# A System Dynamics Model of Health Care Surge Capacity

**Alexander Lubyansky**
Ph. D. Student,
Department of Public Administration,
Rockefeller College of Public Administration and Policy,
University at Albany,
State University of New York
6 South Lake Avenue, Apartment S1R
Albany, NY, 12203
al8295@albany.edu

*The author*[1] *has created a system dynamics model to investigate how health care providers can and should respond to increases in patient demand for treatment above usual levels. This response by the health care system is called surge capacity and is an important issue in emergency and disaster planning and response. The model describes how hospital and home care treatment providers can alter their internal staffing and patient treatment policies as well as movements of staff and patients between each other. These providers can fail to respond adequately to surge events by exhausting their staff or by moving too much burden from the hospital sector to the home care sector.*

Key Words: Emergency, Disaster, Response, Planning, Hospital, Home Care

## Problem Statement

Importance of Surge Capacity Planning

Surge capacity is the ability of a health care system to respond to an increase in patient demand for treatment above usual levels. Events such as terrorist attacks, natural disasters, industrial accidents, and other mass casualty events can produce potentially overwhelming surges of patients into local health care systems. Policy makers must understand how health care systems react to surge events in order to save the largest number of lives. Current emergency planning tools provide policy makers with only a very limited understanding of surge capacity. Using system dynamics to model surge capacity can overcome some of these limits. The system dynamics model described in this paper is one attempt to try to understand and improve the response of health care systems to surge events.

Current Approaches to Surge Capacity Planning

Given the staggering complexity of surge capacity planning, United States federal and state government agencies have created standards and tools to try to understand and improve surge capacity. While useful to various degrees, these standards and tools have several disadvantages.

The official standards for surge capacity generally used in the United States (United States Department of Health and Human Services / Health Resources and

[1] The research work for this model and paper was done with the help and financial support of a client organization, the Home Care Association of New York State. Funding for this project was provided through a Health Resources and Services Administration grant coming from the New York State Department of Health.

Services Administration / Special Programs Bureau, 2004, May) show a lack of understanding about how surge capacity works. The most commonly used standard is, "the ability to treat 500 acutely ill patients per 1,000,000 people for 48 hours." Another standard is simply, "a 15 percent increase in treatment capacity." It is very hard to determine what "capacity" means in these phrases or why specific numbers like 500 or 15 are chosen.

Most surge capacity tools focus on the hospital sector. Non-hospital treatment providers have not yet been highly integrated into surge capacity planning. This fact is reflected by the names of the information tools that planners and responders use to deal with surge capacity. For example, in the State of New York, the database used to gather patient information in a surge event is called the Hospital Emergency Response Data System (New York State Office of the Governor, 2003, March 25). The main tools for health care information gathering and dissemination as well as intra-provider communication are called the Hospital Provider Network, the Hospital Alert Network, and the Hospital Information Network (New York State Department of Health, 2004, August; New York State Department of Health, 2002, April). Even the command system that is used in surge events to coordinate health care providers is called the Hospital Emergency Incident Command System (Greater New York Hospital Association, 2002). While there are ongoing efforts to include non-hospital treatment providers in these systems, surge capacity planning remains very hospital-centric.

Aside from the tools mentioned in the above paragraph, planners have a specific array of modeling and simulation approaches that are used for surge capacity planning, specifically table-top exercises, drills, and linear statistical models. All three tools have their disadvantages. Table-top exercises and drills take large amounts of time and money to perform and make very limited use of mathematics and computers. Linear statistical models use mathematics and computers, but their purpose is usually to estimate flows of people through various parts of the health care system. These models tend not to use feedback loops and do not seek to offer normative prescriptions about macro-level policies. Instead, these models usually seek to optimize micro-level processes such as the administration of vaccines in mass-prophylaxis scenarios. (Hupert & Cuomo, 2003)

<u>The Usefulness of a System Dynamics Model</u>

The tool of system dynamics can help create understanding about surge capacity in ways that other tools can not. A system dynamics model can be simulated quickly and cheaply, can simulate many types of scenarios, has openly stated and rigorously testable mathematical assumptions, is specific about what data are necessary to determine model outcomes, and shows how system feedback structure causes behavior. There has already been some preliminary system dynamics work trying to do this, such as a conference paper by Gary Hirsch (2004) that explores the effects of surge events on critical health care infrastructure. Rather than being an exploratory work, the model in this paper has a problem-solving focus.

## Purpose of the Model

<u>Model Goals</u>

The model in this paper has two main goals. The first goal is to figure out how health care systems can best respond to surge events. The second goal is to understand what role home and community based treatment providers play in this response. In order to show how the model accomplishes these two goals, the main assumptions and dynamic hypothesis of the model must be stated and explained.

Assumptions of the Model

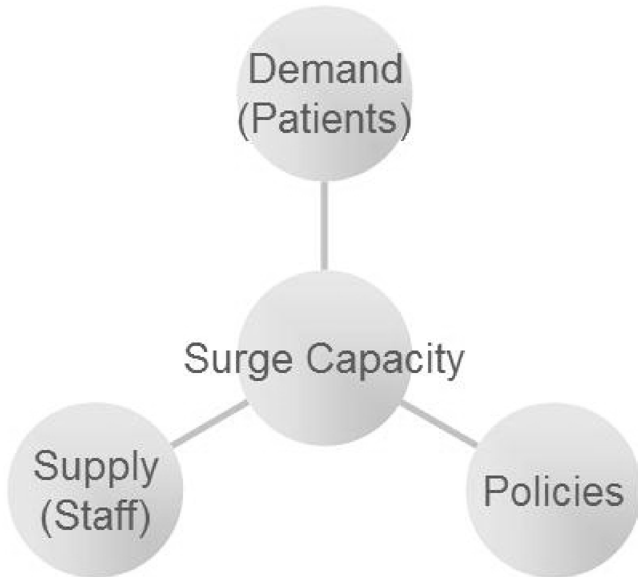


**Fig. 1. A System Dynamics Perspective of Surge Capacity**

Fig. 1 shows the concept of surge capacity that is used in this model. From a system dynamics perspective, it is useful of think that surge capacity is dynamically determined by the mutual interaction of three components: the demand for treatment, the supply of treatment, and the policies used to allocate supply to satisfy demand. The demand for treatment in a surge event comes from people who require or ask for treatment. The supply of treatment consists of the resources that are necessary for treatment providers to treat patients. Such resources include staff (personnel), beds, supplies, machines, physical space, public utilities, transit, and security. This model focuses on only one of these resources: medical staff.

