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System design and improvement of an emergency department using Simulation-Based Multi-Objective Optimization

A Goienetxea Uriarte[1], E Ruiz Zúñiga, M Urenda Moris and A H C Ng

School of Engineering Science, University of Skövde, PO Box 408, Skövde, SE 54128 Sweden

E-mail: ainhoa.goienetxea@his.se

Abstract. Discrete Event Simulation (DES) is nowadays widely used to support decision makers in system analysis and improvement. However, the use of simulation for improving stochastic logistic processes is not common among healthcare providers. The process of improving healthcare systems involves the necessity to deal with trade-off optimal solutions that take into consideration a multiple number of variables and objectives. Complementing DES with Multi-Objective Optimization (SMO) creates a superior base for finding these solutions and in consequence, facilitates the decision-making process. This paper presents how SMO has been applied for system improvement analysis in a Swedish Emergency Department (ED). A significant number of input variables, constraints and objectives were considered when defining the optimization problem. As a result of the project, the decision makers were provided with a range of optimal solutions which reduces considerably the length of stay and waiting times for the ED patients. SMO has proved to be an appropriate technique to support healthcare system design and improvement processes. A key factor for the success of this project has been the involvement and engagement of the stakeholders during the whole process.

1. Introduction

Healthcare facilities and specially Emergency Departments (ED) are complex systems to design and operate, some of the main reasons are: the high amount of different resources involved in the processes, the uncertainty of these processes occurring at different moments and the high possibility of simultaneously needed resources [1]. As a result, long patient waiting times are a usual problem on EDs. In order to better understand the inherent complexity and improve the system, the use of different simulation methodologies is applied. One of the most commonly used simulation method is Discrete Event Simulation (DES). Additionally, considering the multiple objectives that are typically involved in the design and improvement of an ED the need to apply a Simulation-based Multi-Objective Optimization (SMO) approach is superior to a single objective method.

This article presents the results of an ongoing research project developed by the Production and Automation Engineering Division of the University of Skövde together with the ED of the regional Skaraborg Hospital Skövde (SkaS) in Sweden. The aim of this paper is to present the process followed to improve the ED of SkaS in reaching the required target patient waiting times and length of stay

[1] To whom any correspondence should be addressed.

defined for EDs in Sweden. The article describes the steps from the development of a DES model to the final stage of applying SMO for decision support.

The structure of the article is divided as follows: a literature review is presented in the second section; followed by a description of the ED project; the fourth section describes the results of the optimization; and to finalize, some conclusions and future work are identified.

2. Literature review

EDs are becoming the main entrance of patients to hospitals. It is reported by many institutions that around 50% of the patients admitted to the hospital come from the ED [2]. Moreover, emergency care units are characterized by their complexity due to the stochastic behaviour of patient arrivals and the unpredictable care needed by them [3], as well as the occupation of shared staff and resources between the ED and correlated departments [4]. Additionally, an ED is usually intended to deal with patients in a critical or life threatening situation instead of dealing with patients presenting low acuity injuries or illnesses [3] which makes the system even more complex. A specific issue that also characterizes EDs is the reception of patients. The first evaluation of the patient is made in the triage area where his condition and acuity level is defined, generally by a nurse. Many EDs have a poorly conceived first encounter system; usually the triage areas are too small or without enough capacity to face the stochastic pattern of patient's arrivals [2]. This common situation combined with the priority sorting due to patient´s acuity, results in long waiting times for patients, acting as a bottleneck of the system [2].

Simulation is an analytical tool to create, maintain, evaluate or improve a system or process. The first use of simulation within healthcare systems dates back to the fifties. It was applied to increase the efficiency in the use of resources of a healthcare unit and later on, simulation was identified as the most powerful tool for healthcare system analysis and improvement [5].Since the early 1990s the number of studies applying simulation in healthcare has grown rapidly [6]. Nowadays, the application of simulation technologies for the improvement of healthcare systems has increased considerably [4, 7]. The main use of simulation in ED systems has been the utilization of the so called "what-if" scenarios. Within these scenarios new patient arrival patterns, resource settings and work proceedings can be tried out without disturbing the real system, or be developed even before a system is constructed [8]. An important benefit of simulation when it comes to improve systems is that it helps to identify the bottlenecks of the process. In healthcare systems this means there are not enough beds, resources or staff to treat the patients efficiently from the arrival to the discharge [8].

