned two patient groups that share the same OR resources: hip-fracture and other non-elective orthopaedic patients in need of surgical treatment. We simulated three scenarios developed based on the literature and interaction with staff and managers: 1) baseline; 2) reduced turnover time between surgeries by 20 minutes; 3) one extra OR during day time, Monday to Friday. The outcome variables were waiting time to surgery and the percentage of patients who waited longer than 24 hours for surgery.

Results

The mean waiting time in hours was significantly reduced from 16.2 hours in scenario 1 (baseline) to 13.3 hours in scenario 2 and 13.6 hours in scenario 3 for hip-fracture surgery and from 26.0 hours in baseline to 18.9 hours in scenario 2 and 18.5 hours in scenario 3 for other non-elective patients. The percentage of patients who were treated within 24 hours significantly increased from 86.4% (baseline) to 96.1% (scenario 2) and 95.1% (scenario 3) for hip-fracture patients and from 60.2% (baseline) to 79.8% (scenario 2) and 79.8% (scenario 3) for patients with other non-elective patients.

Conclusions

Healthcare managers who strive to improve the timelines of non-elective orthopaedic surgeries may benefit from using simulation modelling to analyse different strategies to support their decisions. In this specific case, the simulation results showed that the reduction of surgery turnover times could yield the same results as an extra OR.

Strengths and limitations of this study

- The simulation experiment was conducted with real world data from a Swedish university hospital.
- This is one of the few studies applying simulation modelling to non-elective patient flows.
- The simulation study has been carried out in collaboration with hospital staff and the model was continuously validated.
- The outcome variables were limited to waiting time and percentage of patients undergoing surgery within 24 hours.
- Unexpected incidents such as patient health status or employee sick leave were not included in the simulation model.

Introduction

The planning and scheduling of activities in the operating room (OR) is a complex task and if done inappropriately it can generate unnecessary costs and delays in patient treatment.[1] The negative consequences of poorly managed OR resources become evident for patients with hip fracture. Delay to surgery is associated with post-operative complications, prolonged recovery and length of stay, as well as increased mortality.[2-5] Despite the positive effects of improvement efforts to reduce waiting time to surgery, the management of ORs resources still represents a challenge for the timely delivery of surgical services for this vulnerable patient group.[6, 7] Waiting time to surgery is consequently still one of the most important performance variables for managing non-elective patient flows in order to prevent unnecessary patient suffering.

One of the challenges in the management of OR resources relates to the management of multiple patient groups that compete for the same resources. A major issue is the trade-off between elective and non-elective cases.[8, 9] In orthopaedics, non-elective surgical cases have historically been added to the elective schedules which result into several problems including disruptions to elective cases and after-hour surgery.[10, 11] To overcome these problems, hospitals have introduced dedicated day-time orthopaedic ORs for non-elective orthopaedic patients. The use of dedicated orthopaedic ORs is associated with shorter after-hour surgeries for trauma cases and less disruptions to elective schedules,[8, 12] as well as improved patient care, e.g. decreased rates of perioperative mortality, post-operative complications, and length of stay.[13] The management of non-elective orthopaedic patient flows, is however still a challenge as it is often based on "ad-hoc" strategies,[14] and limited research is applied to non-elective patient flows.[1]

Non-elective patient flows are different from elective flows because patients can arrive at any day and night time, seven days a week and this creates specific planning requriements. In this respect, there are two main approaches to manage health care demand: the unit and the process perspective.[15] The unit perspective aims to maximize resource efficiency within a single unit or department whereas the process perspective focuses more on maximizing the service level for specific patient groups. These two strategies are not in conflict to each other; in fact, it is claimed that a focus on creating efficient processes indirectly also yields a more efficient use of resources.[16] The challenge for health care organizations lies in developing operational strategies that are aligned with the perspective they chose to prioritize. In an OR, the adoption of a unit perspective would mean to focus on how to increase the utilization of OR resources such as surgeons' time and OR-teams; a process perspective instead would emphasize the timeliness of care delivery for specific patient groups.

