Health Care Manag Sci (2017) 20:532–547
DOI 10.1007/s10729-016-9369-z

Sustaining critical care: using evidence-based simulation to evaluate ICU management policies

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Received: 20 November 2015 / Accepted: 10 May 2016 / Published online: 23 May 2016

Abstract Intensive Care Units (ICU) are costly yet critical hospital departments that should be available to care for patients needing highly specialized critical care. Shortage of ICU beds in many regions of the world and the constant firefighting to make these beds available through various ICU management policies motivated this study. The paper discusses the application of a generic system dynamics model of emergency patient flow in a typical hospital, populated with empirical evidence found in the medical and hospital administration literature, to explore the dynamics of intended and unintended consequences of such ICU management policies under a natural disaster crisis scenario. ICU management policies that can be implemented by a single hospital on short notice, namely premature transfer from ICU, boarding in ward, and general ward admission control, along with their possible combinations, are modeled and their impact on managerial and health outcome measures are investigated. The main insight out of the study is that the general ward admission control policy outperforms the rest of ICU management policies under such crisis scenarios with regards to reducing total mortality, which is counter intuitive for hospital administrators as this policy is not very effective at alleviating the symptoms of the problem, namely high ED and ICU occupancy rates that are closely monitored by hospital management particularly in times of crisis. A multivariate sensitivity analysis on parameters with diverse range of values in the literature found the superiority of the general ward admission control to hold true in every scenario.

Keywords Intensive Care Unit (ICU) · ICU management policy · Critical care management · Patient flow · System dynamics · Simulation · Evidence-based policy analysis · Performance measure

1 Introduction

Intensive Care Units (ICU) are costly yet critical hospital departments that should be available to care for patients needing highly specialized critical care. There is a shortage of ICU beds in many countries [1–5] and ICU occupancy rates are increasing [6]. When demand for critical care is high relative to available ICU capacity, ICU becomes a bottleneck to patient flow [5], making critical patients access to ICUs limited [7]. As a result, critically ill patients may be boarded in emergency departments (ED) which causes ED overcrowding [8, 9] and potential closure [10] and puts pressure on ED physicians who have to care for boarded patients in addition to ED patients [11]. Most importantly, boarding critically ill patients in ED puts the patients at risk of higher adverse events and mortality [12, 13], potentially increasing risk of ICU mortality by 1.5 % for each hour of waiting [14]. In addition to disrupting the workings of the ED, shortage of ICU beds could cause elective surgery cancellations [5, 7], affect discharge decisions [15–17], and increase risk of early death [18].

Various ICU management policies have been proposed and implemented over time in hospitals to lower ICU occupancy rates and improve critical care availability. While all are good intentioned and have positive intended consequences in terms

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Electronic supplementary material The online version of this article (doi:10.1007/s10729-016-9369-z) contains supplementary material, which is available to authorized users.

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of improving patient flow, there is evidence of unintended consequences that could put patient health at risk.

While there is empirical research within the medical and hospital administration literature on the silo effects of individual ICU management policies on particular aspects of care outcomes, there seems to be a research gap in terms of the combined effects of such management policies in a typical hospital. As such, clinicians and hospital administrators may have a difficult time putting all the evidence together to conclude what the best ICU management policies are in times of crisis. The purpose of this research is to address this gap in the literature by quantitatively assessing the combined effects of select ICU management policies in a typical hospital, and identify the best performing policy in managing ICU capacity.

To do so, a system dynamics modeling approach [19] has been applied to the context of emergency patient flow in a typical hospital. The choice of this methodology was based on the fact that by modeling the interactions of various elements of the patient flow at the aggregate level, it enables gaining a strategic perspective on the effects of management policies at the system level. System dynamics not only offers a rigorous approach to focus on the interconnectedness inherent in healthcare settings, but also the models can serve as learning environments for decision makers to understand why a certain structure produces a behaviour and conduct policy analysis to see how varying the conditions can change behavior [20]. The latter was of utmost importance to us in this study, as we intend that our fully documented generic model of a typical hospital can be used to test ICU management policies by decision makers in the field, using either the generic parameter values in this study or institution-specific parameter values applicable to their local circumstances. System dynamics has been applied to modeling patient flow problems extensively. Some examples include Brailsford et al. (2004) [21], Lattimer et al. (2004) [22], Desai et al. (2008) [23], Lane and Husemann (2008) [24], and Rashwan et al. (2015) [25].

The paper is organized as follows. First, the literature on ICU management policies is reviewed. The following section presents the research question and focus of the study. Next, a high-level cause and effect dynamic hypothesis of the effects of ICU management policies on system performance is discussed, followed by a system dynamics simulation model of emergency patient flow at a typical hospital, populated and calibrated with data from the literature. After a description of system-level performance measures, output of a baseline scenario that represents a typical hospital operating under stable conditions is presented. Subsequently, a crisis scenarios of a natural disaster that could put significant pressure on the critical care capacity of the hospital is introduced. Various ICU management policies are tested to assess their effects on alleviating the pressure on the ICU under this crisis scenario. The final sections discuss ICU management insights derived from the simulation, sensitivity of these insights to input parameters, as well as a discussion of study limitations and areas for future exploration.

2 ICU Management policies

Due to the fact that ICU is the best place for critically ill patients [4] to receive early interventions, many policies have been suggested to increase ICU bed availability [5, 7, 26]. Most common policies, starting from the three policies within the scope of this study that a single hospital can implement on short notice without incurring high costs, include:

1. Premature Transfer from ICU: Shortening ICU Length of Stay (LOS), estimated to occur for 6 to 42 % of initial discharges from ICU [27, 28], is another intuitive policy for admitting more patients into an ICU [17, 29]. However, it has been shown that transferring patients faster and sicker to the general ward is associated with increased in-hospital, ICU and Post-ICU, mortality [30, 31] as well as increased readmission rates [32, 33]. Early transfer out of ICU is responsible for 22 to 42 % of ICU readmissions [28] and 39 % of discharge mortality [34].
2. Boarding in Ward (ICU Admission Control): Under this policy, when ICU is full, critical patients waiting for ICU admission are admitted to the general ward instead [4, 14, 26]. It has been shown that admitted critical patients in ICU have better outcomes compared to those admitted to wards [14]. Parkhe et al. (2002) found that critically ill patients who were detoured to the Ward had an increased relative risk of 30-day mortality of 2.46 versus patients directly admitted to the ICU from ED [35].
3. General Ward Admission Control: Dunn (2003) mentioned that in order to decrease hospital overcrowding we may need some priorities in allocation of scarce resources in hospital [36]. Under this policy, ICU patients ready to be transferred to the general ward are given priority over those waiting for a ward bed in ED.
4. Expanding ICU Capacity: Adding more beds to ICU is usually seen as an intuitive yet costly policy that is widely discussed in the literature. By investigating five hospitals in UK, Lyons et al. (2000) estimated that to meet demands 95 % of times a two-fold increase in the number of ICU beds is required for a region [3]. Daly et al. (2001) concluded that to avoid post-ICU death caused by inappropriate discharge, a 16 % increase in the number of ICU beds in UK is necessary [34]. Yet, Kim et al. (2014) estimated that adding each bed to ICU costs \$0.8 million per year [26]. It has been mentioned that investments in ICU beds also resulted in higher fixed costs, excess capacity, and long-term inefficiencies [37]. Limitations in the number of ICU staff, spaces within hospitals, government regulations and high costs

associated with adding more beds to ICUs are mentioned as main reasons that hinder expansion of ICUs [1, 38, 39].

5 Expanding General Ward Capacity: Inadequate availability of beds in the general ward is seen as a reason for prolonged ICU stay, which in turn may cause blocked access to ICU beds [40, 41]. As such, expanding general ward capacity is considered as another policy to free blocked ICU beds.

