Instituto Superior Técnico
Industrial Engineering and Management

A management flight simulator for intensive care units – a System Dynamics approach

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Abstract

The Intensive Care Unit (ICU) of a major Lisbon hospital cannot cope with hospital's demand. At the core of the problem is ICU's director inability to simultaneously satisfy patient needs and hospital Administration service level demands. For the Administration, the source of the problem is the patient discharge policy of the ICU's director, which keeps patients hospitalized at ICU longer than what is clinically needed. In ICU's director perspective, this procedure is absolutely necessary to avoid the high readmission request rates of the past, observed when the patients where in transition between the ICU and the general wards.

In this paper we present the development of a management flight simulator for intensive care units, based on System Dynamics methodology. Through this process we expect to be able to understand how the problematic behavior originates from the system internal structure. We also explore some possible solutions, such as the introduction of a High Dependency Care Unit.

As main conclusions we found out the ICU is insufficiently dimensioned given the hospital daily operation characteristics, and the introduction of a High Dependency Care Unit is the only solution simultaneously able to lower the conflicts and raise the motivation, allowing, as well, for a lower average length of stay without causing an increase in readmission request rates.

Key words: System Dynamics, management flight simulator, simulation, critical care.

Introduction

Through an informal conversation with the director of an Intensive Care Unit (ICU) of a major Lisbon hospital, we became aware that this Unit cannot cope with hospital's demand. The dilemma for this health care professional lies in her inability to simultaneously satisfy patient needs and hospital Administration demands. This situation persists since the opening of the unit, in 1994.

ICU's director keeps patients hospitalized until their health condition is strong enough to withstand the care levels of the general wards. This does not mean that general wards level of care is poor. For economic reasons not every ward can benefit from the level of equipment, monitoring and medical surveillance available to the ICU. From this perspective, critical patients are treated at the ICU, and as their health condition improves, they are transferred to the general wards of other services.

Although there are significant quality differences between general wards within the hospital, we can consider, for the problem at hands, that there are only two levels of care available – the ICU and the general wards. This implies a huge gap in terms of available levels of care. At the beginning, ICU's director policy consisted in keeping patients hospitalized only as long as it was clinically recommended[1]. This policy was quickly abandoned because soon an inadmissible readmission requests rate was observed[2], since general wards are not capable, by definition, to sustain these patients in transition. Soon, it was replaced by the current policy which consists in keeping patients hospitalized at ICU until their health condition can be properly served by a general ward. The main consequence of this policy is an excessive[3] average length of stay at ICU. According to available data[4], the current average length of stay is approximately 13.35 days and the strictly clinically necessary ranges between 8 to 10 days, according to ICU' director.

Notice that the policy described in the previous paragraph would have no impact in the system if it were not already endemically in stress. According to Lane (2000), reducing the amount of resources in a hospital system does not imply poorer service, as long as shorter amount of resources can be compensated by a high utilization rate of these resources. But this is clearly not the case since bed occupancy rate at ICU is already at 91%.

Given the current admission requests number, it has great impact on the system placing the average length of stay at 13.35 or at 10 days. The system poor performance is clearly visible in the high emergency admission request rejection rate, estimated at 50%, and in the high waiting time for elective admission, currently at 7 to 10 days. It is undisputable that a reduction in the average length of stay would have a positive impact in these variables. As previously mentioned, another symptom is the very high bed occupancy rate, currently at 91%. From queuing theory, we know that when the system utilization rates goes over 70%, the waiting

[1] The criteria stating which patients to treat at which level of care is very well defined. (Audit Commission, 1999) (Goldhill, 2002).

[2] The actual value is unknown. The literature recommends a maximum 4% rate.

[3] But absolutely necessary in ICU's director point of view.

[4] Collected from January 1 2007 to July 2 2008.

time starts to grow exponentially (Hines, et al., 2003).

As the system is already in stress, ICU's director policy is perceived by most within the hospital as the cause of the problem. Although it is clear her policy focuses on protecting the patients (Walker, et al., 2003), it is not so clear, at least for the hospital Administration, that it is absolutely necessary, blaming her for the current state of the problem.

Please note that mortality rate for ICU patients is very high, around 25%. It is not clear whether the increase in average length of stay is saving a significant number of lives, through avoiding regress in patients' health condition. On the other hand, in hospital Administration perspective, ICU's director seems to ignore that a longer average length of stay implies a higher emergency admission requests rejection rate. ICU's director needs to keep this delicate balance between lives saved through avoiding later regresses in patients' condition and rejected admission requests. For the moment she keeps faithful to her principle that once hospitalized in her Unit, it is her obligation to maximize patients' chance of survival.