Simulation modelling is one approach that can help to develop effective operational strategies to plan non-elective surgeries. Stemming from Operations Research, simulation modelling allows for the development and testing of changes before they are implemented in reality.[17, 18] Simulation modelling can also function as a system analysis tool[19] to identify processes in need of improvement in order to reach the goals of the organization. Simulation modelling applied to operating room departments and surgery often focuses on optimising capacity of flows, schedule and utilization.[20-22] However, most research still focuses on elective patients despite the challenge non-elective patients represent when it comes to planning care.[1]

Rationale and aim of the study

In summary, there is a concrete need to develop operational strategies to plan and schedule OR resources and activities in order to improve the timeliness of care delivery. Simulation modelling can be a valuable approach to evaluate the effects of strategies that, while they may have been tested for elective patient flows, have not been explored for non-elective ones. Thus, in this study we explored the value of simulation modelling to evaluate the effects of strategies to plan and schedule OR resources aimed at reducing the time to surgery for non-elective orthopaedic inpatients. We specifically analysed the effects for patients with hip fracture and other non-elective orthopaedic inpatients who often share the same OR resources.

Method

The applied simulation method was Discrete Event Simulation (DES). DES is often applied to healthcare for patient-flow management, resource allocation, and scheduling,[23] and is the predominant method used in surgical care.[24] DES represents the components of a system and their interactions and looks at specific events in a given process (e.g. surgical procedure) and their chronological sequence.[25] The state of the system observed and simulated is updated as each event takes place making DES a suitable tool to evaluate and improve system performance.[26] The effects of OR planning and scheduling strategies were measured by waiting time to surgery and the percentage of patients operated within 24 hours, a common improvement target for patients with hip fracture.[7] The study has been granted ethical approval by the Regional Ethics Committee in Stockholm (ref no. 2009/1657-31).

Setting

This study was carried out at a Swedish university hospital with a catchment area of approximately 450,000 inhabitants. The 52-bed orthopaedic department has an annual admittance of approximately 3,700 patients, mainly for non-elective care. Patients with hip fractures constitute the major non-elective group with an annual surgical rate of approximately 600 fractures. In Sweden, the National Board of Health and Welfare recommends that patients with hip fracture receive surgical treatment within 24 hours from admission.[27] When this study was conducted, the County Council requirement was that 80% of patients with a hip fracture should be operated within 24 hours from admission. At the hospital, several efforts have been made during the years to reach this goal. Despite the improvement observed, variability in the process still exists.[7, 28] Staff and managers at the hospital expressed that further improvement could be achieved by improving the process at the OR, which became the focus of the simulation model.

There were 12 ORs at the current OR department and five (six on Mondays) were dedicated for orthopaedic surgeries and the remainder were dedicated for general surgical and urological cases. Two ORs were dedicated during day shift to serve non-elective orthopaedic surgeries and one OR during night shift. At weekends there was one OR dedicated during both the day and night shift. In 2014, a total of 10,574 surgeries were performed at the operating department; of these 4,512 were orthopaedic surgeries, 2,230 non-elective and 2,282 elective surgeries. Normally, according to a regional guideline, multi trauma cases were treated at another hospital in the County Council and therefore very few underwent surgery at this hospital. Non-elective orthopaedic patient arrives 24 hours a day, seven days a week. The patients arrive at ED and then pass several units preoperatively; different kind of assessments and procedures are carried out in order to prepare the patient for surgery. An anaesthesiologist makes the final decision and decides when the patient is ready for surgery.