6 ICU Direct Discharge Home: Johnson et al. (2013) propose directly discharging ICU patient home from ICU in instances where they have waited for a ward bed for a long time [40].

7 Discharge Home without Admitting to ICU: Armony et al. (2014) propose that patients who have waited long enough for admission to ICU in another department may have recovered and no longer need admission to ICU, and as such may be ready to be discharged [42]. This is confirmed by Hodgins' (2011) observation that 14 % of admitted patients spend all of their hospital stay in ED [43]. Similarly, Dunn (2003) mentions that some admitted patients in the ED admission group recover enough during their waiting times in ED that are discharged directly from the ED without ever being transferred to a hospital bed [36].

8 Intermediate Units: To decrease ICU occupancy rates, intermediate units such as a Step Down Unit (SDU) or High Dependency Unit (HDU) can be used. These units provide an intermediate level of care between ICU and the general ward for semi-critical patients who do not need the level of care in ICU but are not ready to be transferred to the general ward either [44, 45].

9 Ambulance Diversion: To overcome crowding in ED, ambulances may be diverted to other hospitals. Given that many ICU patients are brought into the hospital by an ambulance [46], this policy also alleviates the pressure on ICUs by reducing the demand for ICU beds. However, Scheulen et al. (2001) states that diverting patients is ineffective in decreasing ED volume [47]. More importantly, Begley et al. (2004) found a higher mortality rate among trauma patients who were admitted during ambulance diversions [48].

10 ICU Patient Transfer: In times of inadequate ICU beds, patients may be transferred from a hospital to another hospital in order to be admitted in the latter hospital's ICU. It has been found that these patients experience worse outcomes than those admitted to the ICU in the same hospital [49, 50].

11 Elective Surgical Demand Control: Elective surgery cancellation is another way to make room in ICU, basically by reducing the demand for ICU beds generated from elective surgical cases. Moreover, demand from elective surgeries can be controlled through better scheduling. McManus et al. (2003) investigated the impact of variability in patient flow on access to medical care and found that variability in scheduled surgical cases was higher than variability in unscheduled ICU admissions [51]. By smoothing the number of elective surgeries over the days of the week, Kolker (2009) made an 8.5 % reduction in ICU diversions [52].

3 Research question and focus of the study

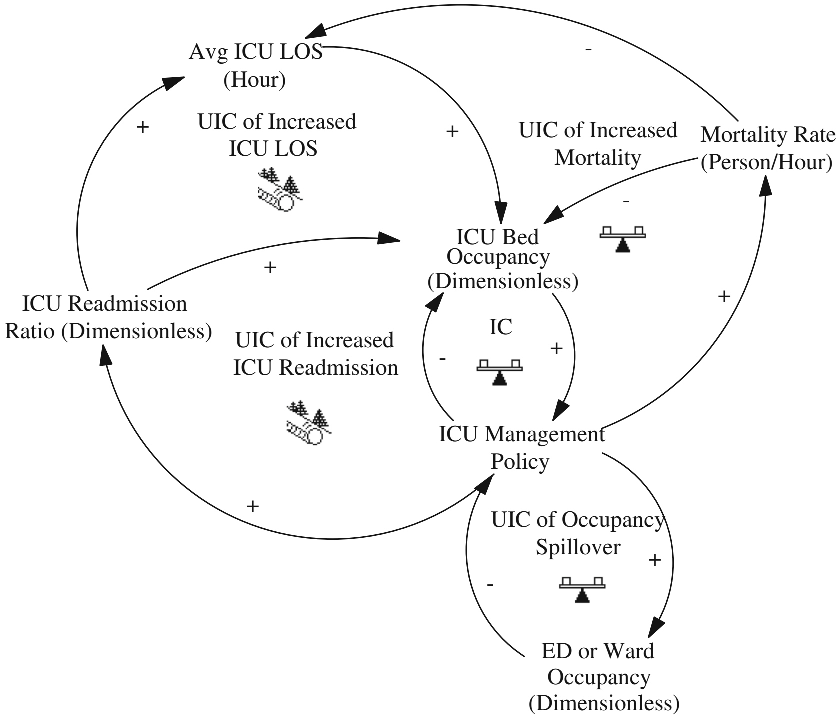
The study aims to analyze ICU management policies that a single hospital can implement on short notice in times of crisis to alleviate the pressure on the ICU without incurring additional costs or the need for coordination with other sectors, and most importantly without jeopardizing the rest of its operations (e.g. regarding the care for elective patients). As such, cost-incurring or long term capacity decisions (i.e. expanding ICU capacity, general ward capacity, and intermediate units), policies where patients are transferred to other hospitals and as such cannot be implemented by a single hospital in silo (i.e. ambulance divergence and ICU patient transfer), or else need coordination with the community to care for prematurely discharged patients from hospitals (i.e. ICU Direct Discharge Home and Discharge Home without Admitting to ICU policies) as well as the elective surgical demand control policy which disrupts the operations of the hospital for other patients are not investigated. In short, three policies of Premature Transfer from ICU, Boarding in Ward and General Ward Admission Control, as well as their combinations, are fully analyzed to reveal the best performing policy under the crisis scenario.

4 Cause and effect hypothesis

Figure 1 shows a high level cause and effect dynamic hypothesis of the relationships between the selected ICU management policies and particular performance measures. The diagram is not meant to be a comprehensive demonstration of all causal and feedback relationships. The purpose here is to show main intended consequences (IC) and unintended consequences (UIC) of the selected ICU management policies, namely Premature Transfer from ICU, Boarding in Ward, and General Ward Admission Control, and possible combinations of these.

All the selected policies share the central balancing loop, which shows the intended consequence (IC) of reducing higher than desired ICU bed occupancy through implementing these policies, regardless of the degree to which this intended consequence is realized. To varying degrees, as empirically demonstrated in the literature and summarized

Fig. 1 High-Level Cause-and-Effect Dynamic Hypothesis of Managing ICU Occupancy through ICU Management Policies



under section 2, the policies could also result in UIC of increased ICU readmissions, UIC of increased ICU LOS, UIC of increased mortality, and UIC of occupancy spillover.

The "UIC of Increased ICU Readmission" loop demonstrates how responding to higher than desired ICU occupancy rate by implementing selected ICU management policies, to varying degrees, could result in a higher percentage of patients who would require ICU readmission (i.e. higher ICU readmission ratio) [32, 33], and as a result increase ICU occupancy rate.

The "UIC of Increased ICU LOS" loop depicts how higher ICU readmission rate (as part of the dynamics of "UIC of increased ICU readmission") could increase average ICU LOS [27, 53, 54], further increasing ICU occupancy rate above the intended level.

The "UIC of Increased Mortality" loops shows how responding to higher than desired ICU occupancy rate by implementing selected ICU management policies, to varying degrees, could result in a higher mortality rate [30, 31, 34, 35], decreasing average ICU LOS, and as a result decreasing average ICU occupancy rate. Such a decrease in ICU occupancy rate is of course not desired, as it is achieved through higher mortality.

Finally, the "UIC of Occupancy Spillover" indicates how responding to higher than desired ICU occupancy rate by implementing selected ICU management policies, to varying degrees, could have spillover effects on occupancy rates of other departments, as patients transferred prematurely out of ICU or otherwise boarded in other departments inevitably increase occupancy rates of those departments.

We quantify these cause and effect relationships in the context of emergency patient flow based on empirical evidence from the literature, so that a whole system analysis of effects of any combination of ICU management policies can be performed to inform best practices in managing precious ICU capacity.