The choice to make the model focus on staffing problems reflects the fact that staff are one of the most necessary resources for treatment providers as well as the most perplexing. Staff are a necessary resource because most modern medical care can only be adequately provided by trained medical personnel. Staff are a perplexing resource because they are human and, thus, harder to measure and predict. Current surge capacity planning tends to focus on beds and supplies because these resources are inanimate and easy to quantify. It is much harder to gather data on what people will be available to provide treatment in a given surge event or how much treatment they will be able to provide.

The policy set that treatment providers use to match supply to demand is the link between the structure of a health care system and its behavior during a surge event. The model in this paper simulates the key policies that treatment providers can use to handle surge events. Specifically, these policies include making staff work longer hours, cutting corners in the provision of treatment to patients through the reduction of paperwork and medically unnecessary procedures, refusing admission to patients, moving patients between different treatment providers, and moving staff between different treatment providers. These policies can be divided into two main categories: internal policies and external policies. Internal policies like making staff work more, cutting corners, and refusing admissions can be conducted by a treatment provider without reliance on other treatment providers. To move around patients and staff, treatment providers are dependent on each other because they are directly shifting demand (patients) and supply (staff) between each other.

The model described in this paper represents treatment providers as aggregates of two treatment provider types: hospitals and home care agencies. The choice of the home care agency as one of the treatment provider types reflects the availability of expert knowledge about home care from the client organization as well as the model's focus on community based treatment. The model structure is generic enough so that, with the right parameters, other treatment providers such as nursing homes and adult homes can be represented. The model can even be parameterized to show the interaction between two hospitals.

There are several important things that the model leaves out. As previously mentioned, the model only deals with staffing resources and not other types of resources. The model represents a response to a generic surge: a pulse increase in patients seeking medical care in the hospital sector. This kind of surge is most akin to a blast scenario, weather event, vehicle accident, or some other kind of conventional event. The model cannot represent any spreading of problematic conditions between people; there is no ability to represent infectious disease, radiation, or chemical exposure. There is no money or any sort of financial accounting in the model. There is no representation of staff not showing up for work or staff becoming incapacitated. There is also no representation of physically unhurt "worried well" patients coming into the health care system or any structure dealing with risk communication.

The most important thing left out of the model is the idea of an outside region from which staff can be called up and to which patients can be dropped off. The model is assumed to run in a fixed geographical region separated from the outside world by an impermeable force field. The idea that some outside force can come in to help a given region take care of its surge capacity problems effectively absolves that region from properly planning to deal with surge capacity. This model has explicitly forbidden a "Deus Ex Machina" solution to surge capacity and instead considers only how a given region can deal with surge capacity with the resources that it already has available to it at the time of the surge event. It is because of this assumption specifically that the dynamic hypothesis of this model is designed to focus on the mutual interaction of two types of treatment providers with each other, and no other outside world.

## Dynamic Hypothesis

The dynamic hypothesis of this model deals with the relationship between the hospital and home care sectors of a health care system and how this relationship affects the use of internal and external policies by hospitals and home care agencies to handle a surge in patient demand for treatment. Fig. 2 contains a picture of this dynamic hypothesis.

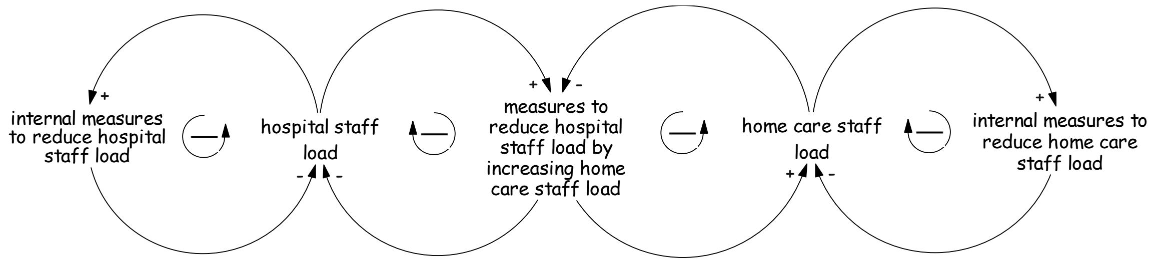


**Fig. 2. Dynamic Hypothesis**

Here is how this dynamic hypothesis works. Since the initial flow of surge patients in a given scenario accrues to the hospital sector, the hospital sector has an increase in its staff load. To reduce this staff load, first the hospital sector uses internal policies such as making staff work more, cutting corners in treating patients, and delaying or refusing admission to some patients. If these policies are not enough to balance the hospital sector's staff load, the hospital sector uses its external policies of calling up staff from the home care sector and dropping off patients to the home care sector. Using these external policies raises the staff load of the home care sector, which then tries to use its internal policies to reduce its staff load. However, if the home care sector's internal policies cannot deal with this higher staff load, the home care sector resists and/or reverses the external policies used by the hospital sector, thus raising the hospital sector's staff load again. The main conclusion from this dynamic hypothesis is that there is a limit to both the internal and external policies that the hospital sector can use to alleviate its staff load. If the hospital sector uses its external policies too much, it hurts the home care sector and eventually hurts itself.

## Model Feedback Structure

A more complex causal loop diagram than that of Fig. 2 is necessary to more fully explain the feedback structure contained in this model. Figs. 3 through 9 show an unfolding view of the model's feedback structure, with an explanation of new pieces of structure as they are added. This set of causal loop diagrams shows as separate variables the different components of patient demand for treatment, staff ability to provide treatment, and the policies that treatment providers can use to balance staff load.

The core of the model begins with Fig. 3. This figure shows the inflow of patients to the hospital sector as well as the components of demand for- and supply of- treatment in that sector. Under normal circumstances, there is a regular inflow of patients into the hospital sector. This inflow increases for some period of time during a surge event. In any given period of time, each patient in the hospital sector needs some amount of work, referred to hereafter as "tasks", performed on him or her per hour to get satisfactory treatment. Similarly, each member of staff can provide a certain amount of tasks per hour. The product of the number of patients and the tasks needed per patient per hour is the hourly patient demand for treatment. The product of the number of staff and the tasks provided by each staff member per hour is the hourly staff ability to supply treatment. The ratio of patient demand for treatment and staff ability to provide treatment is staff load. In a surge event, the staff load of the hospital sector goes up because hospitals receive additional patient demand for treatment from the surge event.