Simulation model

The system modelled used real patient data from 2013 and concerned hip-fracture patients and other non-elective patients arriving for orthopaedic surgery. In the model, we only considered patients who required surgery, and hence, assumed to have already been assessed for surgical needs. However, in reality the time which elapses before surgery actually is scheduled, varies greatly, depending on patient condition, as some patients require other pre-investigations and/or treatments prior to surgery, e.g., stabilization for several days. This variation was not added to the model, as it was not considered to be a hospital-related delay to surgery. Nonetheless, we did add a short time to each of the modelled patients waiting to undergo surgery as they were not very likely to be scheduled for surgery immediately after being assessed by an orthopaedic surgeon. This time was computed as the mean for the 20 fastest patients in the hip-fracture and other non-elective patient groups respectively, i.e., patients that computed the fastest elapsed time, from the time when the patient was admitted to the hospital to the time the patient entered the OR.

Furthermore, we divided the patients into two separate groups (queues), one queue for hip-fracture surgery and one for the remaining orthopaedic non-elective surgical cases (figure 1). These two patient groups shared the same OR resources. Given the few multi trauma cases, the hip-surgery patient in general was considered to have a higher priority and therefore the hip-surgery queue was given higher priority than the other orthopaedic queue. Both queues were modelled by first-come-first-served processing rule. The number of ORs were dynamically modelled according to the authentic number of ORs open for a specific day in the week. In the same way, we modelled the opening hours of the ORs according to how long the specific OR was open for a specific day in week in reality.

< Insert Figure 1 here >

First, the patients arrived according to an arrival process $\alpha(x)$ and were placed in one of the two queues according to the described rules above (figure 1). The process $\alpha(x)$ was assumed to be Poisson, i.e., having exponential arrival intervals with a calculated arrival mean derived for each hour during the day and night.[29] If one of the operating rooms was available, i.e., not occupied with another surgical procedure or closed, the simulation model searched the queues for a patient ready to undergo surgery according to a prioritization scheme (described in the experiment). If a patient's estimated surgical procedure time exceeded the remaining OR opening hours, the patient was forced to wait (remain in the queue) until the next day, and instead the next patient in line was processed. In the model, a distinction was made between the simulated *planned* surgical procedure time and the simulated *actual* surgical procedure time in order to capture the difference in what is known to the staff before the surgery starts and what really happens in terms of surgery duration. The simulation of the *planned* surgical procedure time, was based on the mean procedure time for a particular procedure, whereas the simulation of the *actual* surgical procedure time was drawn from a log-normal distribution with specified mean and variance[30] and was unknown before the simulated surgery started. This means that the opening hours of an OR may be exceeded and over time will be required in order to complete the surgical procedure already underway. After surgery was completed, the patient was sent out of the system.

The data obtained from the hospital was pre-processed by use of Python script language and the simulation model was developed in Java.

Simulation experiment with scenarios

The simulation experiment was set up to evaluate the effects of three scenarios on the mean waiting time and the percentage of patients waiting longer than 24 hours for surgery. These two variables were measured for both hip-fracture patients and other non-elective orthopaedic patients. The experiment was conducted by simulating three scenarios that were developed based on the literature and through interactions with staff and managers at the hospital. The first scenario represented the planning and scheduling of the non-elective orthopaedic cases using current practice (baseline scenario), the second scenario represented current practice but the turnover between surgeries was reduced by 20 minutes and the third scenario represented current practice with the exception of one extra OR in day time (Monday to Friday). Scenario 2 and 3 represent potential areas for improvements discussed at the involved departments, i.e., the operating department, the orthopaedic department and the anaesthesia and intensive care department. Each scenario was simulated 10 times using different random seeds.

Non-elective orthopaedic data from 2013 extracted from the hospital OR-system was used as input to the simulation model. After ocular inspection, incomplete case records were omitted from the data set. In table 1 the various setting parameters used for the simulation are listed. The prioritization parameter at the bottom in the table describes the logical flow of how the priority between hip-fracture patients and other non-elective orthopaedic patients was simulated.

The turnover time including post - and pre-procedure of two subsequent surgical cases was estimated at the included hospital to be 60-90 minutes depending on the surgical cases. A reduction of 20 minutes turnover time altogether was deemed reasonable and well motivated by the staff.