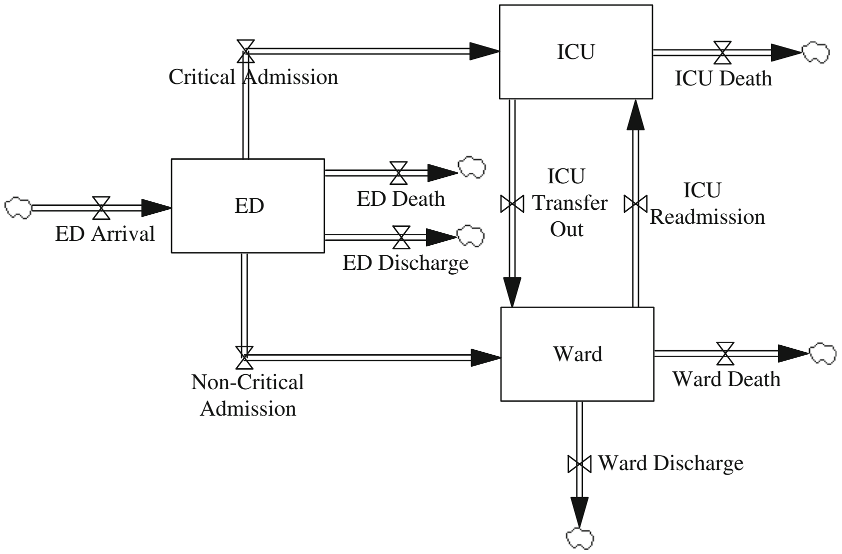
The following section explains the high level structure of a system dynamics model developed for this purpose.

5 Model structure

We developed a system dynamics simulation model of emergency patient flow within a typical acute care hospital consisting of an Emergency Department (ED), an Intensive Care Unit (ICU), and a general ward (Ward). A high level schematic picture of the model is presented in Fig. 2. The full model consists of 36 stock and 50 flow variables, as well as 86 auxiliary variables. To ensure replicability of the results and enable various hospitals to run the model with generic parameter values presented in this study, as well as institution-specific parameter values to obtain hospital-specific results (if desired), we have provided model documentation following the guidelines devised by Sterman and Rahmandad [55] in the Appendix: Model Documentation. Our model documentation also includes sources of data for each parameter, where applicable.

The general emergency patient flow of the baseline model is as follows. Patients arrive at the hospital through the ED, and depending on the severity of their condition, are either

Fig. 2 High-Level Schematic Model of Emergency Patient Flow



discharged from the ED (titled "non-admitted patients"), earmarked to be transferred to the ICU (titled "critical patients") or to the Ward (titled "non-critical admitted patients"). Most admitted patients are discharged home from the ward, though some need to be readmitted to the ICU due to deterioration of their medical condition. Consistent with the literature [8, 10], the baseline model assumes that if ICU is full, patients would remain (board) in ED until there is capacity to admit them to ICU and that regardless of the boarding time in ED, patients would still require their full LOS in ICU. However, non-critical admitted patients boarding in ED and waiting for a ward bed may be discharged home from ED [56].

To keep the model simple, although some emergency patients require surgery and are admitted to ICU or the ward post operation, the model does not explicitly model the operating room (OR). It is assumed that once the patients leave the ED for OR, the few hours spent in OR can be modelled as part of the subsequent ICU or ward LOS, as a bed is usually vacated for these patients as early as the start of the operation.

To evaluate various ICU management policies, the model also allows variations to the generic emergency patient flow described earlier. For instance, the percentage of patients readmitted to ICU is a function of the baseline percentage of ICU readmission and the effect of "premature transfer from ICU" policy on ICU readmission rates. Similarly, ICU mortality rate is a function of baseline ICU mortality rates and the effects of average wait time for admission into ICU on ICU mortality rate. Another example is the average ICU LOS, which depends on the percentage of patients who have been readmitted to ICU and require longer ICU LOS. Overall shape and specific values of these functions are also derived from the literature [14, 32, 33, 56] and documented under the Appendix: Model Documentation section.

6 Performance measures

We analyze the policies with regards to two sets of performance measures. One set of performance measures captures the intended effect of ICU management policies, namely decreasing hospital overcrowding by reducing departmental (ED, ICU, and Ward) occupancy rates. Occupancy rates are closely monitored by hospital management in times of crisis and their reduction is usually interpreted as controlling the crisis. The other set of performance measures deal with the ultimate health outcome measure of mortality, as hospitals' mission is to save lives, especially in times of crisis. We would like to assess the ICU management policies with regards to alleviating the symptom of the problem (occupancy rates) as well as potential unintended effects on mortality.

There are numerous possible intermediate outcome measures, such as total time spent in ICU, number of blocked beds in one department and wait times associated to get admitted to another department, readmissions to ICU, etc., which are all modeled in detail but are not reported individually in the results section, as their combined effect demonstrates itself on either the occupancy rates or mortality (or both). For instance, longer time spent in ICU (either due to ICU readmissions of health-deteriorated patients prematurely transferred out of ICU or alternatively due to insufficient beds in the ward resulting in bed blockage in ICU) affects both ICU occupancy rate and mortality. Similarly, long wait times in ED for ICU beds affects both ED occupancy and mortality. As such, occupancy rates (as the managerial performance measure representing the alleviation of the symptoms of the problem) and mortality (as the health outcome performance measure representing unintended consequences of ICU management policies) are the two main performance measures reported in this study.

With regards to departmental occupancy rates, two different performance measures should be distinguished here. One is the departmental instantaneous occupancy rate, which measures the occupancy rate at a point in time. The other is the departmental average occupancy rate, which measures the average of the departmental occupancy rate from the beginning of the simulation to a particular point in time. We have reported both these performance measures in this paper, as the instantaneous occupancy rate could best reflect what happens at any point during a crisis and the average occupancy rate could demonstrate a cumulative effect of various policies on departmental occupancy rates over time.

7 Baseline results

The baseline scenario mimics the performance of a typical hospital at equilibrium for 2000 h (nearly 3 months). As documented under the model documentation section, values of medically-driven model parameters for the baseline model, such as average length of stay at each department, percentage of patients leaving one department for another, percentage of patients dying in each department, and percentage of patients readmitted to ICU, are derived from the literature. To best mimic a typical hospital, arrival rate is set close to the average of 89 EDs studied by Schneider et al. (2003) [57]. Ratio of bed capacities in each department to overall hospital beds is set in line with what is observed in the literature [57–60]. To calibrate the model, total number of hospital beds and initial number of patients in each department are set in a way that results in occupancy levels close to what is typically reported in the literature [61–63] (See sources of parameter values under Appendix: Model Documentation).

Table 1 outlines the performance of the baseline scenario against the performance measures. As seen in the table, average ED occupancy of 97.88 %, average ICU occupancy of 87.78 %, and average ward occupancy of 85 % in the baseline model are close to 100 % ED occupancy observed in 6 EDS [61], 90 % ICU occupancy [62], and 85 % ward occupancy [63] respectively. These results ensure some level of face validity where a full validation of the model is not possible due to lack of data from a single source.

Table 1 Baseline performance measures under equilibrium conditions

Scenario	Avg. Occupancy [Dmnl (Dimensionless)]			Hospital-Wide Hourly Mortality Rate [Person/Hour]
	ED	ICU	Ward	
Baseline	97.88 %	87.78 %	85.00 %	0.1628 (1 death every 6.14 h)

8 Crisis scenario

We consider a crisis scenarios to evaluate the effects of different policies on the performance measures. Under this scenario, beginning from the second day of the simulation and for a duration of 2 days, we double the hospital arrival rate. We call this scenario a "natural disaster" scenario, as it could represent a disaster such as a flood or mass accident that brings an influx of patients over a period of time (in this scenario assumed to be 2 days), after which the majority of remaining victims are found deceased on the scene and as such not taken to the hospital. Such a crisis could put a lot of pressure on the critical care capacity of a hospital that is operating under stable conditions before the crisis, and as such provides good grounds for evaluating the effects of various ICU management policies on selected performance measures.