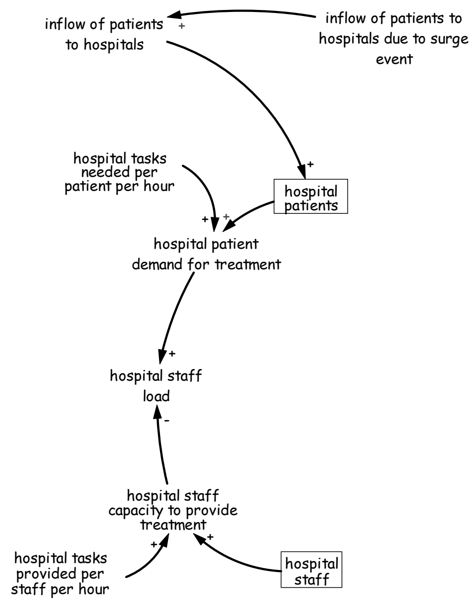


**Fig. 3. Supply of and Demand for Treatment in the Hospital Sector**

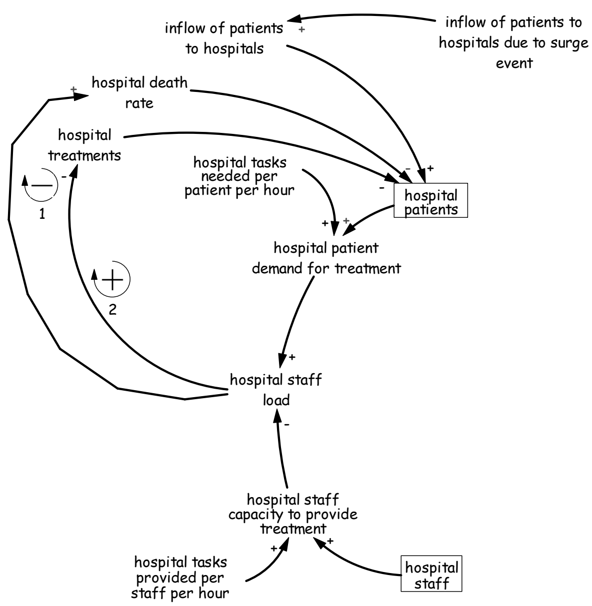


**Fig. 4. Deaths and Treatment**

Staff load affects both the rate at which patients die and the rate at which patients complete their treatments (Fig. 4). The higher the staff load, the higher the death rate is for patients in the hospital sector. If the ratio of demand to supply is higher, the adequacy of treatment must, by necessity, be lower. If more patients die as a result of higher staff load, there are fewer patients left to treat and staff load decreases. So, patient deaths form a balancing feedback loop (loop 1) with staff load. In addition to increasing patient deaths, a higher staff load slows down the pace at which patients become fully treated and leave the hospital. This, in turn, further reinforces the increase in staff load (loop 2). Avoiding an overly high staff load is in the interest of the hospital sector in terms of both providing treatment and avoiding deaths.

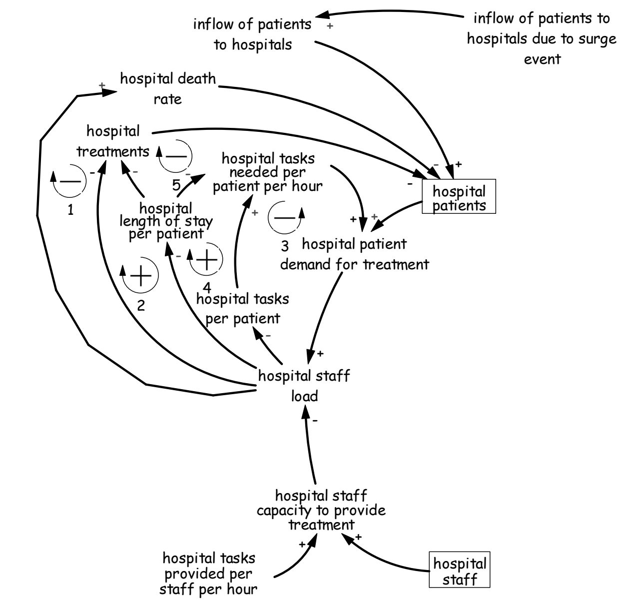


**Fig. 5. Reducing Patient Tasks and Lengths of Stay**

One of the policies the hospital sector can use to balance staff load is to cut corners in providing treatment to patients by reducing their required tasks and lengths of stay (Fig. 5). Loop 3 shows how the reduction of tasks per patient leads to a reduction in patient demand and staff load. The effect of a reduction in patient lengths of stay is slightly more complicated. Reducing the length of stay per patient increases the tasks needed per patient per hour because the same treatment must be performed within a smaller time span (loop 4). However, reducing the length of stay per patient also allows patients to finish their treatments more quickly and thus more quickly exit the hospital sector (loop 5).

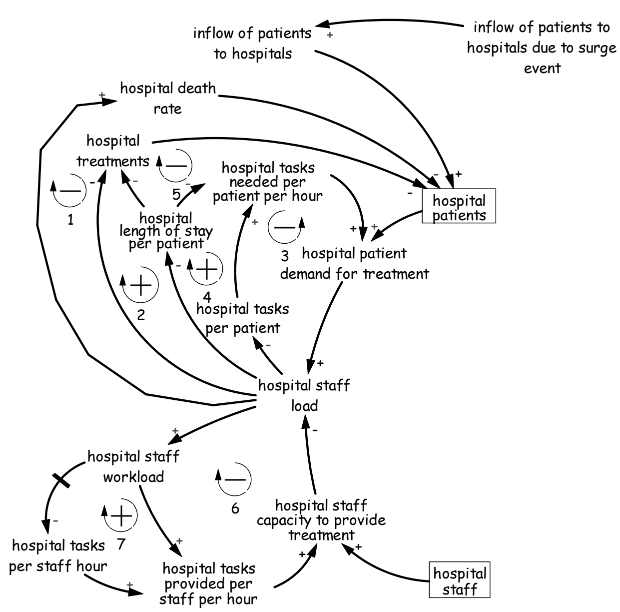


**Fig. 6. Staff Workload and Exhaustion**

Another policy that hospitals can use to reduce staff load is to make their staff work longer hours (Fig. 6). The direct effect of increasing staff workload is an increase in staff ability to provide treatment and a decrease in staff load (loop 6). The side effect of increasing staff workload is exhaustion. If staff work more hours, they become exhausted after a delay. If staff are exhausted, they can perform less useful work for each hour that they spend at work (loop 7). The treatment output of staff that work long hours and are exhausted can be lower than the treatment output of staff that work regular hours.