To ensure that the simulation model was a representation of, or as close to, the real orthopaedic surgical system as possible, the model was validated continuously throughout the study, i.e. the baseline scenario was validated. Several meetings with orthopaedic surgeons, anaesthesiologists, OR nurses, OR coordinators and registered nurse anaesthetists were carried out along with intermittent observations at the operating department. When comparing baseline scenario with real world data, the simulated data showed slightly better results in terms of waiting time to surgery. This difference can be explained by design decisions in the simulation model that were taken due to limited data availability. For instance, we lacked data that could explain the variation in time from arrival at the Emergency Department to the time the patients are declared ready for surgery. This variation could be due to the need for pre-operative investigations for patients which could delay the surgery. Since this delay was not dimmed relevant for this study, we decided to build the simulation model based on the mean of the 20 fastest patients; the mean time between arrival at the Emergency Department and surgery start for these patients was 5 hours.

< Insert Table 1 here >

Table 1. Description of parameters used in the simulation model

Parameter	Value in baseline scenario	Distribution type	Data source
OR opening	8.00 am		Personal communication with staff
OR closing (day time)	4.00 pm		Personal communication with staff
OR closing (Friday)	2.00 pm		Personal communication with staff
OR closing (night shift)	9.00 pm		Personal communication with staff
Number of ORs open per week	2 OR day time and 1 OR evening shift. Weekends: 1 OR daytime and 1 OR evening shift		Expert opinion
Patient arrival		Poisson	OR scheduling system
Time from Emergency Department to OR	5 hours for hip-fracture patients and 3.5 hours for other non-elective patients		Patient records
Simulated actual surgical procedure time	All patient time included. Included surgical preparation as cleaning and anaesthesia, i.e., pre- and post-procedure	Lognormal	OR scheduling system
Simulated planned surgical procedure time	Mean (all patient time included)		OR scheduling system
Turnover time	The turnover time including post- and pre - procedure of two subsequent surgical cases was estimated to be 60-90 minutes		Expert opinion
Prioritization (hip-fracture patients vs other non-elective patients)	a. **If** hip < 24h **and** other < 36h **then** hip priority		Expert opinion
	b. **If** hip < 24h **and** other > 36h **then** other priority		
	c. **If** hip > 24h **and** other > 36h **then** hip priority		
	d. **If** other > 36h **and** postponed **then** other priority		

Statistical analysis

The arrival of patients was modelled by a Poisson process and the uncertainty of surgical duration was modelled by a log-normal distribution. A parametric approach using 95% confidence intervals for waiting time in hours and percentage of cases treated within 24 hours was used to compare the three scenarios. Box-plot was used to graphically represent the data.

Results

The reduction of the turnover time by 20 minutes (scenario 2) and the introduction of an extra OR during day time (scenario 3) contributed to a significant, as indicated by the lack of overlapping between the confidence intervals, reduction in waiting time to surgery for both patient groups, compared to scenario 1 (baseline). For hip-fracture patients, the mean waiting time decreased from 16.2 hours in scenario 1 to 13.3 hours in scenario 2 and 13.6 hours in scenario 3. The corresponding change in mean waiting time for the other non-elective patients was a reduction from 26.3 hours to 18.9 hours and from 26.3 hours to 18.5 hours, in scenario 2 and 3 respectively (table 2).

< Insert Table 2 here >

Table 2. Performance of the three simulated scenarios

		Scenario 1 (baseline)	**Scenario 2**	**Scenario 3**
Mean waiting time in hours with 95% confidence interval	Hip-fracture patients	16.2 hours (95% CI, 15.4-17.1)	13.3 hours (95% CI, 13.1-13.5)	13.6 hours (95% CI, 13.4-13.9)
	Other non-elective patients	26.3 hours (95% CI, 24..3-27.6)	18.9 hours (95% CI, 18.1-19.7)	18.5 hours (95% CI, 18.1-19.0)
Percentage of patients treated within 24 hours with 95% confidence interval	Hip-fracture patients	86.4% (95% CI, 83.5-89.3)	96.1% (95% CI, 95.5-96.7)	95.1% (95% CI, 94.0-96.1)
	Other non-elective patients	60.2% (95% CI, 56,9-63.7)	79.8% (95% CI, 77.6-82.1)	79.8% (95% CI, 78.5-81.1)

The level of improvement achieved in scenario 2 and, compared to baseline, were similar for both scenarios. Scenarios 2 and 3 showed better results for all simulation runs compared to

baseline except for one run in scenario 3 (figure 2). Figure 3 shows the same results, viewed as box plot.