Figure 3 shows the instantaneous departmental occupancy rates under the crisis scenario in the baseline model, which assumed no ICU management policies are implemented. As shown in the figure, the model is at equilibrium before the start of the crisis. Then the instantaneous occupancy rates rise sharply (and in case of ED, are allowed to go well beyond 100 %) during the crisis and stay high shortly after the crisis as well. The model reaches equilibrium again at time 1356 (on day 56.5). It should be noted that the term Dmnl in Fig. 3 and elsewhere in the paper stands for dimensionless.

Figure 4 shows the average departmental occupancy rates under the crisis scenario in the baseline model, in essence smoothing the occupancy rates over time. This performance measure may better reflect the cumulative occupancy rate from the start of the simulation to a particular point in time.

Figure 5 shows the behavior of health outcome measures of hospital-wide hourly mortality rate and accumulated total hospital mortality under the crisis scenario in the baseline model (i.e. assuming no ICU management policies are implemented). As seen in Fig. 5, hospital-wide hourly mortality rate sees a temporary and sharp increase during and shortly after the crisis, but then decreases to near pre-crisis equilibrium values. As a result of the temporary increase in hospital-wide mortality rate, the rate of increase in the accumulated total hospital mortality increases temporarily, but reverts back to the pre-crisis rate of increase shortly after the end of the crisis.

9 ICU Management policies under the crisis scenario

Figures below show the selected performance measures under the crisis scenario given the implementation of each policy (or combination of policies). It is assumed that the hospital, operating under stable equilibrium conditions only starts to implement the policies after the beginning of the crisis (i.e. the second day) and continues to apply the policies to the end of the simulation period.

Fig. 3 Instantaneous Occupancy Rates under the Crisis Scenario (Baseline Model)

We first evaluate ICU management policies against their intended effect of reducing average ICU occupancy rate which sees a sudden increase after the crisis. As seen in Fig. 6 below, all policies except the boarding in ward policy actually reduce the average ICU occupancy rate against the baseline scenario of implementing no policies. We rank the policies at time 1356, which is the time the baseline model would have reached equilibrium if no policies were implemented. Most effective policies in reducing average ICU occupancy rate at time 1356 are 1) General Ward Admission Control and Premature Transfer from ICU, 2) All Policies, 3) Premature Transfer from ICU, 4) Boarding in Ward and Premature Transfer from ICU, 5) General Ward Admission Control, 6) Boarding in Ward and General Ward Admission Control, 7) Baseline, and 8) Boarding in Ward policy respectively.

Average ED occupancy rate also skyrockets after the crisis. As seen in Fig. 7 and the zoomed version in Fig. 8 around time 1356, policies most effective at controlling average ED occupancy at time 1356 are 1) All Policies, 1) Boarding in Ward and Premature Transfer from ICU, 2) Boarding in Ward and General Ward Admission Control, 3) Boarding in Ward, 4) General Ward Admission Control and Premature Transfer from ICU, 5) Premature Transfer from ICU, 6) General Ward Admission Control, and 7) Baseline. When we use the same rank number for two policies, it means that the two policies had the exact same performance.

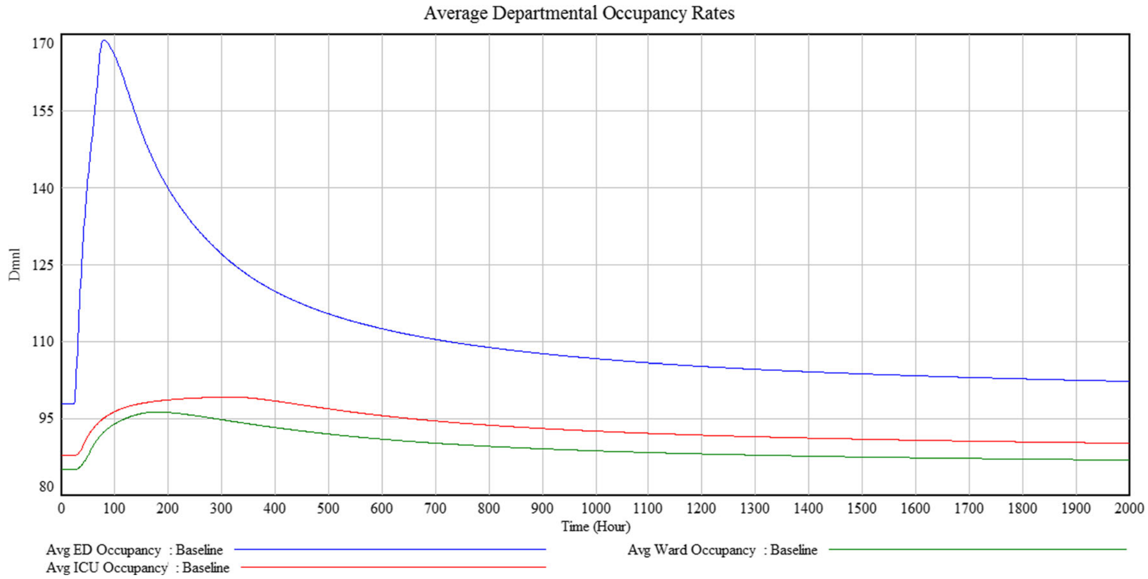


Fig. 4 Average Occupancy Rates under the Crisis Scenario (Baseline Model)

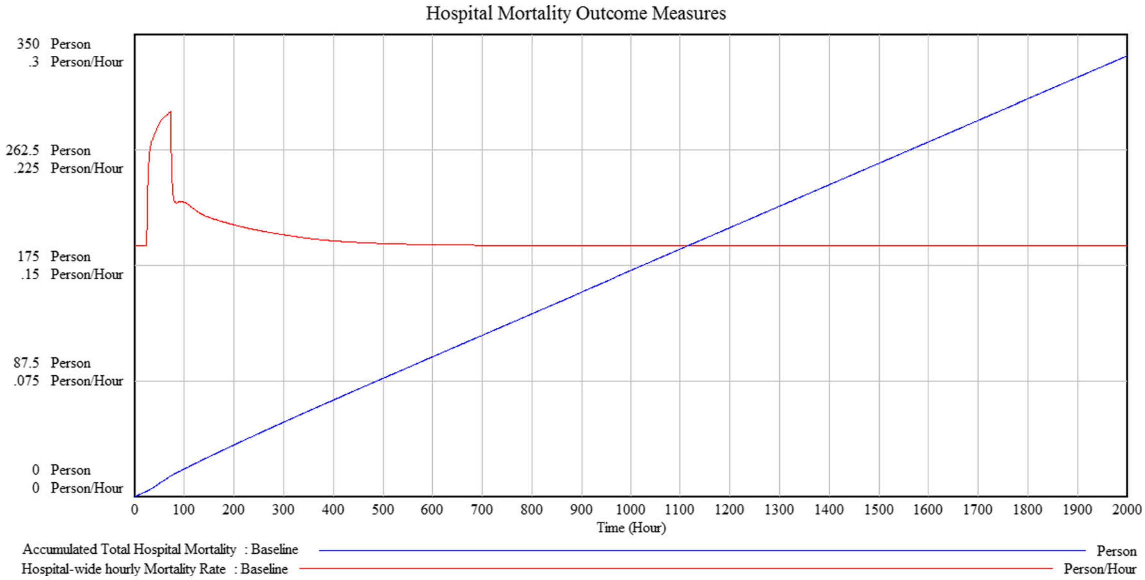


Fig. 5 Hospital Mortality Outcome Measures under the Crisis Scenario (Baseline Model)

The crisis also affects the average ward occupancy rate. As seen in Fig. 9 and the zoomed Fig. 10, policies most effective at controlling average ward occupancy at time 1356 are 1) General Ward Admission Control, 2) Baseline, 3) General Ward Admission Control and Premature Transfer from ICU, 4) Premature Transfer from ICU, 5) Boarding in Ward and General Ward Admission Control, 6) All Policies, 7) Boarding in Ward, and 8) Boarding in Ward and Premature Transfer from ICU respectively.