DES is necessary in order to be able to model and represent the complex and stochastic flow of patients that usually go through healthcare clinics [9]. Furthermore, it is the most reported technique for healthcare improvement in the literature followed by Montecarlo Simulation and System Dynamics [1]. There are several simulation studies that present how DES can be used to identify improvements or better design EDs. Gunal and Pidd [3] analyse how to increase the ED performance through DES and Hay et al. [4] present a new ED modelling approach. Ferrin et al. use DES to improve the flow and access to care, but the main outcome was to demonstrate simulation´s unique ability to target parameters to maximize the operational and financial impact [8]. Additional studies look at improving patient flow and throughput analysis [10-13] and estimating the future capacity of the ED [14, 15].

DES provides the results of specific what-if experiment scenarios. But in order to analyse several scenarios, a large amount of modelling time is usually required and although an improved solution can be found, the optimal one is not guaranteed. Since simulation is not an optimization tool by itself, a step that combines simulation and optimization is needed [16]. Traditionally, simulation and optimization have been considered as different approaches in the operational research domain, but they have developed together and finally the idea is to use the great detail of simulation together with the ability of optimization to give optimal solutions [17]. It has been demonstrated that combining optimization and simulation tools allow decision-makers to quickly determine optimal system configurations, even for complex integrated facilities [9]. Depending on the type of problem to analyse, there are different optimization methods that can be used in combination with simulation, of which several are presented by Figueira and Almada-Lobo [17]. Meta-heuristic optimization is a flexible approach to examine any solution space and it is characterized by quickly achieving good quality solutions, therefore it has usually been used in combination with DES [17]. Consequently, the integration of meta-heuristic optimization together with simulation is necessary if the optimal range of solutions for the given input is wanted. Moreover, if there are multiple objectives to be analysed at the same time then SMO is the correct approach to be applied. SMO facilitates the search for trade-offs between several conflicting objectives [18].

Different authors have described how simulation and optimization techniques applied together have improved EDs, for example Ahmed and Alkhamis [19] use Monte Carlo simulation together with genetic algorithms for optimal staff allocation. Chen [20] presents in his article an analysis of an ED where SMO was applied to find an optimal ED resource allocation. Nevertheless, there are not many cases in the literature where DES and SMO have been applied together to analyse EDs.

3. Emergency Department study

3.1. Background

In the Swedish healthcare system, the responsibility for health and medical care is shared by the National Board of Health and Welfare (SoS), county councils and municipalities. Due to the long patient waiting times that are experienced in EDs in the country, the SoS set out specific targets that should be met by all the county councils in Sweden. These targets were the following: 90% of the patients should get a triage within 10 minutes from arrival; 90% of patients should meet a physician within 1 hour from arrival; and 90% of patients should have a maximum total length of stay of 4 hours. Despite the efforts done in previous years to reach these targets, the ED unit at SkaS was not making significant improvements towards reaching them. The waiting times were far from what was expected. For example, the time to triage was in some cases up to one hour and the time to meet a physician and the length of stay of patients were also far from the established objectives. Considering the situation, SkaS contacted the Production and Automation Division at the University of Skövde in order to extend their collaboration and target the ED and its objectives.

3.2. Emergency department and process description

SkaS is the largest hospital in the area of Skaraborg in Sweden, giving service to around 277.000 inhabitants. The ED is open 24 hours a day and receives an average of 51.000 visits per year. Besides its internal capacity, the ED shares resources and staff with other departments of the hospital, such as the children department, the X-ray department and the laboratory unit. The ED is divided in 4 different specialities according to the patient classification: surgery, orthopaedics, medicine and children. The personnel is composed by resident and intern physicians for every speciality of the ED, registered nurses (RN), ambulance nurses, triage nurses, laboratory and X-ray personnel and the receptionist. The resources which have been considered and modelled are: the reception, the waiting room, the triage rooms, the surgery area, the orthopaedics area, the medicine area, the children area, the laboratory, the X-Ray department, the urgent care rooms and the patient observation areas.