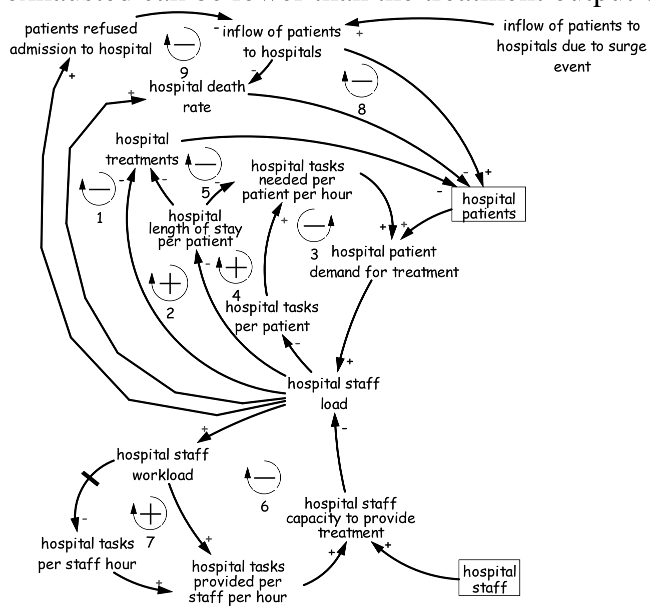


**Fig. 7. Reducing Patient Inflow by Delaying or Refusing Admissions**

A third hospital policy is to admit fewer patients for treatment (Fig. 7). Since patients that are refused admission are not moved to other treatment providers, they wait in a waiting area until they are admitted. The benefit of this policy is a reduction in hospital sector staff load (loop 8). The cost of this policy is that more people die while waiting to be admitted for treatment (loop 9).

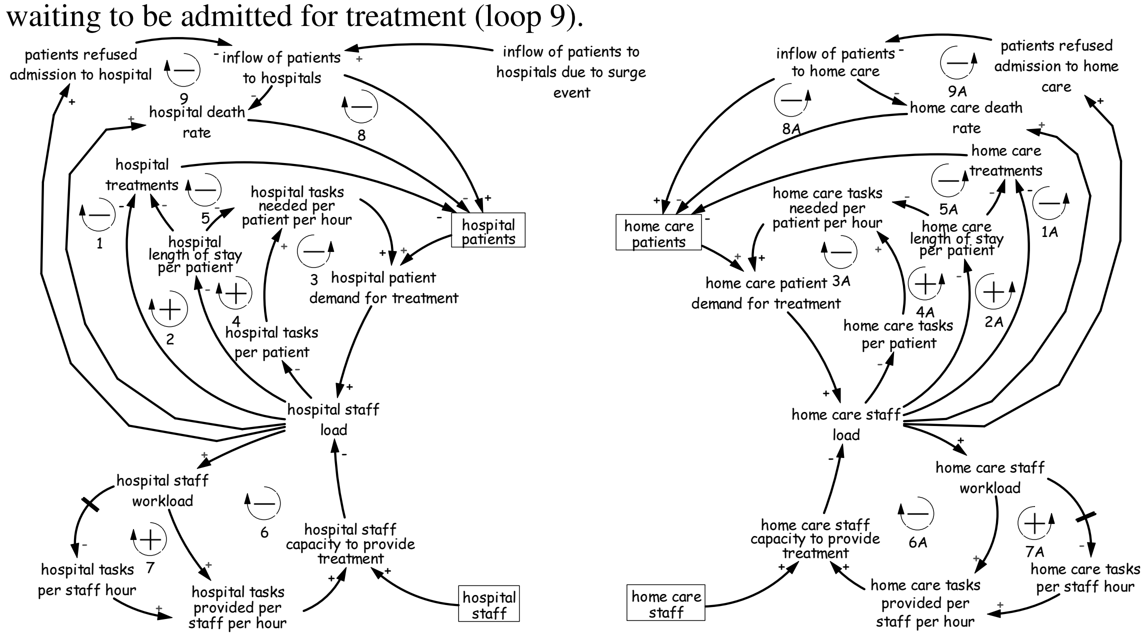


**Fig. 8. Two Types of Treatment Providers: Hospitals and Home Care**

The main insights of the model come from looking at the ways in which the hospital sector tries to reduce its staff load by increasing the staff load of the home care sector. Planners generally regard the home care sector as either and infinite source/sink of staff/patients for hospitals or as some specific numbers of staff/patients that hospitals can gain/lose. These planners are incorrect in their assessments because the home care sector has essentially the same structure as the hospital sector (Fig. 8). Just like the hospital sector, the home care sector has a staff load that it tries to keep in balance through the use of both internal and external policies (loops 1A through 9A).

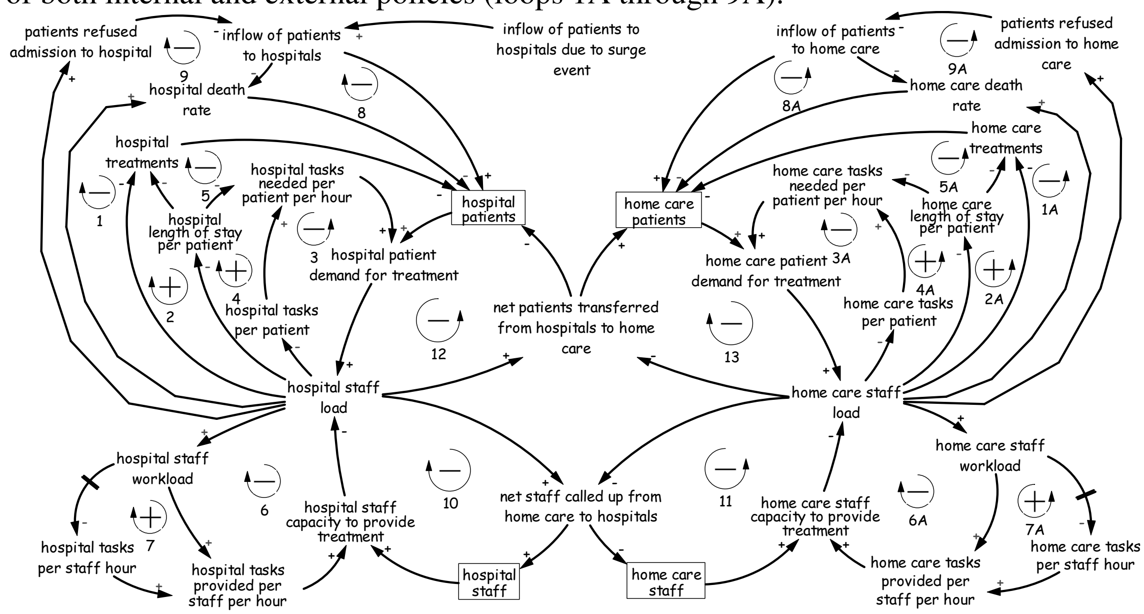


**Fig. 9. Staff Call Up and Patient Drop Off**

The hospital sector can try to reduce its staff load by calling up staff from the home care sector (Fig. 9). This policy reduces the hospital sector's staff load by increasing the supply of staff working in hospitals (loop 10). The drawback of this policy is that it increases the staff load of the home care sector. If the home care sector is unable to take care of its increased staff load with its internal policies, it must resist or reverse the staff call up policy of the hospital sector (loop 11).