As the ultimate measure of health quality, measures of mortality are of utmost importance. In terms of accumulated total hospital mortality, as seen in Fig. 11 and the zoomed Fig. 12, the best performing policies at time 1356 are as follows: 1) General Ward Admission Control, 2) Baseline, 3) Boarding in Ward and General Ward Admission Control, 4) Boarding in Ward, 5) General Ward Admission Control and Premature Transfer from ICU, 6) Premature Transfer from ICU, 7) All Policies, and 8) Boarding in Ward and Premature Transfer from ICU.

As for hospital-wide hourly mortality rate, as seen in Fig. 13 and the zoomed Fig. 14, the best performing policies at time 1356 are as follows: 1) Baseline, 1) General Ward Admission Control, 2) Boarding in Ward and General Ward Admission Control, 2) Boarding in Ward, 3) Premature

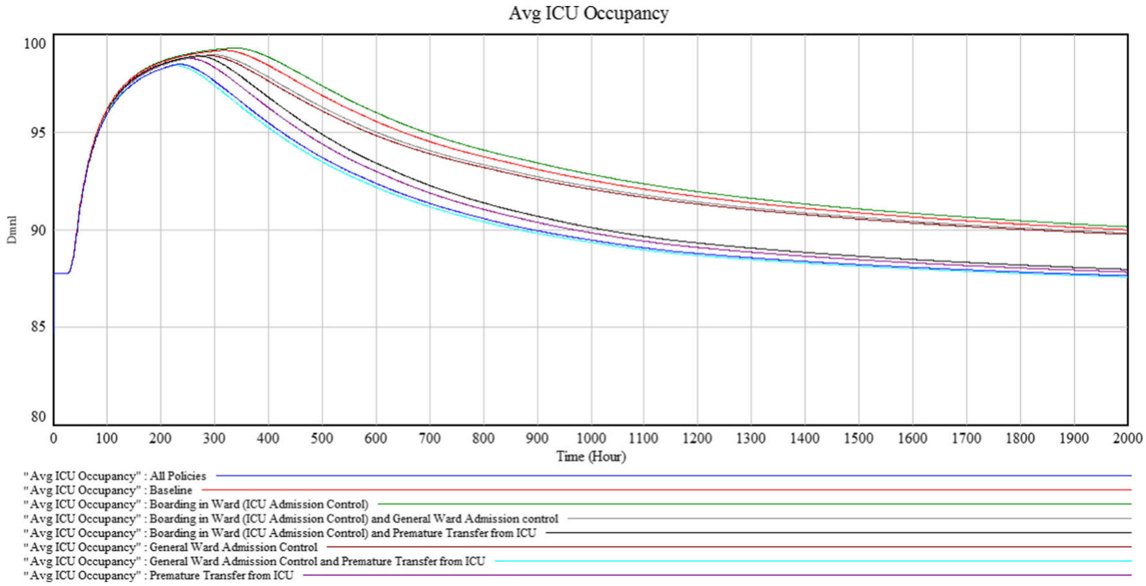


Fig. 6 Average ICU Occupancy under the Crisis Scenario

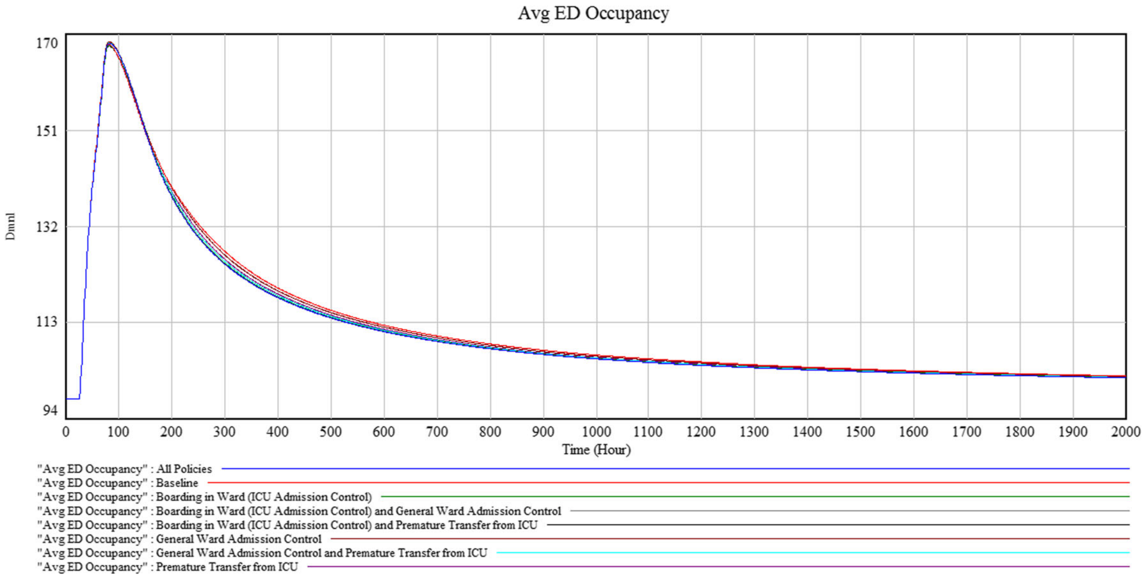


Fig. 7 Average ED Occupancy under the Crisis Scenario

Transfer from ICU, 4) General Ward Admission Control and Premature Transfer from ICU, 5) Boarding in Ward and Premature Transfer from ICU, and 6) All Policies.

10 Discussion and management insights

Which ICU management policies are the best in terms of alleviating the pressure on hospitals in times of temporary crisis? Table 2 summarizes the performance of the various analyzed policies or combination of policies at time 1356, the point at which the baseline model would have reached equilibrium after the crisis without implementing any ICU management policies.

In terms of the ultimate health outcome measure of accumulated total hospital mortality, which measures the total number of deaths from the beginning of the simulation to the particular point in time (1356 in this case), all ICU management policies except the General Ward Admission Control perform worse than the Baseline policy of doing nothing. So one may argue that by implementing any of the ICU management policies or their combinations except in the case of the General Ward Admission Control, hospitals may be indeed putting patients' lives at higher risk and do more harm than good. The General Ward Admission Control policy