The process begins when a patient enters the ED. There are two paths for patients who arrive to the ED, walk-in (66.6% of the patients) and ambulance patients (33.3%). The ambulance patients usually get a triage in the ambulance and once they arrive to the ED they are redirected to an emergency care room, area speciality room or to the observation area, depending on the acuity and type of care needed. The walk-in patients wait in the waiting room until they are transferred to a triage room. The RNs conduct the first examination of the patient. The necessary samples are taken, the care priority is established, the necessary documentation is filled and the routine each patient needs before he is seen by a physician is established. After this triage process, the patient is registered and sent back to the waiting room or to a designated speciality room (surgery, orthopaedics, medicine or children). Once the patient has arrived to the room, he waits to be examined by a physician and thereafter to be sent at home or to take additional laboratory samplers or X-Ray scans (in the case of orthopaedic patients).

The patient stays in the room until the results are received and evaluated by the physician. Lab results are often ready within one hour and in the case of X-ray or scans, patients have to visit (usually accompanied by a nurse) the X-ray unit of the hospital. If additional tests are needed, the same procedure would follow i.e. waiting for results and meeting the doctor (for modelling purposes, a maximum of three meetings with the doctor has been estimated). When the process at the ED has finished, the doctor sends the patient, either home or to a ward of the hospital. Finally, the required documentation about the patient is filled in by the physician (considered administrative task in the model).

3.3. Modelling the Emergency Department

The modelling process that has been followed is based on the steps defined by Banks et al.[21]. It started by defining the objectives for the project and ensuring a clear understanding of the process. This was done through iterative meetings and discussions with the stakeholders of the hospital and several visits to the ED. This step was followed by a considerable data collection and analysis phase. The stakeholders provided data from an entire year containing around 50.000 patient visits to the ED. Information about patient arrival time and duration of the different activities performed during his stay, as well as doctor and nurses´ activities were extracted from the data. Non-reliable data, such as wrong patient registration or records with missing information, were excluded from the data analysis. A few number of processes such as the time to get the results from the laboratory or the time the doctors spend with the patients in each meeting were missing, consequently a time study was conducted in order to get this information. The results of the time study were validated with the ED personnel before using them into the simulation model.

The number of patients' arrivals each month, day and hour is different and also the acuity level and type of patient can vary. The number of patients arriving each hour was spaced randomly in the model within that hour. In order to imitate the behaviour of the real system, the data was analysed in detail and different probabilities and statistical distributions were defined in the model accordingly. Additionally, different parameters such as variable service time for patients, variable number (1-3) and duration of meetings with the physician depending on the type of patient and its acuity, priority waiting time queue depending on the acuity and the length of stay of the patient, variable pattern of visits to the X-Ray department, variable administrative task for physicians, variable waiting time for lab and X-Ray processes, etc. were introduced.

A number of assumptions were made and implemented in the model. These assumptions were defined together with the hospital personnel in order to limit the complexity of the system or when needed data was missing, but also to ensure that the results would not be compromised in any case.

Taking into account the data described above, a detailed DES simulation model was implemented in FlexSim HC 3D Simulation Software. The main resources simulated were the patients, rooms and beds, resident and intern physicians (surgery, medicine, orthopaedics and children), the receptionist, triage nurses, ambulance nurses and RNs (surgery, medicine, orthopaedics and children), laboratory and X-Ray staff. Resident physicians are considered expert physicians who spend a percentage of their time interrupted either by hospital calls or assisting other departments of the hospital and also supporting intern physicians in the ED. Interns have been considered to be slower than the residents, spending an additional 20% of the estimated time when meeting a patient. The number of nurses has been modelled according to the reality but their activities haven´t been introduced in detail, this will be done in a future project.

The model was verified and validated in order to ensure that its behaviour is an accurate representation of the real-world system [22]. A simulation of 90 days and 10 replications was run in order to verify and validate the model. The validation phase consisted in analysing the average and 90 percentile of the Time To Triage (TTT), Time To first Meeting with the Doctor (TMD) and Length Of Stay (LOS) for all the ED patients. A maximum deviation of 5% for the average and 10% for the 90 percentile was established (there are some exceptions for low values of specific type of patients). The

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implication of the stakeholders was a key factor in this stage of the process. Various meetings were held with them in order to validate the output and adjust parameters if needed.