The hospital sector can also try to reduce its staff load by diverting or discharging some of its patients to the home care sector (Fig. 9). This policy reduces the hospital sector's staff load by decreasing the number of hospital patients (loop 12). As with the previous policy, the drawback of this policy is that it increases the staff load of the home care sector. If the home care sector is unable to take care of its increased staff load with its internal policies, it must resist or reverse the patient drop off policy of the hospital sector (loop 13). Fig. 9 shows the full feedback structure of the model. The interaction of the hospital and home care sectors through the use of internal and external policies determines the set of behaviors that the model can produce.

## Model Behavior

Assumptions of the First Three Simulation Runs

The model exhibits three main types of behavior under its default parameters: sustainably handling a surge, being highly stressed by a secondary surge from the home care sector to the hospital sector, and being completely overwhelmed by a surge. Before these examples are shown, it is useful to summarize the parameters of these model runs.

Time in the model is measured in hours. The surge of patients into the system is represented by a one hour pulse of patients into the waiting queue for admission to the hospital sector. In the first run, there are 1000 surge patients, in the second run there are 1050 and in the third run there are 1100. The staff in the model represent trained nursing staff, since these are the kinds of staff that can move between hospitals and home care agencies. The hospital sector starts out with 500 staff and the home care sector starts out with 333 staff. The equilibrium number of patients in the hospital sector is 3000, assuming an average patient to nurse ratio of six to one. The equilibrium number of patients in the home care sector is 3663, assuming an average patient to nurse ratio of eleven to one. The surge of patients to the hospital sector stretches its staff load more than proportionally, because the workload required by the surge patients is one nurse for every patient. This is the usual ratio of patients to nurses required to provide critical care.

The hospital sector regularly drops off 12 percent of its patients to the home care sector as part of its usual operations. Both the hospital and home care sector are not allowed to let their staff loads rise above 1.5, if they can help it. Both types of providers can cut corners by 20% for both patient tasks and lengths of stay. The movement of staff is disabled in these runs for simplicity, but the movement of patients is enabled, allowing the hospital sector to move patients to the home care sector.

<u>Simulation Run 1: the Health Care System Sustainably Handles a Surge</u>

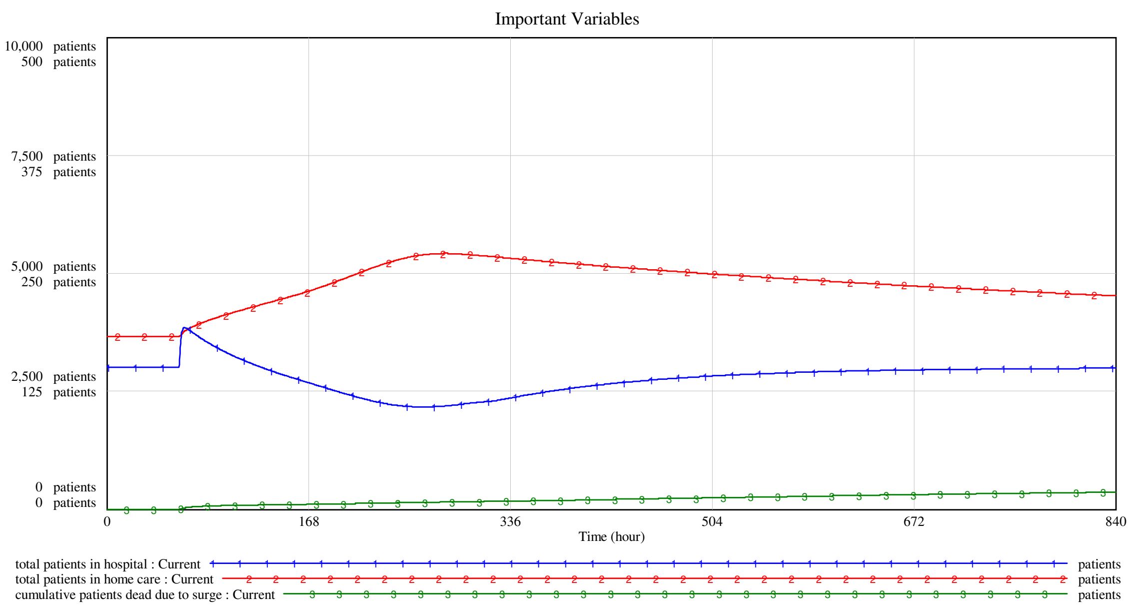


**Fig. 10. Simulation Run 1: Important Variables**

With a surge of 1000 patients at time 60, the health care system successfully handles the surge and is well on its way to restoring its usual patient levels by time 840 (Fig. 10). In this and most other surge scenarios, it takes weeks for the health care system to return its equilibrium patient sizes. This is because, even with corner cutting in place, patients need certain minimum lengths of stay to complete their treatments.

In simulation 1, the hospital sector mostly uses its internal policies of cutting corners (loops 3, 4 and 5) and increasing staff workload (loop 6) to reduce its staff load. The hospital sector also uses its external policy of moving patients to the home care sector (loop 12). The hospital sector only delays the admission of a few patients (loops 8 and 9). Although the hospital sector's staff become somewhat exhausted from their high workloads (loop 7), they are able to take care of their patients quickly enough to be able to catch up on their work and reduce their workloads again. The home care sector supports the hospital sector by taking on additional patients from hospitals and treating them (loops 3a,4a,5a and 6a) without making home care staff more than slightly exhausted (loop 7a). The home care sector does not send any of its patients back to the hospital sector (loop 13).