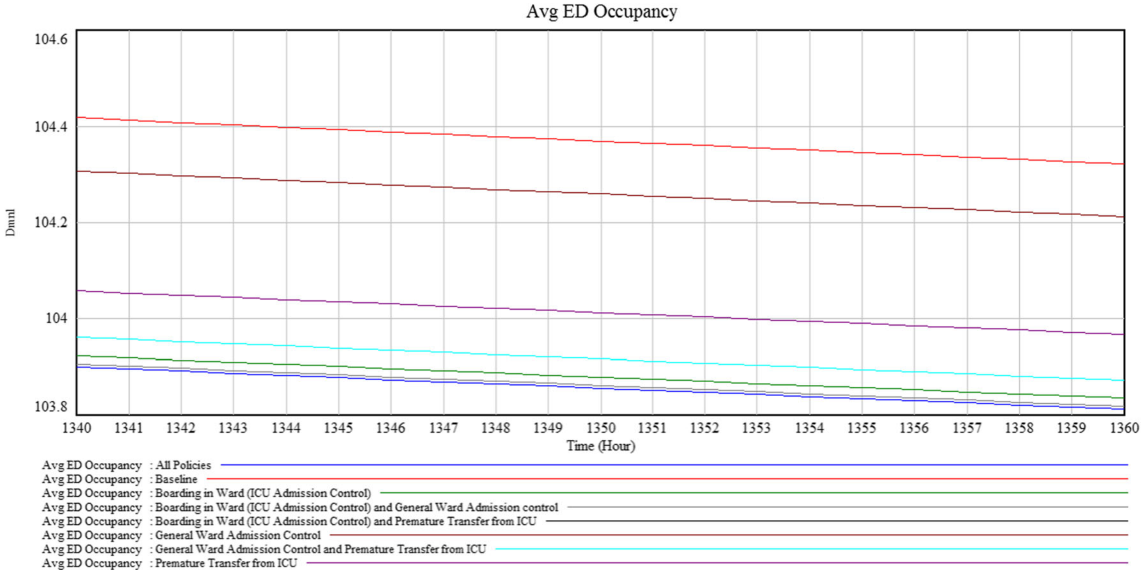


Fig. 8 Average ED Occupancy under the Crisis Scenario (Zoomed Version)

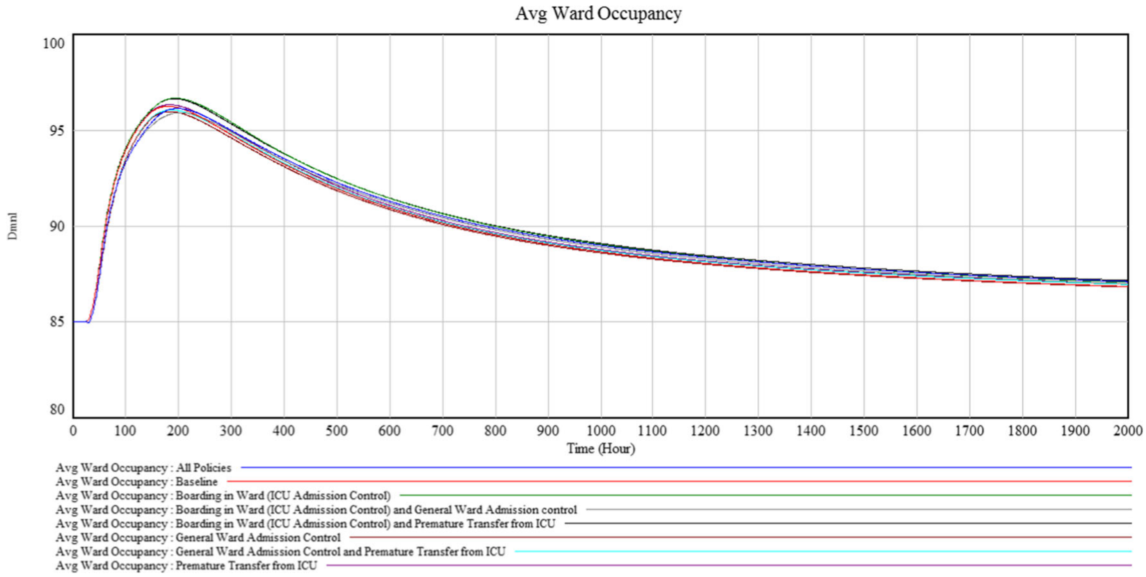


Fig. 9 Average Ward Occupancy under the Crisis Scenario

outperforms the Baseline policy of doing nothing, but even this superiority in performance does not appear to be very significant (0.1 lives saved compared to the Baseline policy). As we show later under the sensitivity analysis though, this degree of significance could be higher under different departmental capacity assumptions.

The fact that the General Ward Admission Control policy outperformed the rest of the ICU management policies (by a range of 0.9 to 3.3 lives saved) may be counter intuitive to hospital management used to assess the situation of the crisis based on the managerial outcome measure of departmental occupancy rates. Indeed, one might have hypothesized that the General Ward Admission Control policy even increases ED occupancy over the Baseline as it prioritizes critical patients who have completed their medically-necessary critical care period in ICU in accessing general ward beds over emergency patients in ED who are competing for the same ward beds. The results show that this is not the case and the policy decreases (albeit slightly) the ED occupancy rate over the Baseline, but overall is not that effective in decreasing occupancy rates when compared to the rest of the policies.

The counter intuitive finding that the General Ward Admission Control policy which is among the worst in alleviating the symptoms of the problem (i.e. high ED and ICU occupancy rates) outperforms the rest of the policies has a logical explanation though. Unlike policies involving Premature Transfer of Patients from ICU, this policy does not put the patients' health at risk by making them receive

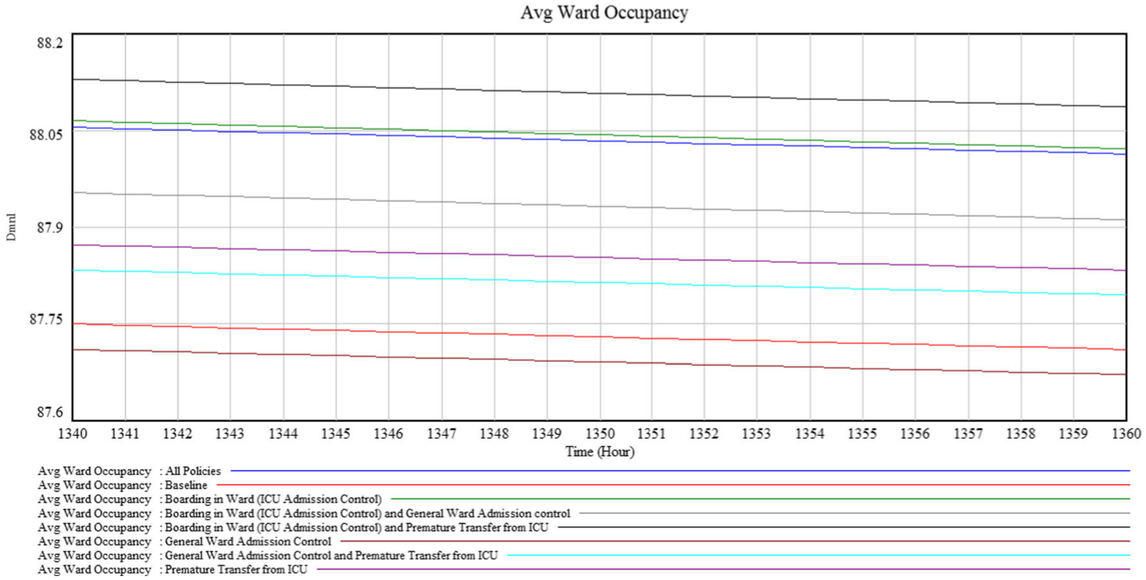


Fig. 10 Average Ward Occupancy under the Crisis Scenario (Zoomed Version)