In table 1 the LOS values (mean and 90 percentile values) are presented for the total amount of patients, ambulance patients and walk-in patients. The simulation results were compared with the data obtained from the real system. This comparison was also performed for eight sub-classifications of patients in order to validate the model accurately. The columns under “difference” show the variance between the results of the real system and the model.

Table 1. Model validation results. Length of stay.

	Real ED (minutes)		Difference (%)		Model (minutes)	
	P90	Mean	P90	Mean	P90	Mean
Total patients	265.00	144.69	3.95	0.07	276.30	144.80
Ambulance patients	263.00	146.25	6.20	-2.11	279.30	143.16
Walk-in patients	267.00	143.96	3.10	0.97	275.29	145.36

The TTT table, table 2, represents the time from the patient arrival (just for walk-in patients) until the patient enters the triage room. In this case, comparing the difference column, there is a value bigger than the established maximum of 5 %. As explained above, this value has been considered as correct due to the low values which are being compared (between 7 and 8 minutes).

Table 2. Model validation results. Time to triage.

	Real ED (minutes)		Difference (%)		Model (minutes)	
	P90	Mean	P90	Mean	P90	Mean
Walk-in patients	21.00	7.85	8.45	-8.36	22.77	7.20

The TMD table, table 3, shows a summary of the validation results of the time patients wait before they meet a physician.

Table 3. Model validation results. Time to first Meeting with the physician.

	Real ED (minutes)		Difference (%)		Model (minutes)	
	P90	Mean	P90	Mean	P90	Mean
Total patients	141.00	63.77	-4.01	2.39	135.34	65.30
Ambulance patients	109.00	46.48	1.59	-0.57	110.74	46.22
Walk-in patients	151.00	72.05	-5.99	0.69	141.95	72.55

The figures from table 1-3 show that the model of the ED of SkaS represents in a fairly accurate manner the real system.

3.4. Designing improvement scenarios

As described above, one of the strengths of DES is the support it offers to design alternative what-if scenarios. The aim of these improvement scenarios is to find a more optimal configuration of the ED in order to achieve the goals defined by the SoS to reduce the patient waiting times and LOS and thereby, increase its service level.

The following table 4 presents a summary of the overall results of the different improvement scenarios. The scenarios are organized in two columns: scenarios without a significant impact and those with a significant improvement impact in the system output.

Table 4. Summary of tested scenarios.

Scenarios without significant impact in the results	Scenarios with significant impact in the results
- To keep opened the X-Ray department 24 hours a day. - Every physician at the ED is modelled as resident physician. - To eliminate the exits of surgery physicians to the hospital. - Reduce in 50% the exits to the hospital for all the physicians.	- Reduce in 50% the time needed for the X-Ray process. - Reduce in 50% the time needed for the lab process. *(Objective LOS achieved)* - To eliminate physician´s exits to the hospital. - To open the second triage room when more than two patients are waiting for triage. *(Objective TTT achieved)*

The results from these initial what-if studies show that several system changes lead to a clear system improvement by increasing its service level and efficiency. The waiting time and LOS for some categories of patients was reduced in a significant manner and it lead to an overall system reduction, even achieving the goals defined by the SoS (requirements are on system level). However, it was not possible to get a system solution which reached the goal of the 90% of the patients meeting a physician within 60 minutes from the arrival (TMD).

Combinations of several improved scenarios, personnel and resources were later on implemented in the model without success. The results were close to fulfil the goal of TMD but it implied a disproportionate amount of extra physicians, rooms and process time reductions.

The analysis of the what-if scenarios concluded that the process time for X-Ray and Laboratory were key parameters in order to get good results. The stakeholders were aware of this importance, but the analysis of the scenarios showed that the improvement of just these parameters, although giving better results than the original system, were not enough to achieve the defined goals. Additionally, an implemented scenario solved the TTT objective without the need of having a second triage room opened 24 hours a day. The definition and experimentation stage of these scenarios, took a considerable amount of time and made it still very difficult to get an overview of the impact each combination of parameters and policy options had. Instead of continuing defining new possible scenarios, which would have been a nearly never ending process, the project experimentation effort changed the focus in order to embrace a SMO analysis for the improvement of SkaS ED.

4. Optimization results

The objective of the optimization is to find an optimal configuration of the ED which reaches the TMD and LOS levels defined by the SoS for the different categories of patients (medicine, surgery, orthopaedics and children).