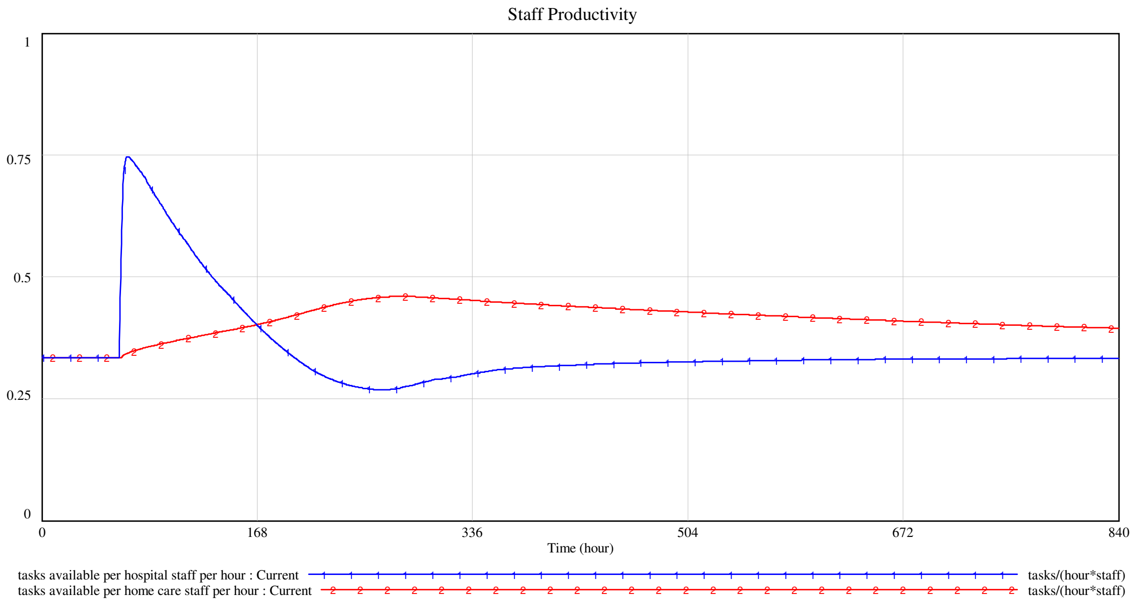


**Fig. 11. Simulation Run 1: Staff Productivity**

Fig. 11 shows the tasks produced by hospital and home care staff over time. Hospital staff productivity increases immediately following the surge because hospitals increase their employees' workloads to very high levels. Because hospital staff maintain these high workloads over an extended period of time, they become exhausted and their tasks per hour decrease to below original levels after time 180. As the hospital sector moves through handling its toughest patient workload, that of the surge patients, it is able to reduce its staff workloads and staff can recover from their exhaustion. The staff working in the home care sector can cover most of their extra staff load by cutting corners and thus only need to increase their workloads by a moderate amount.

Simulation Run 2: the Health Care System is Highly Stressed by a Secondary Surge

Simulation run 2 shows a situation where a surge size of 1050 causes a potentially dangerous interaction between the hospital and home care sectors (Fig. 12). In this simulation run, extra patients are admitted to the hospital sector at time 60. In addition to using the same internal policies as in simulation run 1, the hospital transfers more of its patients to home care (time 60 to 280) and, in so doing, temporarily takes better care of its remaining patients. The home care sector tries to use its internal policies to handle its extra patients but begins to exhaust its staff. By time 280, the home care sector can no longer adequately take care of all of its patients and is forced to ship some of them back to the hospital sector. By that time, the hospital sector's staff are recovered from their exhaustion and can take on these extra patients. Because the hospital sector's staff are able to recover from their exhaustion in time for the secondary surge, the health care system of simulation run 2 is able to recover from the surge event as well as in simulation run 1, but over a longer period of time.

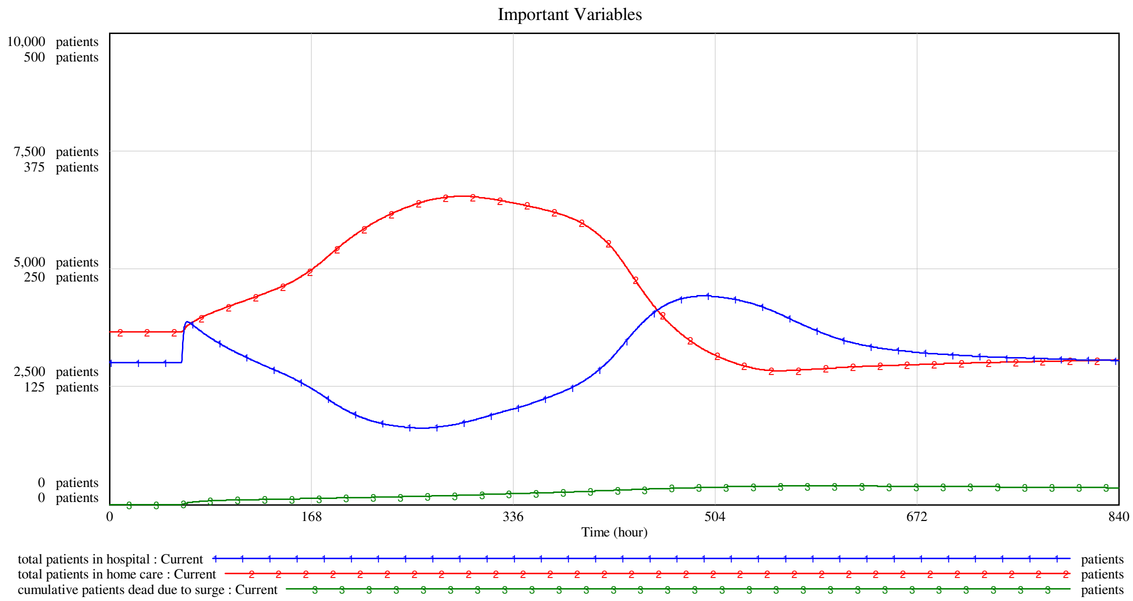


**Fig. 12. Simulation Run 2: Important Variables**

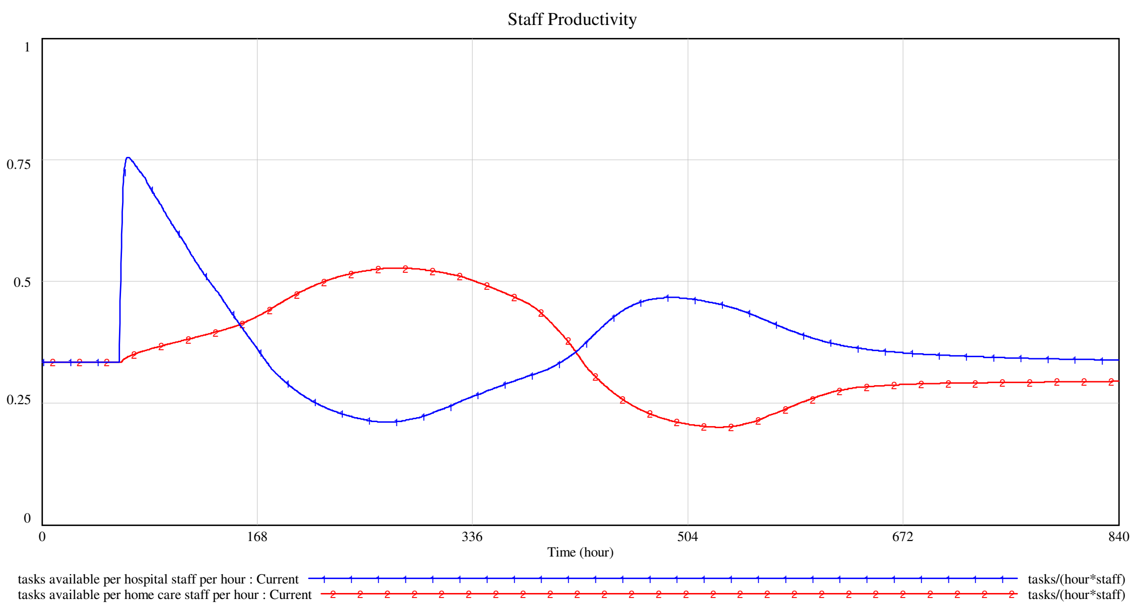


**Fig. 13. Simulation Run 2: Staff Productivity**

Fig. 13 shows staff productivity in simulation run 2. In this run, the productivity of hospital staff rises right after the surge, gradually falls due to exhaustion, and recovers in time to handle the secondary surge of patients from home care. The productivity of home care staff slowly rises after the surge, reflecting the increased workload of home care staff. After that, home care staff productivity falls due to exhaustion and recovers again after the home care sector sends some of its patients to the hospital sector.