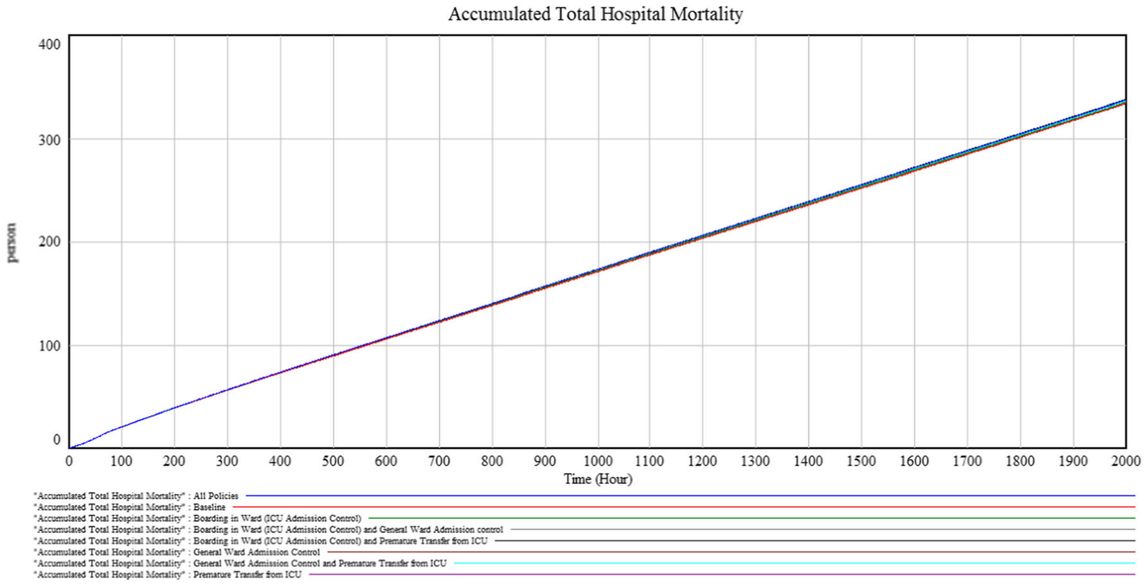


Fig. 11 Accumulated Total Hospital Mortality under the Crisis Scenario

sub-standard critical care in the general ward when they should have still been occupying an ICU bed. Furthermore, unlike policies involving boarding in ward that make it hard for ED patients to get admitted to ICU, this policy helps empty to a greater extent ICU beds for ED patients, and as such somewhat alleviate the pressure on the ICU by housing critical patients whose critical care period in ICU is completed where they belong (in general ward) and ED patients who need ICU beds in ICU. Putting patients where they medically need to be is the right medical decision and as such should have positive effects on health outcomes.

The main management insight from this research, as such, is that while on the face of it the General Ward Admission Control policy is not an effective policy in times of crisis, as it does not adequately alleviate the symptoms of the problem (high ED and ICU occupancy rates), it is indeed the policy that outperforms the rest of the policies with regards to the ultimate measure of saving patients' lives.

11 Sensitivity analysis

We populated our model with parameter values found in empirical studies published in the medical as well as hospital administration literature. While for the most part the values of these parameters showed little variation from one study to

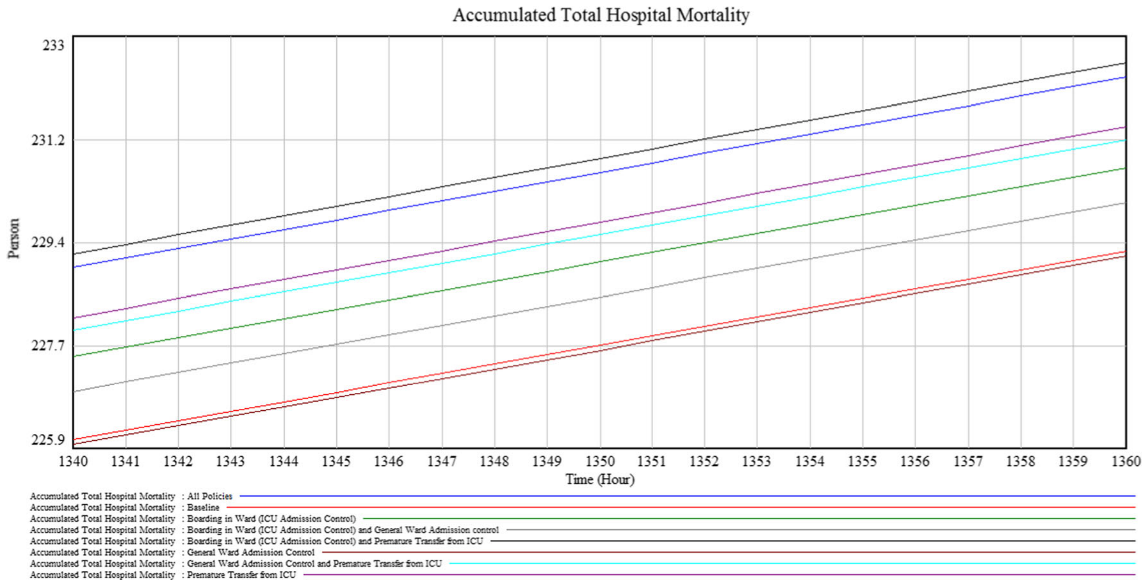


Fig. 12 Accumulated Total Hospital Mortality under the Crisis Scenario (Zoomed Version)

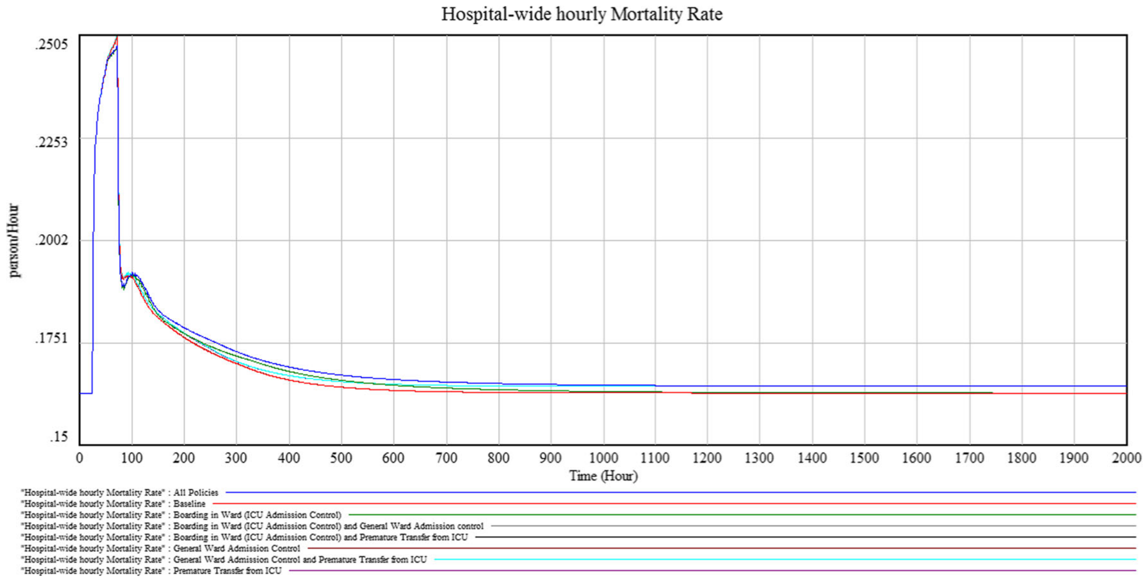


Fig. 13 Hospital-Wide Hourly Mortality Rate under the Crisis Scenario

another (see sources of parameter values under Appendix: Model Documentation), there were three parameter values that showed a wide range of empirical values in the literature, namely: Non-Survivor LOS in Ward, Ward LOS for Non-Critical Admitted Patients, and Ward LOS for Critical Discharged home Patients.