The parameters of the experimentation phase which had a major impact on the system performance, were selected as the input variables of the optimization. These parameters are the amount of different extra physicians (medicine, surgery, orthopaedics and children), the amount of extra beds per department (medicine-children and surgery-orthopaedics) and the reduction of the processing time of three activities: the administrative task performed by physicians, the respond time from the laboratory and the respond time from the X-Ray. In table 5 the range for each one of these optimization input variables is presented.

Table 5. Optimization parameters.

Parameters	Values
X-Ray time reduction	0,5,10,15,20 (minutes)
Laboratory time reduction	0,5,10,15 (minutes)
Administrative task reduction	0,5,10,15 (minutes)
Medicine-children extra beds	0-3
Surgery-orthopaedic extra beds	0-3
Children extra doctors	0-3
Medicine extra doctors	0-3
Orthopaedic extra doctors	0-3
Surgery extra doctors	0-3

The TTT was excluded from the optimization analysis because the changes in the described parameters don´t affect it and a what-if scenario had already found a good enough solution.

Apart from the TMD and LOS, three other objectives were included in order to drive the optimization towards resource effective solutions: to *minimize the total amount of extra physicians*, to *minimize the number of extra beds* and to *minimize the number of reductions* of the different processing times for *physician administration task*, *respond time for Laboratory* and *respond time for X-Ray*. Without the formulation of these additional objectives, the optimization algorithm would have just selected solutions with a high number of resources without considering its effective use. On the other hand, even though it is important to understand the impact a process time reduction has on the system performance, it is also difficult to implement that change in the real system. The implementation of parameter reduction changes in the real system will require modifications in the working methods and will include not only new technical systems but also to run a Lean standardization process. Method improvement and sustaining the day-to-day system performance are two common approaches to increase and maintain the productivity of a system. The other objectives add new resources (physicians or hospital beds) and represent the typical approach to increase capacity by investing. These parameters are discrete and the implementation of them is much more straight forward and do not really change the way the work is done. It is obviously an easier approach, if physicians are available and if money is not an issue. Sometimes it is even the necessary approach, especially when the system has clear bottlenecks or its capacity is far from the target goals of the business, but from a productivity point of view it should not be the first option.

The chosen optimization algorithm was the NSGA-II, which is a robust multi-objective algorithm that proves to be suitable for this project´s optimization characteristics [23].

The first results from the optimization are presented in the two following Scatter 3D charts, figure 1 and figure 2. Each point in these charts represent a possible configuration of the ED. Figure 1 shows the TMD of patients (TTL) in the X axis, the total amount of physicians (Docs) in the Y axis and the total amount of process time reductions (Reductions) in the Z axis. Figure 2 shows the LOS of patients in the X axis, the total amount of physicians (Docs) in the Y axis and the total amount of process time reductions (Reductions) in the Z axis. In both charts the Pareto front of solutions is shown highlighted. The Pareto front is the set of optimal solutions for the different combinations of personnel, resources, waiting times and processing times.

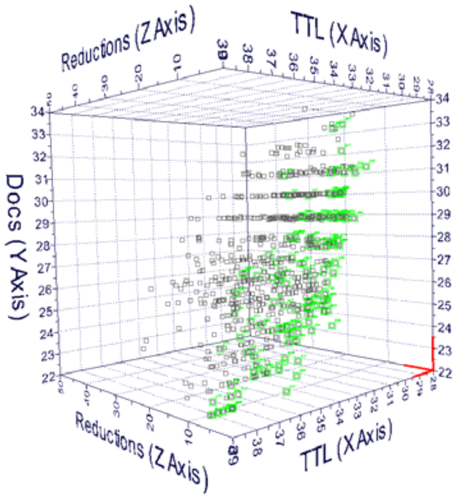

Figure 1. Optimization results. Scatter 3D chart of TMD (TTL), number of physicians (Docs) and process time reductions (Reductions).