For the hospital Administration, the solution consists in ICU's director strict observance of correct discharge criteria. For ICU's director the problem is solved by introducing a High Dependency Unit, in the hospital, as this solution would allow for lower ICU hospitalization times without being afraid of later regresses in patients' condition. But maybe the ICU is poorly dimensioned in the first place, in which case none of the solutions will solve the problem.

In this system we observe an increasingly high level of conflicts and an ever declining motivation of ICU professionals. ICU's director needs a tool to show that the cause of the problem does not lie in her discharge policy.

In this paper we report the development of a management flight simulation model for ICUs used to understand and help solve the problem at hands. We present a relevant counterintuitive behavior found during the modeling process, and answer the question: "Is the ICU insufficiently dimensioned for the level of hospital demand?" The base methodology is System Dynamics, although we have used Discrete Event Simulation to establish the relationship between some variables in the model.

Literature review

Most System Dynamics health care applications have a strong economic focus, dealing mainly with cost reduction and resource allocation. This paper, on the other hand, focuses on a human problem – ICU's inability to adequately serve the patients of the hospital.

According to Sedehi (2001), the construction of management flight simulators for health care units has two purposes: to better understand the dynamics of the process, while building the dynamic model, and evaluate in advance the effects of the decisions through the run of the simulator. In our case, we seek to understand how the problematic behavior arose and test ICU's insufficient dimensioning and some solutions.

We did not find any System Dynamics application to Intensive Care Units, in the reference literature. The closest is a paper by

Lane (2000) in which he models an Accident & Emergency Unit. Prior to his study, it was believed the cause of strangling in the service was the insufficient number of beds. Lane has shown that the root of the problem lay instead in the high utilization rate of the medical staff, and not in the beds. In fact, fewer beds could be compensated by an increase in occupancy rate with a minor impact in system's performance. In Lane's case study the dynamic behavior arises from the daily periodic pattern of patient arrival. Our problem is very different. The number of beds is undoubtedly the strangling factor and not the medical staff. The dynamic behavior does not arise from the demand pattern which is assumed to be constant in the base case scenario. Instead the dynamic behavior arises when changes are performed to some variables, such as the average length of stay or the number of beds.

In a later paper (Lane, et al., 2003) on the same case study, Lane recognizes some problems with his admission process modeling. We felt a similar struggle. It is difficult to model the admission flow because it is constrained by the bed occupancy, and stock and flow models must work with average values all the time. To overcome this, we elaborated a sub discrete event simulation model, to discover how some key variables in the system would vary with average length of stay, number of beds, and number of admission requests.

Since, in our case study, hospital Administration has not performance metrics for ICU, we still refer to Lane´s paper for some examples, such as: average waiting time and bed occupancy rate.

Methodology

The base methodology is System Dynamics because we want to explore how the problematic situation developed from the internal structure of the system, and propose some solutions.

A Causal Loop Diagram (CLD) was used as a mean of validating our perception of the problem. Then we built a mathematical model based on stock and flow programming. To calibrate some relations between variables we resorted to a smaller Discrete Event Simulation Model.

The chosen approach requires heavy interaction with our interlocutors within the hospital. A set of meetings were undertaken at the hospital including one with the President of the Administration Board where an early Causal Loop Diagram was shown, in an attempt to obtain as much input from this source as possible. The CLD was validated by the ICU's director.

Modeling

In this chapter we present the CLD constructed, with which we were able to find a possible counterintuitive behavior. We then briefly summarize the core stock and flow structure of the model.