To test the sensitivity of our findings to different values of these parameters, we first conducted a series of single variable sensitivity analyses. We varied Ward LOS for Non-Critical Admitted Patients from 120 h (used in the baseline model) to 144 [64], and 175.2 h [65]. We also varied Non-Survivors LOS in Ward from 297.6 h (used in the baseline model) to 369.6 h [66], 499.2 [67], and 1202.4 [68]. Similarly, we varied Ward LOS for Discharge-from-Ward Critical Patients from 126 h (used in the baseline model) to 93.8 h [69], 513.6 h [67], and 895.2 h [68]. In each of these 11 experiments, the General Ward Admission Control remained as the best performing policy with regards to accumulated total hospital mortality. In all but two experiments, the second best performing policy was the Baseline policy of implementing no particular ICU management policy. In two experiments, one setting the Ward LOS for Non-Critical Admitted Patients to 175.2 h and the other one setting the Ward LOS for Discharge-from-Ward Critical Patients to 895.2 h, the

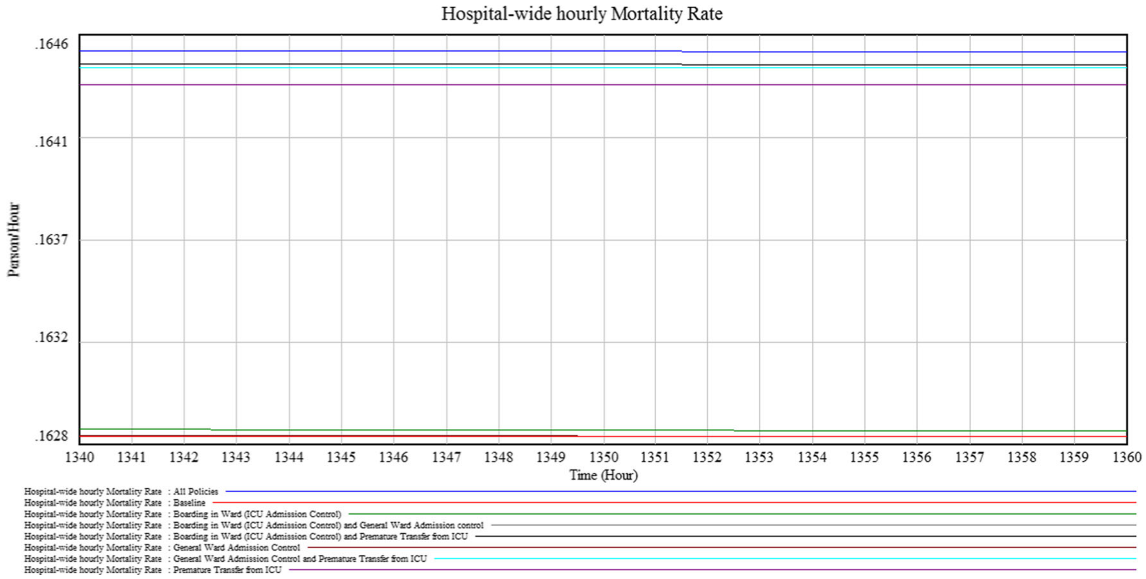


Fig. 14 Hospital-Wide Hourly Mortality Rate under the Crisis Scenario (Zoomed Version)

Table 2 Performance of ICU management policies at time 1356

Policy Performance Measure	Avg ICU Occupancy (%)	Avg ED Occupancy (%)	Avg Ward Occupancy (%)	Hourly Mortality Rate (Person/Hour)	Accumulated Total Hospital Mortality (Person)
All Policies	88.37	103.83	88.02	0.16452	231.6
Baseline	91.28	104.34	87.72	0.16284	228.7
Boarding in Ward	91.5	103.85	88.03	0.16286	230.1
Boarding in Ward and General Ward Admission Control	91.06	103.84	87.92	0.16286	229.5
Boarding in Ward and Premature Transfer from ICU	88.85	103.83	88.09	0.16447	231.9
General Ward Admission Control	90.96	104.23	87.68	0.16284	228.6
General Ward Admission Control and Premature Transfer from ICU	88.28	103.89	87.8	0.16446	230.6
Premature Transfer from ICU	88.65	103.99	87.84	0.16438	230.8

second best performing policy changed from Baseline to “General Ward Admission Control and Premature Transfer from ICU”.

The reason that the second best performing policy changes to “General Ward Admission Control and Premature Transfer from ICU” in these two scenarios is that in both scenarios, the pressure on the ward is increased significantly due to higher ward LOS for a large portion of patients. As such, discharging critical patients more quickly from ICU and prioritizing them over non-critical admitted patients in the ward admission process make more ICU beds available for those who are boarded in ED (and at risk of higher mortality) and helps reduce overall mortality rates.

We also conducted a series of multi-variable sensitivity analyses using the combination of the three values for Ward LOS for Non-Critical Admitted Patients (120, 144, 175.2), four values for Non-Survivors LOS in Ward (297.6, 369.6, 499.2, 1202.4), and four values for Ward LOS for Discharge-from-Ward Critical Patients (126, 93.8, 513.6, 895.2). This resulted in 48 combination of values. We implemented the eight ICU management policies or combination of policies in each of the 48 scenarios (i.e. a total of 384 simulation experiments) and found that in every single scenario, the General Ward Admission Control was the best performing policy with regards to accumulated total hospital mortality. The second best policy in the various scenarios was either the Baseline or the “General Ward Admission Control and Premature Transfer from ICU”.

To assess the sensitivity of the findings to relative departmental capacity assumptions, we conducted another series of multi-variable sensitivity analyses. We evaluated the impact of 15 % change in each departmental capacity. This resulted in 27 combination of values. Like the previous sensitivity analyses, we implemented the eight ICU management policies or combination of policies in each of the 27 scenarios and found that in every single scenario, the General Ward Admission Control outperformed the rest of the policies with regards to accumulated total hospital mortality. We also found that the degree of its significance over the second best performing policy could range from 0.081 to 1.837 lives saved. As the number of beds in the ICU or general ward decreases, the number of lives saved as a result of implementing the General Ward Admission Control policy increases.

12 Areas for future research

The model and insights gained from the analysis presented in this paper are a first step in understanding the performance of various hospital management policies on managerial and health outcome measures. With the ever growing empirical evidence of the effects of various policies on intermediate and ultimate performance measures, it may be possible to add a costing layer to the analysis to evaluate the cost effectiveness of various management policies, especially those that involve significant investments such as capacity expansion policies.

Other crisis scenarios especially those that are of a more permanent nature, such as the ever increasing pressure on hospitals to serve an ageing population in many countries [70–72], could be an interesting line of research for future exploration. These type of crisis scenarios would likely require more fundamental (and potential costly) management policies than the short term policies implementable by a single hospital explored in this study.

13 Conclusions

In light of the fact that there is a shortage of costly ICU beds in many regions of the world necessitating constant fire-fighting to make these beds available through various ICU management policies, we studied the intended and unintended consequences of these policies on managerial and health outcome measures in the context of emergency patient flow. The system dynamics simulation model is based in empirical evidence found in the medical and hospital administration literature. The model is fully documented so that it can be customized with institution-specific parameter values where applicable. Nonetheless, the preliminary insight generated by populating generic models such as ours with "typical" data can firm up guideline thinking, by facilitating the thinking for the relationship between the structure of an organization and its behaviour over time [73].

The main policy implications of the study is that the General Ward Admission Control policy outperforms the rest of the ICU management policies under a defined natural disaster crisis scenario. This policy basically prioritizes critical patients whose medically-necessary episode of critical care in ICU is completed in accessing general ward beds over emergency patients competing for ward beds in ED. This policy saves more lives when compared to implementing no policies (Baseline), Premature Transfer of Patients from ICU, Boarding in Ward, and possible combinations of these policies. The superiority of the General Ward Admission Control policy over other policies may be counter-intuitive to hospital administrators, as this policy is not as effective as other policies in alleviating the symptoms of the problem, which are the high ED and ICU occupancy rates closely monitored by hospital administrators during any bed crisis period. More importantly, our findings show that the other ICU management policies may be doing more harm than good in saving patients' lives, and as such implementing no ICU management policy could be regarded a relatively good policy compared to all the ICU management policies studies except the General Ward Admission Control policy.

Future research could look into exploring the performance of various policies under different crisis scenarios, and adding a costing layer to the model to assess the cost-effectiveness of these policies.

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