< Insert Figure 2 here >

< Insert Figure 3 here >

Significant results were also observed for the percentage of patients who waited longer than 24 hours for surgical treatment, i.e. similar levels of improvement were identified for scenario 2 and 3 compared to baseline (table 2).

The percentage of hip-fracture patients who underwent surgery within 24 hours was simulated at 86.4% in the baseline scenario. In scenario 2 and 3, however, simulated results showed that 96.1% and 95.1%, respectively, of the hip-fracture patients underwent surgery within 24 hours. Furthermore, in the other non-elective patient group a significant increase in percentage of patients who underwent surgery within 24 hours were simulated in scenario 2 (79.8%) and 3 (79.8%) compared to baseline (60.2%) (table 2).

Discussion

In this paper we investigated how simulation modelling can be used to analyse different operational strategies to reduce waiting time to surgery for patients with hip fracture and other non-elective orthopaedic patients. In this specific hospital, we found that a reduction in turnover time by 20 minutes in an OR can yield the same level of improvement as adding an extra OR during daytime.

This study contributes to the literature on how to improve the planning and scheduling of non-elective patient flows using simulation, a field in which empirical research is limited.[1] The main contribution, in terms of simulation results, lies in showing how, in a hospital setting where non-elective orthopaedic surgeries are performed in dedicated ORs, the reduction of the turnover time may have the same effect as adding an extra OR. The latter strategy may yield higher costs as it would require investing in additional human resources, physical space and associated equipment. The experimental results can be explained by the pattern in patient arrival rate. An increase in OR resources during the daytime has limited effect on waiting time since non-elective patients typically arrive 24 hours a day, 7 days a week, although the arrival rate is likely to be less frequent during the night. The benefits of reduced turnover time [31, 32] for elective patients have been described earlier; this study clearly shows that such strategy is valuable to improve process efficiency while ensuring efficient resource utilization at the OR also in the context of non-elective patient flows.

This study does not directly provide answers to how turnover time can be reduced, but the literature suggests parallel processing as a viable way.[31, 32] Friedman and colleagues found that turnover time could be reduced through parallel processing in ORs designed for outpatient inguinal hernia repair. Parallel processing was achieved without additional resources by having the operating team of surgeon, nurses, and scrub technicians working on two patients simultaneously. The maintenance of a constant team throughout the entire day also contributed to the observed improvement.[32] Another approach to parallel processing is to start the pre-procedure of the upcoming surgical case before the post-procedure of the current surgical case is closed. This approach however requires extra resources in terms of surgical teams. Holmgren and Persson present an optimization model that sequences surgical cases in such a way that parallel processes are scheduled for many ORs subject to a limited number of surgical teams.[31] Future studies can investigate how parallel processing, as well as other strategies, can be used to improve the efficiency of non-elective surgical flows.

Like in our study, the specific operational strategies adopted should be tailored to the specific context of application and developed in collaboration with managers and professionals. While the results obtained in this study may be influenced by the setting of application, this study clearly shows the value of using simulation modelling when analysing management strategies that involve stochastic processes, such as patient arrival, case-mix, and procedure duration. In the case organization, the results of the simulation analysis were the starting point for two new research and development projects that aim to investigate how parallel processing can be implemented to increase patient throughput in the OR and how 6-hours workday in the OR can be implemented.