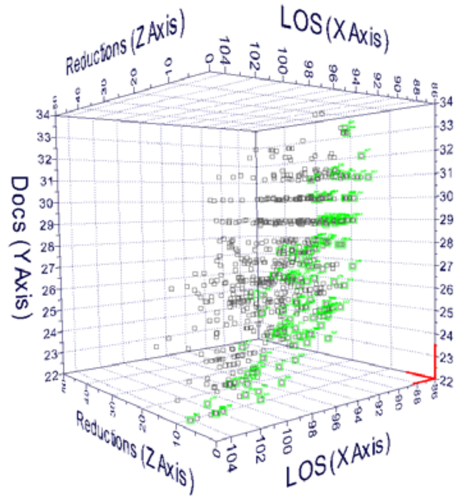

Figure 2. Optimization results. Scatter 3D chart of LOS, number of physicians (Docs) and process time reductions (Reductions).

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The following chart in figure 3 represents around 1000 possible combinations of the ED of SkaS with the given inputs. Every combination shows its correspondent average values of the TMD (TTL in the chart) and LOS of patients. The optimization parameters (see table 5) are placed in the initial columns and the results of LOS and TMD in the last two columns. The numbers in each column correspond to the values of each parameter (amount of minutes and the number of beds or doctors depending on the parameter). The colours in the diagram represent a range of values in the resultant LOS or TMD (the range for TMD is shown in the chart below).

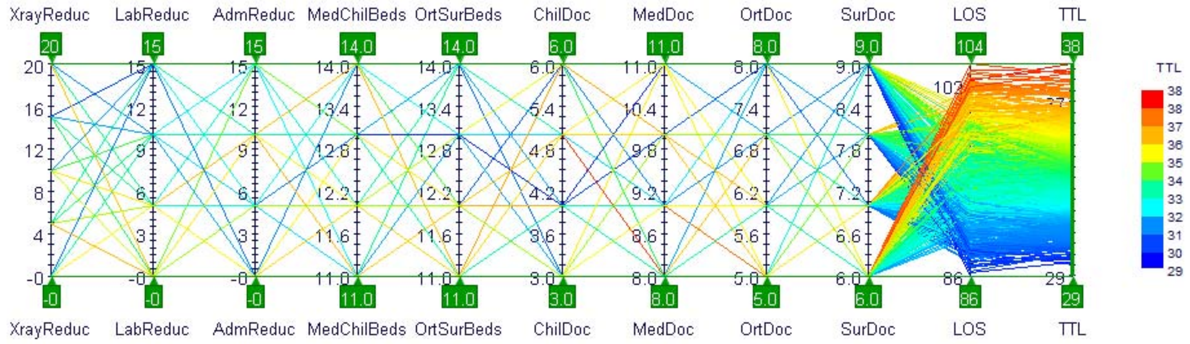

Figure 3. Parallel coordinates chart. Optimization results of LOS and TMD (TTL in the chart) in minutes. The rest of parameters shown in columns are in minutes or number of resources.

This parallel coordinates chart is used to help decision makers navigate among the possible optimal trade-off solutions generated by the optimization. With this chart they can establish maximum and minimum values for each variable /column in order to define possible solutions in areas that are more interesting. It is not uncommon that the initial budget or objectives shifts during a project. Having access to the whole solution space makes it easier for decision makers to look for solutions that are relevant to the new circumstances. Another important parameter that would impact in the final solution is the availability of physicians. The final solution can therefore be optimal but still tailor made to the category and number of physicians that the clinic manages to recruit. All these considerations can easily be included in the final solution thanks to the chosen multi-objective approach.

An example of some specific optimal solutions is shown in figure 4. The boundaries of the input parameters have been delimited and as a result four optimal solutions are shown. These solutions include adding to the ED a maximum of one extra orthopaedic physician, two extra surgery physicians, two extra surgery-orthopaedic beds, reducing the time for laboratory respond by 10 minutes and 5 minutes for X-Ray respond time.