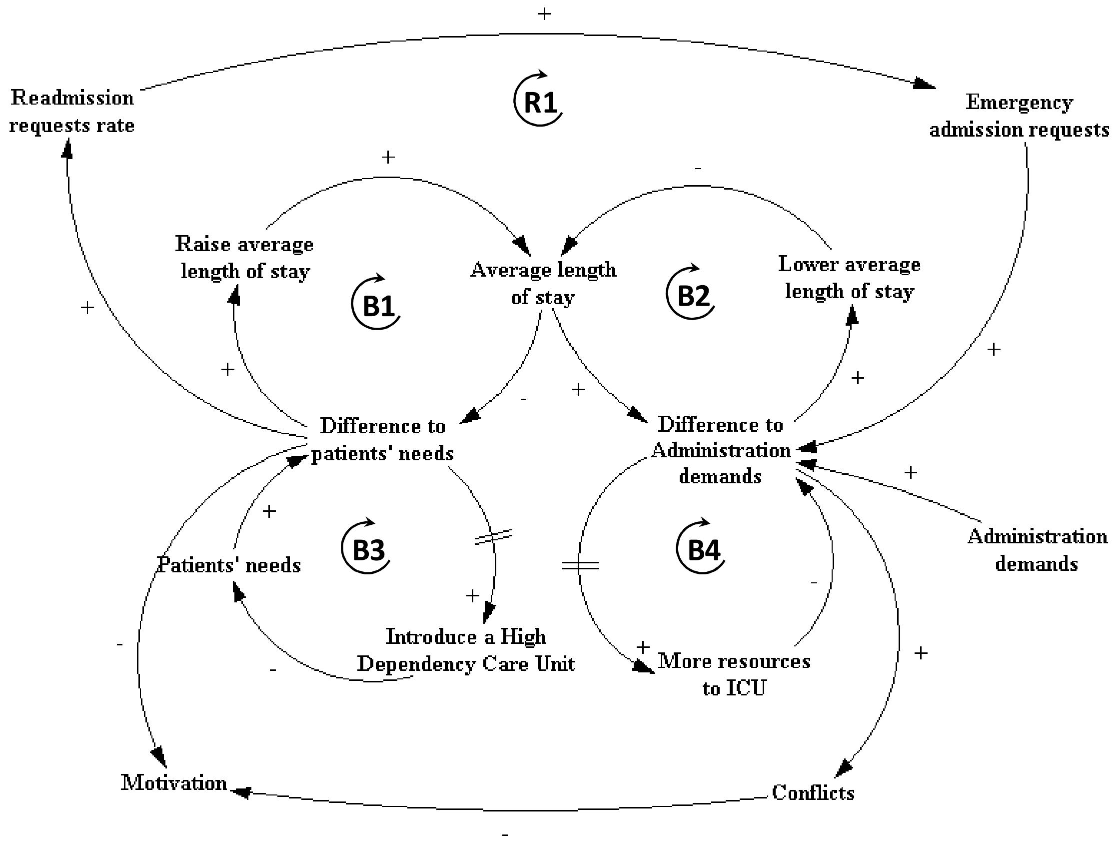

Figure 1: Causal Loop Diagram

Since quality of the service at ICU is not our focus of discussion and is not meant to change, let us assume that “Patients’ needs” can be solely measured as a given number of hospitalization days. When patients first arrive at ICU they need to be appropriately treated and then stay hospitalized until their health condition is good enough to be moved to the next level of care downstream the health care chain. If “Patients’ needs” are higher than the “Average length of stay”, then there will be a “Difference to patients’ needs”. The ICU’s director can compensate this by raising the average length of stay, completing balancing loop B1. Since hospital Administration has no performance metrics whatsoever for the ICU, let us assume those can be measured as a given average number of hospitalization days, as well. The performance metrics could be the number of yearly admissions, readmission requests rejection rate, bed occupancy rate, etc… All of these depend of the average length of stay, so the previous simplification is not incorrect. So, “Administration demands” are compared to the current “Average length of stay”. If they are higher, then a “Difference to Administration demands” is created which can be compensated if ICU’s director lowers the average length of stay, closing loop B2. The dependency between loops B1 and B2 is not enough to cause the problematic behavior. But for current conditions the value for “Average length of stay” that balances loop B1 is very different from the value that balances loop B2, and this causes the problematic behavior.

To solve the impossibility of balancing loops B1 and B2 simultaneously we could act directly on the “Patients’ needs” or on “Administration demands”. Decreasing “Administration demands” does seem to be a good solution. We would be entering the stereotypical behavior described by Senge (1990) as Eroding goals. Lowering “Patients’ needs” is possible if we introduce a High

Dependency Unit in the hospital. This way, patients' ICU hospitalization period can be shortened because they now have an adequate intermediate level of care to attend before discharge to a general ward. In this way, a lower "Average length of stay" could balance loop B1 and maybe loop B2 would be balanced as well. A solution to balance loop B2 with a lower value for "Average length of stay" consists in giving "More resources to ICU", such as installing more beds, which would lower the "Difference to Administration Demands". Both proposed solutions could be implemented independently.