Strengths and weaknesses of the study

The main strengths of this study are that it was based on real world data from a hospital and the development of the model was grounded on the real needs of hospital staff and managers who had worked for several years to reduce waiting time to surgery for patients with hip fracture.[7] The model itself was developed and validated in collaboration with hospital staff and managers, a process that is of key importance.[33, 34]

The main limitations of the study are twofold. First, the simulation model does not take into account unexpected incidents such as sudden change in patient health status (i.e., not being well enough to undergo a surgical procedure) or sick leave of employees. While one may expect these variables to influence the waiting time to surgery, we sought to overcome this limitation by considering the relative performance, i.e. the difference in results between scenarios. In other words, we would expect a sudden change in patient health status and staff sick leave to have a similar effect on all scenarios and hence not crucial to this study. Second, the outcome variables included were limited to waiting time and percentage of patients undergoing surgery within 24 hours. A more comprehensive evaluation of performance, including measures of cost, utilization rates of the OR, and percentage of cancelled surgeries, can be a way forward to develop better strategies for the management of non-elective patient flows.

Conclusion

This study shows that simulation modelling can be used to understand system performance in the context of non-elective care. In the studied hospital, a reduction of 20 minutes in OR turnover time yielded almost the same effect in patient waiting time as the addition of one extra OR during the daytime. Future research can investigate how this reduction in turnover time can be reached for non-elective patient flows for instance through OR- and staff scheduling. The economic effects of these strategy can also be explored in future research.

We suggest that simulation modelling can become an integral part of health care development to investigate improvement strategies with healthcare managers and professionals.

Contributorship statement

MP, HHF, MU, OGS, AS, PKP, and PM designed the study. MP, MU, PKP, OGS, and PM collected the data. All authors contributed to the development of the model and MP conducted the implementation of the model and result analysis. MP, HHF, MU, and PM drafted the manuscript. OGS, AS, and PKP read and critically revised the manuscript. All authors approved the final manuscript and are accountable for all parts of the work.

Competing Interests

The authors declare that they have no competing interests.

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Data sharing statement

The Excel file with the input and output data from the simulation model (i.e. key activities carried out in the care process and the time when they were carried out) is available upon request by e-mailing marie.persson@bth.se or pamela.mazzocato@ki.se.

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Figure legends

Figure 1. Flow chart of the simulation model
Figure 2. Mean waiting time in hours for hip-fracture patients monitored for each scenario
Figure 3. Box plots of the waiting time for hip-fracture patients for each of the three scenarios

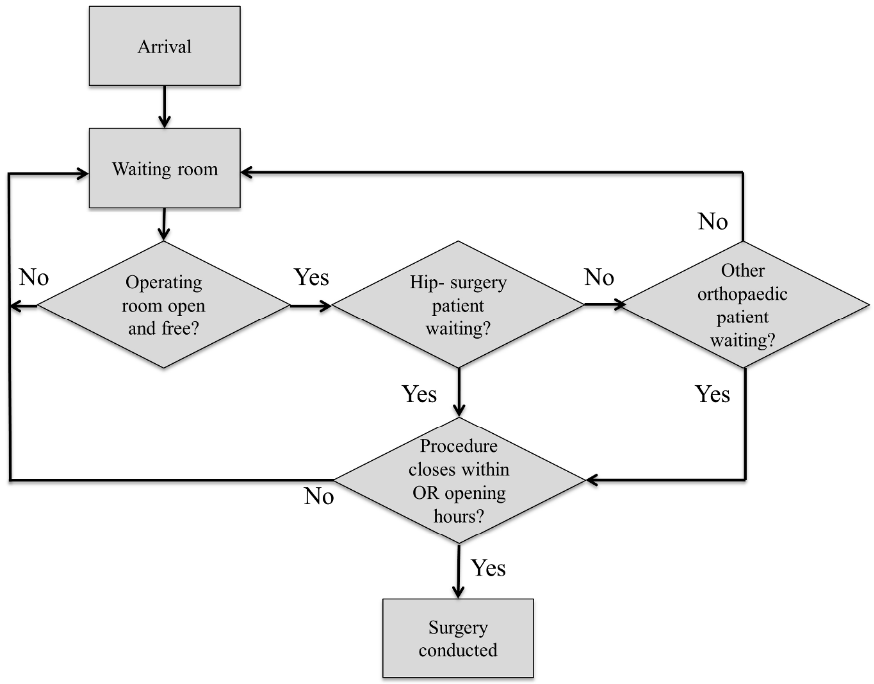

Figure 1. Flow chart of the simulation model

254x190mm (300 x 300 DPI)