Simulation Run 3: the Health Care System is Completely Overwhelmed by a Surge

Fig. 14 shows what happens when the stamina of hospital sector staff does not recover quickly enough to handle a secondary surge from the home care sector. In simulation run 3, the hospital sector's staff get exhausted faster and to a greater degree than in the other simulation runs. The hospital sector sends more patients to the home care sector and the home care sector's staff get exhausted to a greater degree. By the time the hospital sector receives its secondary surge from the home care sector, the staff of the hospital sector are too exhausted to handle it. The staff of both health care providers fall into vicious cycles of exhaustion by time 340 and their productivities descend to very low levels. The hospital and home care sectors become so ineffective at providing treatment that they cannot handle even their usual patient workloads. Because of this, human casualties skyrocket around time 470. This rise in casualties mostly comes from people dying while waiting for treatment.

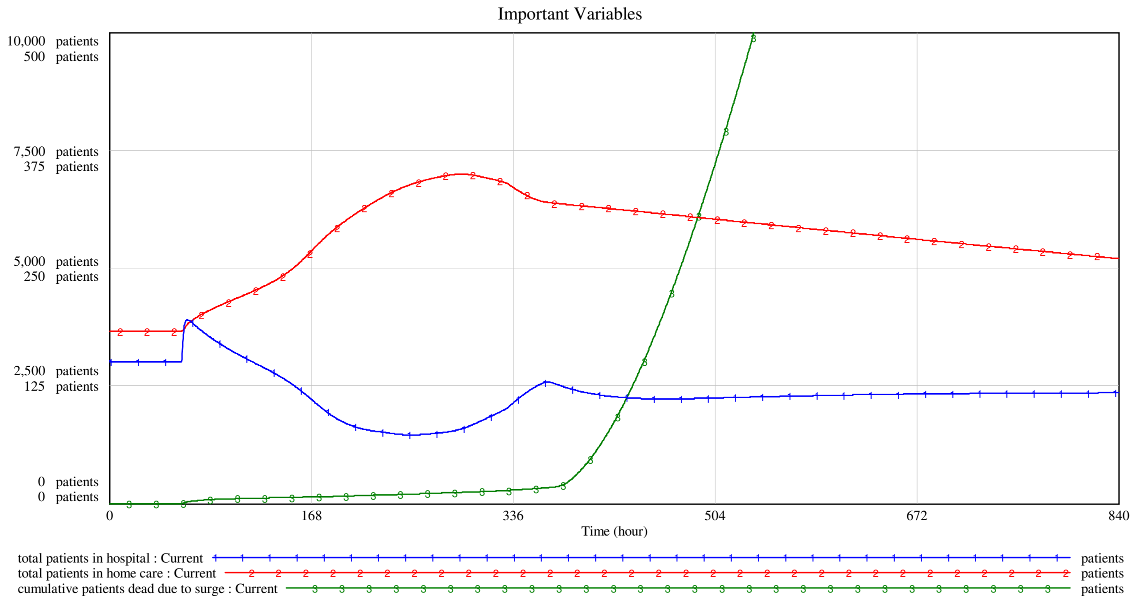


**Fig. 14. Simulation Run 3: Important Variables**

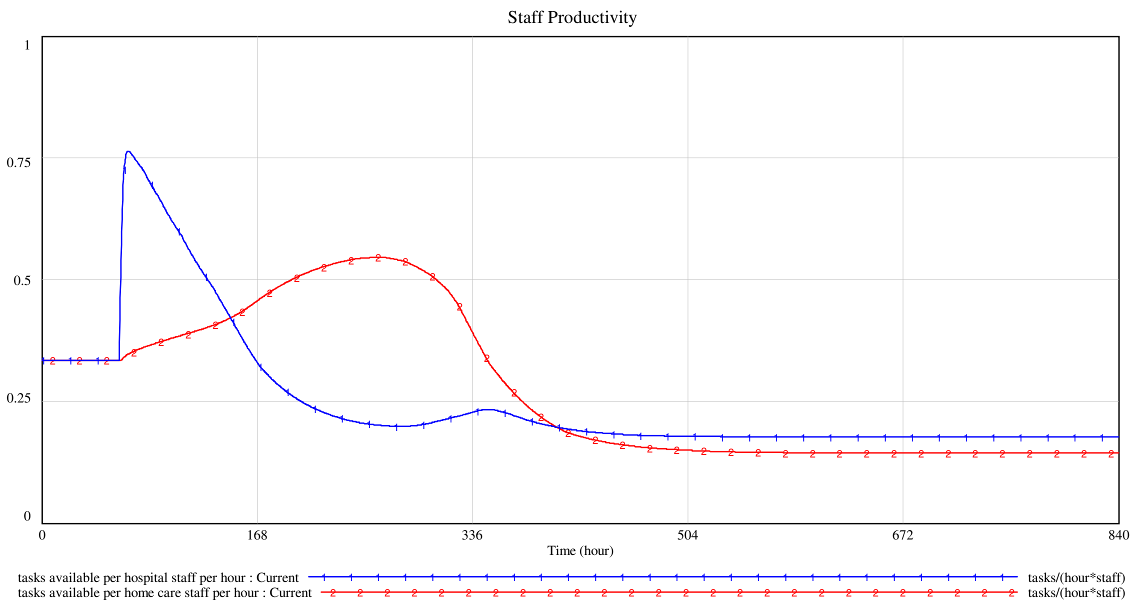


**Fig. 15. Simulation Run 3: Staff Productivity**

The staff productivities in simulation run 3 (Fig. 15) look very similar to those of simulation run 2, at least until about time 350. At this time, staff productivities of both types of treatment providers fall to low levels for the rest of the simulation run.

Simulation Run 4: Reduced Maximum Staff Loads for Both Health Care Sectors

Simulation runs 1 through 3 show how staff exhaustion causes health care systems to poorly handle surge events. Staff exhaustion is the one force in this model that reduces the ability of hospitals and home care agencies to provide treatment. If exhaustion is the problem, then the solution is for treatment providers to avoid increasing their staff workloads so much that their staff burn out from exhaustion. Treatment providers can avoid raising their staff workloads to unsustainable levels by not admitting too many patients into treatment or sending too many patients to (or calling up too much staff from) each other.