As seen on Figure 1, both problem symptoms are not independent. The "Difference to patients' needs" is linked indirectly linked to the "Difference to Administration demands". An increase in the "Difference to patients' needs" will lead to an increase to the "Readmission requests rate", which in turn will increase the flow of "Emergency admission requests" and thus causing an higher "Difference to Administration demands", because a greater "Emergency admission requests" flow will inevitably lead to a higher emergency admission requests rejection rate, higher bed occupancy rates and so on, making the system diverge from "Administration demands". This means that increasing the "Average length of stay" could be in fact decreasing the "Difference to Administration demands" if loop R1 dominates over loop B2. This is a possible counterintuitive behavior, which was only possible to find thanks to the construction of this CLD. Further ahead, in the Results chapter, we explore which relationship between length of stay and readmission requests rate triggers this counterintuitive behavior.

Conflicts arise from the non observance of "Administration demands". Knowing their patients do not have their survival chances maximized together with a conflicting working environment lower the motivation of ICU's medical staff.

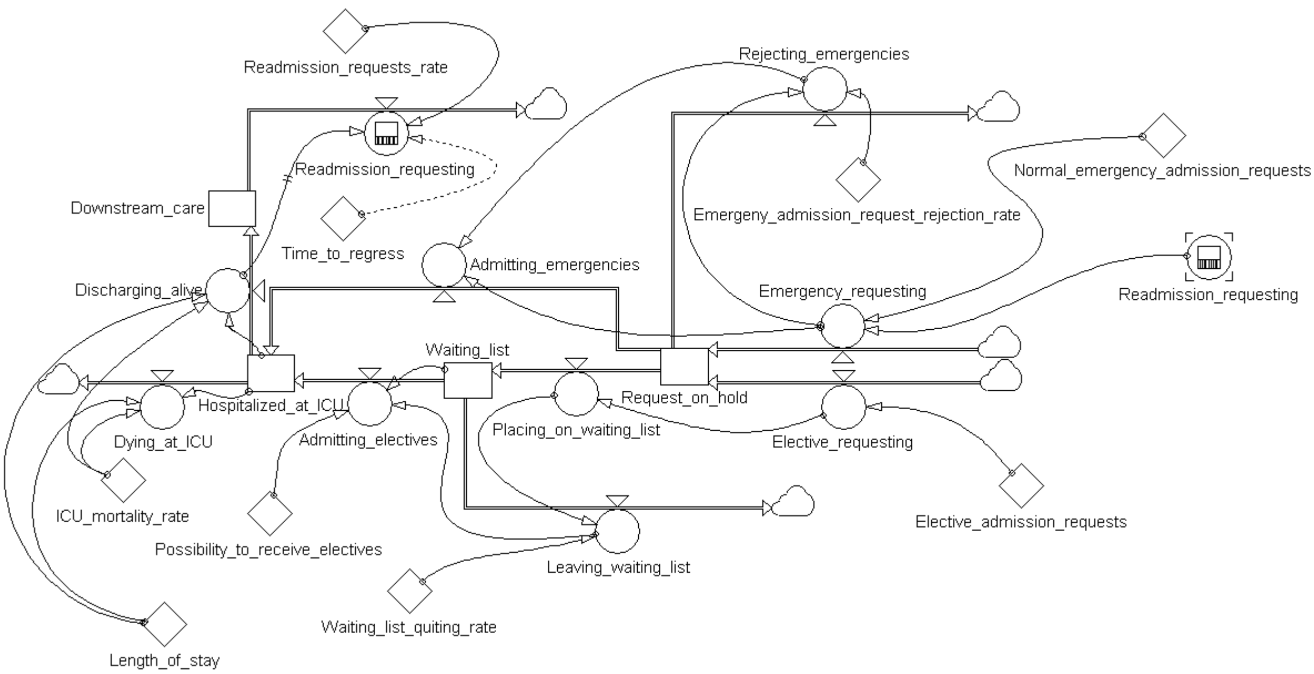

Figure 2: Core Stock and Flow structure.

We will now briefly describe the stock and flow modeling. Figure 2 shows the core stock and flow programming. From the picture is missing how the motivation and conflicts were modeled, which we will describe later.

Patient admission requests arrive trough two possible flows – "Emergency requesting" and "Elective requesting". The first is for emergency admissions and the second for patients who came from elective surgeries. We still break down emergency admission requests into two possible sources – normal requests and readmission request. As these requests arrive they are placed on the level "On hold" waiting for a decision from the ICU's director.