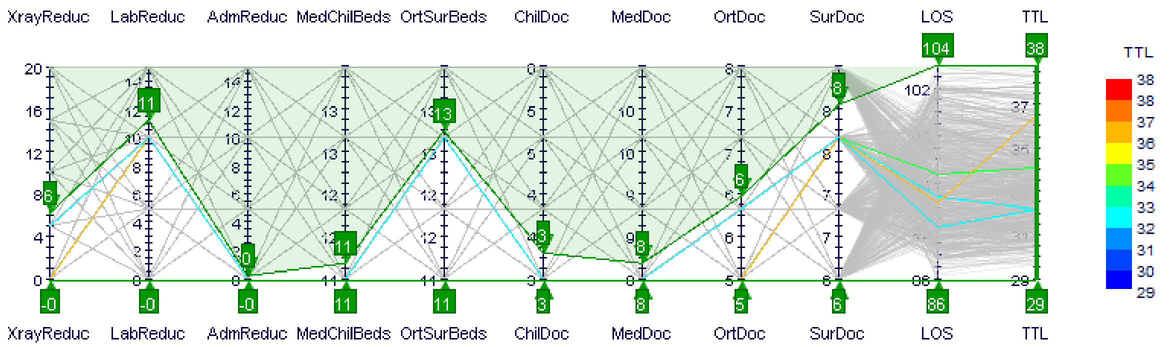

Figure 4. Optimal solutions example.

In the following table 6, the results of one of these possible solutions is presented. It shows the reduction of approximately 45% in the mean value and 90 percentile of TMD and a 35-40% reduction in the mean value and 90 percentile of LOS results compared to the original model.

Table 6. Optimization results. Time to meet the physician and LOS.

	Model (minutes)		Difference (%)		Solution (minutes)	
	P90	Mean	P90	Mean	P90	Mean
Total patients TMD	135.34	65.30	-45.05	-44.40	74.37	36.30
Total patients LOS	276.30	144.80	-38.91	-36.02	168.80	92.65

In the previous table it is possible to appreciate a significant improvement of the TMD and LOS of this particular solution. To implement this solution or a similar one with the mentioned extra physicians, beds and process time reductions would give the ED the chance to get much closer or even achieve the aims defined by the SoS. These reductions mean that if this solution is applied at the real ED, patients would wait 30 minutes less in average to meet a physician (60 minutes for the 90% of the patients) and they would have a 50 minutes shorter LOS in average (105 minutes for the 90% of the patients).

Analysing the whole set of results provided by the optimization, it can be concluded that for the given optimization parameters and values, the objective of the TMD for the 90% of the patients was not possible to achieve at the levels established by the SoS. Anyway, the optimal solutions show significant possible reductions of around 50% for that specific objective. Additional suggestions from the personnel at the ED and the interaction between SMO and Lean improvement will be considered in a future work at hand in order to get the desired levels.

5. Conclusion and future work

This work shows that SMO can efficiently be used to improve healthcare systems and EDs in particular. The study presents how a number of variables need to be simultaneously improved in order to reach a significant system improvement. Additionally, both the importance and limitations of what-if analysis are described. Furthermore, it highlights the importance and strength of SMO, by being able to truly support decision-making through presenting all optimal trade-off solutions. These solutions have guided the managers at SkaS to know what to do and what not to do without prior testing in the real system. It has given them a much higher insight about their system performance and peculiarities, increasing their knowledge and guiding their work in finding better ways of improving it. This process has saved considerable time, money and resources to the ED and is the foundation to reduce the patient’s waiting times and length of stay. Although lots of possible improved combinations have been found as a result of the optimization, not all the objectives defined by the SoS have been achieved yet. Further optimizations with some other configurations of the optimization problem as well as different working methodologies of the ED are now tested in order to get the required results.

The implication and engagement of the stakeholders of the hospital has been a key success factor for the correct development of the project and to define new future collaboration opportunities. In this way, future projects have been identified such as to include a detailed working procedure of the nurses into the model and to participate in the design of the future ED of SkaS.

References

[1] Young T, Eatock J, Jahangirian M, Naseer A and Lilford R 2009 Three critical challenges for modeling and simulation in healthcare. In: *2009 Winter Simulation Conference, WSC 2009,* (Austin, TX, USA: IEEE) pp 1823-30

[2] Harrell C R, Ghosh B K and Bowden R 2011 *Simulation using ProModel* (USA: McGraw Hill Higher Education)