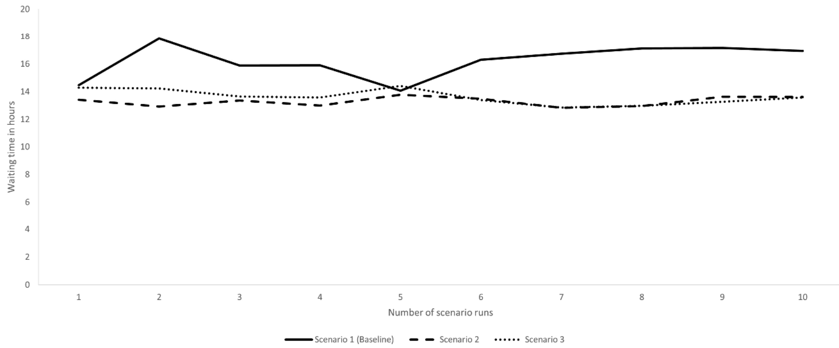

Figure 2. Mean waiting time in hours for hip-fracture patients monitored for each scenario

338x190mm (300 x 300 DPI)

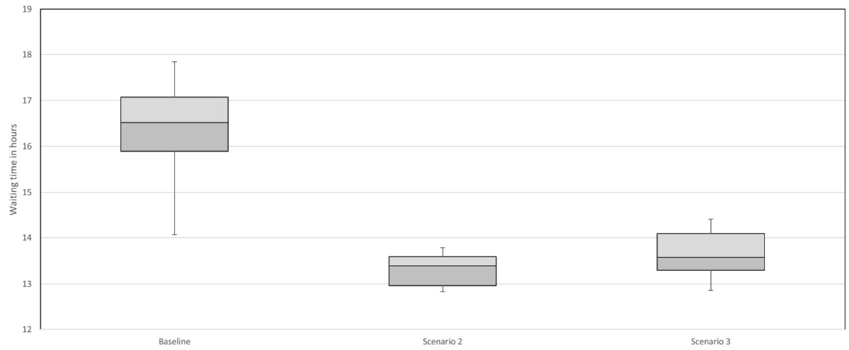

Figure 3. Box plots of the waiting time for hip-fracture patients for each of the three scenarios

338x190mm (300 x 300 DPI)

Requirements in publications of simulation modelling research based on (Fone, Hollinghurst et al. 2003)

Minimum Quality Requirements	**How and where we addressed it in the manuscript**
Clarity of aims and objectives	Stated in the "aim section": "we applied simulation modelling to evaluate the effects of strategies to plan and schedule OR resources aimed at reducing the time to surgery for non-elective orthopaedic inpatients. We specifically analysed the effects for patients with hip fracture and other non-elective orthopaedic inpatients."
Intervention(s)/changes under test adequately defined	Three changes are described in the section "simulation experiment with scenarios."
Outcome measures defined and appropriate	The two outcome variables are described in the methods sections: waiting time to surgery and the percentage of patients operated within 24 hours.
Model adequately described	The Discrete Event Simulation (DES) is described in the methods section.
Parameters specified	Summarized in table 1.
Quality of data sources	Data sources are outlined in table 1.
Explicitness and appropriateness assumptions	All the relevant assumptions are described under the heading "simulation model", including assumption distribution.
Validation of model	Validation was carried out as described in the last paragraph in the section "validation experiment with scenarios."
Presentation of appropriate results with estimation of precision	The results and CI of the experiments are presented in the results section.
Results interpreted and discussed in the context	The results are interpreted in the discussion section.

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