Emergency requests demand an immediate decision whether to hospitalize at ICU or not. If a bed is not empty, the ICU's director must reject this request – "Rejecting emergencies". Emergency requests have priority over elective requests. Elective requests may be put on a waiting list until a bed is vacant at ICU. Only then the surgery is scheduled and the patient admitted to ICU. If in the meantime an emergency request comes along, it has priority over the patient with the scheduled surgery and the surgery must be postponed. If the waiting time is too long, some patients will start to quit the waiting list – "Leaving waiting list" – mostly because their illnesses have progressed beyond a possible surgery treatment.

After patients are hospitalized at ICU they can receive discharge alive or died in the meantime at ICU. Alive patients move down to a lower level of care where they pursue further improvement to their health condition. If the health care service is not good enough their health condition may regress originating readmission requests.

ICU admission is constrained by a critical resource: the number of beds. A System Dynamics model must work with average values all the time, so modeling the admission process was not easy. A Discrete Event Simulation Model (DESM) was built to find out the relationship between the dependent variables "Emergency admission requests rejection rate", "Waiting list quitting rate", "Waiting time" and "Bed occupancy rate" (last two not shown of Figure 2) and the independent variables "Length of stay", "Number of ICU beds" and the number of admission requests (both). With the results of the DESM we were able to guarantee that the "Admitting emergencies" flow will never cause the "Hospitalized at ICU" level go raise over the number of installed beds. The "Admitting electives" flow is controlled by the variable "Possibility to receive electives", which in turn has some of these DESM calibrated variables in its definition. Both admission flows are realistic and "Hospitalized at ICU" level is always lower than the number of installed beds.

Since motivation and conflicts have no intrinsic units, these variables were treated as indexes. An index of 100 corresponds to the present conditions (base case scenario) of their defining variables. Conflicts are a function of the "Emergency admission requests rejection rate", the "Readmission requests rate", the "Waiting list quitting rate" and the "Waiting time". Motivation, in turn, is a function of the "Readmission requests rate", the "Length of stay" and the "Conflicts. We also forced on Motivation and Conflicts that their respective indexes could only improve is a positive trend was present in all their defining variables.

Results

The simulator constants and input variables were calibrated and a base case simulation was run, depicting the current observed state of the system. The results are shown on Table 1.

Table 1: Results for base case scenario

Inputs	
Variable	**Value**
Readmission requests rate	1.1 %
Length of stay	13.35 days
Number of beds	5 beds
Elective admission requests	75.7 requests/year
Emergency admission requests	125.52 requests/year
Outputs	
Variável	**Value**
Waiting list quitting rate	5,9%
Emergency admission requests rejection rate	62.0%
Bed occupancy rate	91.4%
Waiting time	8.5 days
Elective admissions	71.2 patients/year
Emergency admissions	48.1 patients/year
Total admissions	119.3 patients/year
Different patients	118.9 patients/year

We then tested the hypothesis whether the ICU was insufficiently dimensioned given existing hospital demand. To do this, we placed the average length of stay at 8 days, the lowest ever considered, and the readmission requests rate at 0.0%. All other input variables were kept at their presented observed value. For these inputs we ran the simulator and looked for the output value of the “Emergency admission requests rejection rate”. Any value over 10% would be inadmissible. The results are shown on Table 2.

Table 2: Results for ICU dimensioning

Inputs		
Variable	**Value**	**Change to base case scenario**
Readmission requests rate	0 %	-100%
Length of stay	8 days	-40.7%
Number of beds	5 beds	0%
Elective admission requests	75.7 requests/year	0%
Emergency admission requests	125.52 requests/year	0%
Outputs		
Variável	**Value**	**Change to base case scenario**
Waiting list quitting rate	1.5 %	-74.6%
Emergency admission requests rejection rate	32.4%	-47.7%
Bed occupancy rate	73.0%	-20.1%
Waiting time	4.1 days	-51.8%
Elective admissions	74.6 patients/year	+4.8%
Emergency admissions	84.8 patients/year	+75.5%
Total admissions	159.4 patients/year	+29.4%
Different patients	159.4 patients/year	+34.1%

As one can see, even in optimal operating conditions, the "Emergency admissions requests rejection rate" is still at 32.4%, an inadmissible value.

We used the simulator to find out which solution could simultaneously decrease the conflicts and increase motivation. Reducing the average length o stay will increase the conflicts and reduce motivation. Increasing the number of beds will decrease the conflicts but motivation will remain constant. Introducing a High Dependency Unit (HDU) will allow to simultaneously reduce the conflicts and increase motivation. With a HDU scenario, length of stay can be reduced without jeopardizing patients' chance of survival.