[3] Gunal M M and Pidd M 2006 Understanding accident and emergency department performance using simulation. In: *2006 Winter Simulation Conference, WSC,* (Monterey, CA, USA: IEEE) pp 446-52
[4] Hay A M, Valentin E C and Bijlsma R A 2006 Modeling emergency care in hospitals: A paradox - The patient should not drive the process. In: *2006 Winter Simulation Conference, WSC,* (Monterey, CA, USA: IEEE) pp 439-45
[5] Denney S H 1997 MedModel - healthcare simulation software. In: *Proceedings of the 1997 Winter Simulation Conference,* ed S Andradottir, *et al.* (Piscataway, NJ, United States Atlanta, GA, USA: IEEE) pp 581-6
[6] Brailsford S C, Harper P R, Patel B and Pitt M 2009 An analysis of the academic literature on simulation and modelling in health care *J. Simul.* **3** 130-40
[7] Roberts S D 2011 Tutorial on the simulation of healthcare systems. In: *2011 Winter Simulation Conference, WSC 2011,* (Phoenix, AZ, USA: IEEE) pp 1403-14
[8] Ferrin D M, Miller M J and McBroom D L 2007 Maximizing hospital finanacial impact and emergency department throughput with simulation. In: *2007 Winter Simulation Conference, WSC,* (Washington, DC, USA: IEEE) pp 1566-73
[9] Jacobson S H, Hall S N and Swisher J R 2006 *Patient Flow: Reducing Delay in Healthcare Delivery* (Los Angeles: Springer US)
[10] Blasak R E, Starks D W, Armel W S and Hayduk M C 2003 The use of simulation to evaluate hospital operations between the emergency department and a medical telemetry unit. In: *Proceedings of the 2003 Simulation Conference: Driving Innovation,* ed S E Chick, *et al.* (New Orleans, LA, USA: IEEE) pp 1887-93
[11] Samaha S, Armel W S and Starks D W 2003 The use of simulation to reduce the length of stay in an emergency department. In: *Proceedings of the 2003 Simulation Conference: Driving Innovation,* ed S E Chick, *et al.* (New Orleans, LA, USA: IEEE) pp 1907-11
[12] Mahapatra S, Koelling C P, Patvivatsiri L, Fraticelli B, Eitel D and Grove L 2003 Pairing Emergency Severity Index5-level triage data with computer aided system design to improve emergency department access and throughput. In: *Proceedings of the 2003 Simulation Conference: Driving Innovation,* ed S E Chick, *et al.* (New Orleans, LA, USA: IEEE) pp 1917-25
[13] Takakuwa S and Shiozaki H 2004 Functional analysis for operating emergency department of a general hospital. In: *Proceedings of the 2004 Winter Simulation Conference,* ed R G Ingalls, *et al.* (Washington, DC, USA: IEEE) pp 2003-11
[14] Baesler F F, Jahnsen H E and DaCosta M 2003 The use of simulation and design of experiments for estimating maximum capacity in an emergency room. In: *Proceedings of the 2003 Simulation Conference: Driving Innovation,* ed S E Chick, *et al.* (New Orleans, LA, USA: IEEE) pp 1903-6
[15] Wiinamaki A and Dronzek R 2003 Using simulation in the architectural concept phase of an emergency department design. In: *Proceedings of the 2003 Simulation Conference: Driving Innovation,* ed S E Chick, *et al.* (New Orleans, LA, USA: IEEE) pp 1912-6
[16] AlDurgham M M and Barghash M A 2008 A generalised framework for simulation-based decision support for manufacturing *Production Planning and Control* **19** 518-34
[17] Figueira G and Almada-Lobo B 2014 Hybrid simulation-optimization methods: A taxonomy and discussion *Simulation Modelling Practice and Theory* **46** 118-34
[18] Deb K 2001 *Multi-objective optimization using evolutionary algorithms* (Wiltshire, UK: John Wiley & Sons, LTD)
[19] Ahmed M A and Alkhamis T M 2009 Simulation optimization for an emergency department healthcare unit in Kuwait *European Journal of Operational Research* **198** 936-42
[20] Chen T L 2014 Decision support system based on distributed simulation optimization for medical resource allocation in emergency department. In: *Lecture Notes in Computer Science*

(including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp 15-24

[21] Banks J, Carson J S, Nelson B L and Nicol D M 2000 *Discrete-Event Simulation* (Upper Saddle River, New Jersey: Prentice Hall, Inc.)

[22] Banks J 1998 *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice* (New York, USA: John Wiley & Sons, Inc.)

[23] Deb K, Pratap A, Agarwal S and Meyarivan T 2002 A fast and elitist multiobjective genetic algorithm: NSGA-II *IEEE Transactions on Evolutionary Computation* **6** 182-97