The simplest way for treatment providers to do this is to reduce their maximum staff loads. A limit on maximum staff loads limits treatment providers' abilities to accept more patients than they can treat. If treatment providers do not accept too many patients, then they will not have problems with staff burnout or too much shifting of patients and staff between each other.

While it is sensitive to parametric data, the model currently works best with a maximum staff load of 1.3. This maximum staff load is lower than the default maximum staff load of 1.5 that is used in simulation runs 1, 2 and 3. The effect of a lower maximum staff load is shown in simulation run 4, which is the same as simulation run 3, but with maximum staff loads for both the hospital and home care sectors set to 1.3.

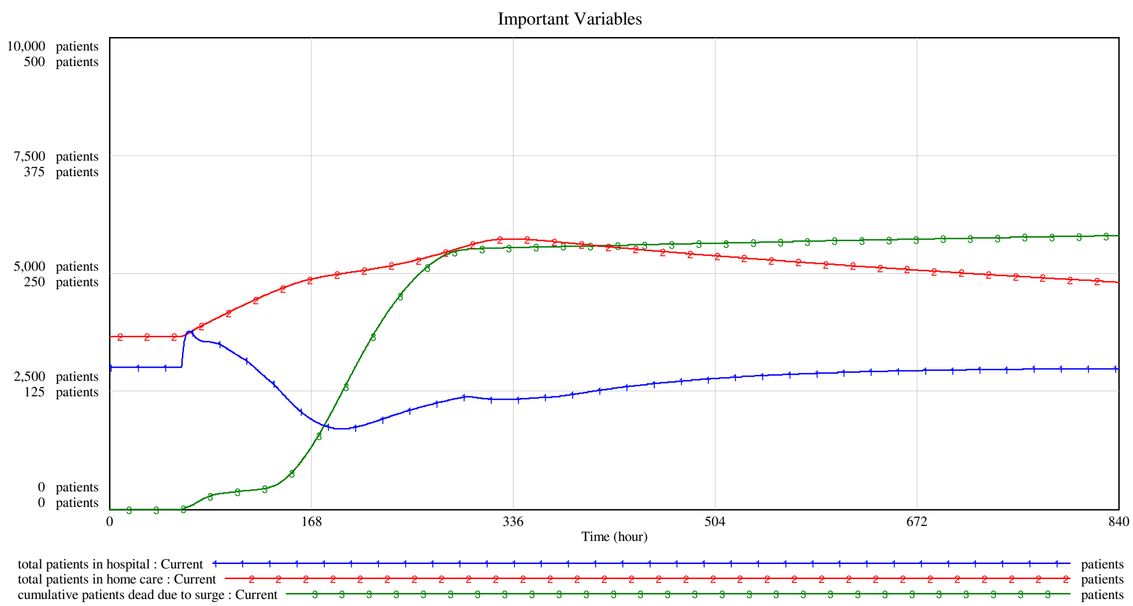


**Fig. 16. Simulation Run 4: Important Variables**

In simulation run 4 (Fig. 16), cumulative deaths go up more quickly than in simulation run 3, but stabilize at around time 300. In simulation run 3, cumulative deaths due to the surge event rise above 500 people by time 550 and continue to go up thereafter. In simulation run 4, deaths end up at a steady 290 people by the end of the run.

In simulation run 4, the hospital sector takes in fewer patients initially than in simulation run 3, but avoids terminally exhausting its staff. This refusal by the hospital sector to take on more patients than it can sustainably treat causes more patients to die while waiting for treatment in the short term, but avoids the potentially much larger loss of life that can occur if the hospital sector exhausts its staff.

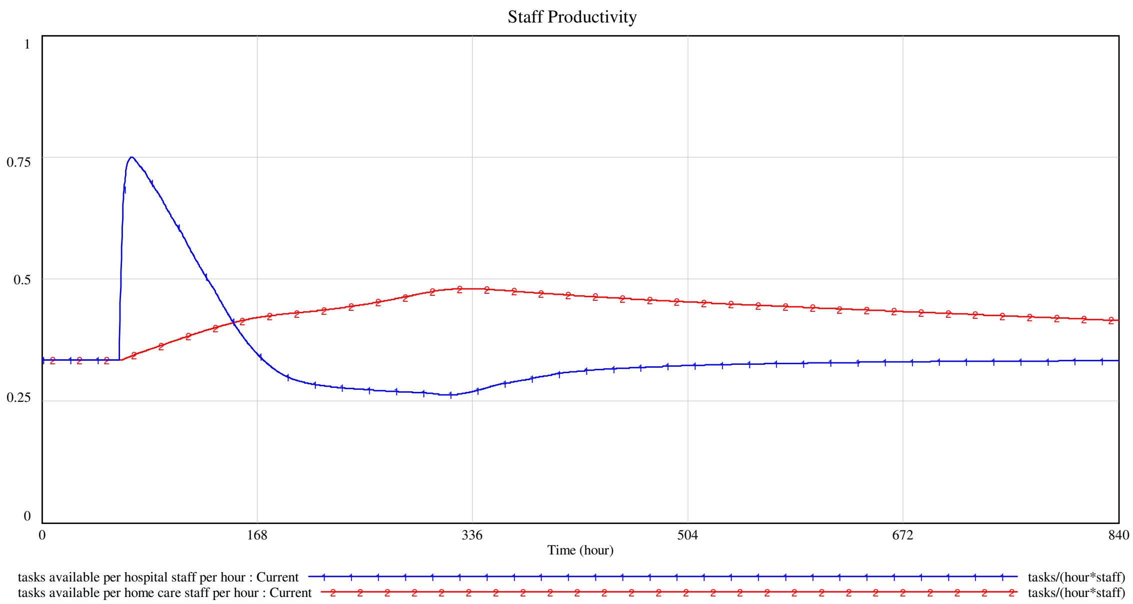


**Fig. 17. Simulation Run 4: Staff Productivity**

Fig. 17 shows that, while hospital staff productivity drops following an initial upward spike, it never deteriorates to a very low level. The staff in the hospital sector never move into vicious cycles of exhaustion.

## Conclusion

In a surge event, health care systems take weeks to recover to their usual levels of operation. During that time, there is a significant risk that high staff workloads can cause staff to become exhausted. This exhaustion causes a long-term decrease in the ability of the hospital and/or home care sectors to provide adequate treatment to prospective patients. Treatment providers should craft policies that ensure the ability of treatment providers to sustainably provide medical treatment for long periods of time. This should be done even at the expense of short term treatment provision ability. Maximum staff loads for treatment providers should set at levels that allow treatment providers to use all of their policies sustainably and in moderation, especially the policy of increasing staff workload.

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