We now show a conservative and best case scenario exemplifying what kind of improvements and how, could be achieved for the ICU. For the conservative scenario we simply place the length of stay at 10 days. This is the most conservative value believed to be possible to archive without increasing the readmission requests rate, as long as an HDU is present. The results for the conservative scenario are shown on Table 3.

The ICU has 6 installed beds but one of them is restricted to patients who need to be in isolation. The opening of the sixth bed also requires the closing of one of the other beds. There is speculation whether it is justifiable to have one bed closed at all times and maybe the transformation of the isolation bed into regular bed is desirable. In the best case scenario we considered the existence of 6 regular beds at ICU. There is also speculation about whether there is an excessive number of elective requests placed due to common ICU lack of availability. In this case, introducing the HDU unit would counter these excessive requests. On the best scenario we also considered an elective admission requests drop from 75.7 to 65 requests/year. Length of stay is further dropped to 8 days, and of course a HDU is present. The results are shown on Table 4.

Table 3: Results for conservative scenario

Inputs		
Variável	**Valor**	**Variação para situação actual**
Length of stay	10 days	-25.9 %
Number of beds	5 beds	0 %
Elective admission requests	75.7 requets/year	0 %
HDU?	Yes	
Outputs		
Variável	**Valor**	**Variação para situação actual**
Emergency admission requests rejection rate	43.7%	-22.3%
Bed occupancy rate	80%	-9.4%
Waiting list quitting rate	3.2%	-37.,3%
Waiting time	5.8 days	-25.9%
Elective admissions	73.3 patients/year	+2.4%
Emergency admissions	71.4 patients/year	+59.6%
Total admissions	144.7 patients/year	+21.5%
Different patients	144.0 patients/year	+21.1%

Table 4: Results for best case scenario

Inputs		
Variável	**Valor**	**Variação para situação actual**
Length of stay	8 days	-40.1%
Number of beds	5 beds	0 %
Elective admission requests	65 requests/year	-14.1%
HDU?	Yes	
Outputs		
Variável	**Valor**	**Variação para situação actual**
Emergency admission requests rejection rate	29.0%	-45.3%
Bed occupancy rate	71.0%	-19.0%
Waiting list quitting rate	0.8%	-76.3%
Waiting time	3.4 days	-52.9%
Elective admissions	64.5 patients/year	-10.0%
Emergency admissions	90.0 patients/year	+106%
Total admissions	154.5 patients/year	+36.7%
Different patients	153.6 patients/year	+29.2%

Even in the conservative scenario the changes to UCI performance are very significant. Emergency admissions rise by almost 60% leading to a total admissions rise 21.5%. In the best case scenario the improvement is even more impressive with emergency admissions more than doubling thanks to a 45.3% reduction in the emergency admission requests rejection rate. Overall yearly admissions go from 119.3 to 154.5 patients/year.

We also found out that adding an extra bed is more or less equivalent to reducing the length of stay by 2 days.

Through the mathematical structure of the model was possible to show that the counterintuitive behavior, described on Figure 1 could take place. Though the use of the simulator, the counterintuitive behavior was actually shown between 10 to 10.75 days of length of stay, for the calibrated system conditions. The behavior takes place in this length of stay frame if the readmission requests rate drops approximately faster than 2.25% per 0.1 days of length of stay. The behavior is almost linear.

Conclusions

The data available spanned only across 18 months. A lot of variability is present in the data, so a larger collecting period would be desirable. Nevertheless, the result showing the poor dimensioning of the ICU is robust enough to withstand data uncertainty and the sensitivity analysis performed on key relations of the model. More data would translate on a more precise outcome of the scenarios on Tables 3 and 4.

The model is useless to judge the importance of a saved human life but even if an HDU is not present substantial performance improvements are possible simply by dropping the average length of stay from 13.35 to 10 days. If we consider a drop in the 8 to 10 days range, we can expect a 31.1% increase in yearly admissions and a drop in emergency admission requests rejection rate from 62.0% to around 38%.

The length of stay is the most relevant decision variable in the model followed by the number of beds and only them by the existence of a HDU. But please note that decreasing the length of stay will cause a surge of health condition regresses on discharged patients unless an HDU is present. The value of the HDU is not clearly captured by the performance metrics of the model.

Even with 6 beds and a supporting HDU, the ICU cannot deal with the flow of incoming requests. We would like to stress the evidence that the system is far achieving it. It is open for further investigation, the development of a model with a broader scope, including variables such as costs to explore which might be the best solution for properly serving the critical patients of this hospital – a single but larger ICU, an ICU and a HDU – and their respective dimensioning.

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