Introduction:

COVID-19 is an especially difficult illness to contain and treat, due to infected persons often presenting no symptoms, as well as presenting a considerable risk to the elderly and those with pre-existing health conditions. Because of this, the global pandemic caused by COVID-19 has proven a considerable burden on the NHS and other healthcare systems worldwide, due to the time and resource intensive care that these patients require. In the hopes of better understanding how the pandemic affects both hospitals and patients, we have implemented a simple model of a hospital which can take in COVID-19 patients from the community and affect their disease outcomes.

Hospital Model Overview:

The hospital model brings three new additions to the COVID-19 IBM;

1. Novel hospital states corresponding to the physical locations of patients within the hospital.
2. Separate wards for both severely ill and critically ill patients, which allow recovering and worsening patients to transition between them.
3. Specialised healthcare worker types which are assigned to hospitals, currently consisting of doctors and nurses, with their own interaction types with the patients and with each other.

Hospital States:

Individuals can have six “hospital states”, which correspond to locations in the hospital and community. These hospital states determine when interventions such as quarantine lifting and testing occur, as well as the progression of the disease and the infectivity of patients.

1. NOT_IN_HOSPITAL
2. WAITING
3. GENERAL
4. ICU
5. DISCHARGED
6. MORTUARY

The first state, “NOT_IN_HOSPITAL”, refers to individuals who have not yet been hospitalised. Individuals who transition to the “HOSPITALISED” disease state, which implies progressing to a severely symptomatic state, are assigned to the hospital with the fewest patients and added to a waiting list for a general ward.

At this point, if a patient can enter a general ward, they do so, and their hospital state is changed to “GENERAL”. Otherwise, their hospital state is set to “WAITING” and they remain in the general ward waiting list. “WAITING” in this context is used for patients who have not entered either a general ward or a critical ward, and is used primarily to represent patients in hospitals with too much overflow. Upon reaching either the “GENERAL” or “WAITING” stage, quarantine is lifted and patients are tested.

Table 1. Table showing the hospital states a patient transitions to when they progress to a particular disease state. In the case of hospitalised or critical patients, the outcomes are waited such that worse progression becomes more likely if they cannot transition to their required ward.

Disease State	**Required Ward/State**	**Better Progression Outcome**	**Worse Progression Outcome**
HOSPITALISED	GENERAL	RECOVERED	CRITICAL
CRITICAL	ICU	HOSPITALISED_RECOVERING	DEATH
HOSPITALISED_RECOVERING	GENERAL	RECOVERED	----------
RECOVERED	DISCHARGED	----------	----------
DEATH	MORTUARY	----------	----------

Should a patient's disease state transition to "CRITICAL" at this stage, then they are removed from either the general ward or the general ward waiting list added to a waiting list for the ICU. As before, if a patient can enter the ICU immediately, they do so immediately, and their hospital state is updated to "ICU". Otherwise, their states remain as they currently are.

Once a patient has become critically ill, they can then begin to recover, in which case they are added to back to a waiting list for a general ward, and their hospital state is moved back to "GENERAL" if they transition back successfully. Otherwise, the patient dies and is moved to a "MORTUARY" state. Recovering patients have to spend at least sometime in the general ward before being "DISCHARGED" and then moving back to "NOT_IN_HOSPITAL".

When a patient transitions to these severe disease states, the choice of which disease state they go to next is decided at the point where availability of ward beds is determined. This is based on the assumption that if a very ill person requires a specific level of care and they do not get it almost immediately, then progressing to a worse state is more likely, regardless of whether they get treated later. To emulate this, if a person cannot transition immediately to their required ward, the worse disease outcome becomes more likely. Otherwise, the probabilities for transitioning to either state remain as they were.

Ward Transitions and Waiting Lists:

As stated in the previous section, patients are added to waiting lists when attempting to enter either the general ward or ICU. These waiting lists are implemented as linked lists, with popping of patients being used to remove patients. The order of patients in the lists is therefore determined by the order in which they are added, which allows us to prioritise patients who have been in the list for longer by scheduling transitions for people earlier in the list. The only exception to this is when somebody in the either the general or ICU wards wishes to swap wards, in which case, they are added to the start of the list. This is to give patients who are already in the hospital priority when it comes to bed allocation. Furthermore, in instances where wards are full, newly recovering and newly critical patients can swap places.

Healthcare Workers and Hospital Networks:

Infections in the hospital occur at both a healthcare worker and a patient level, and are transmitted in a similar fashion to daily and work networks. All healthcare workers, who are currently separated

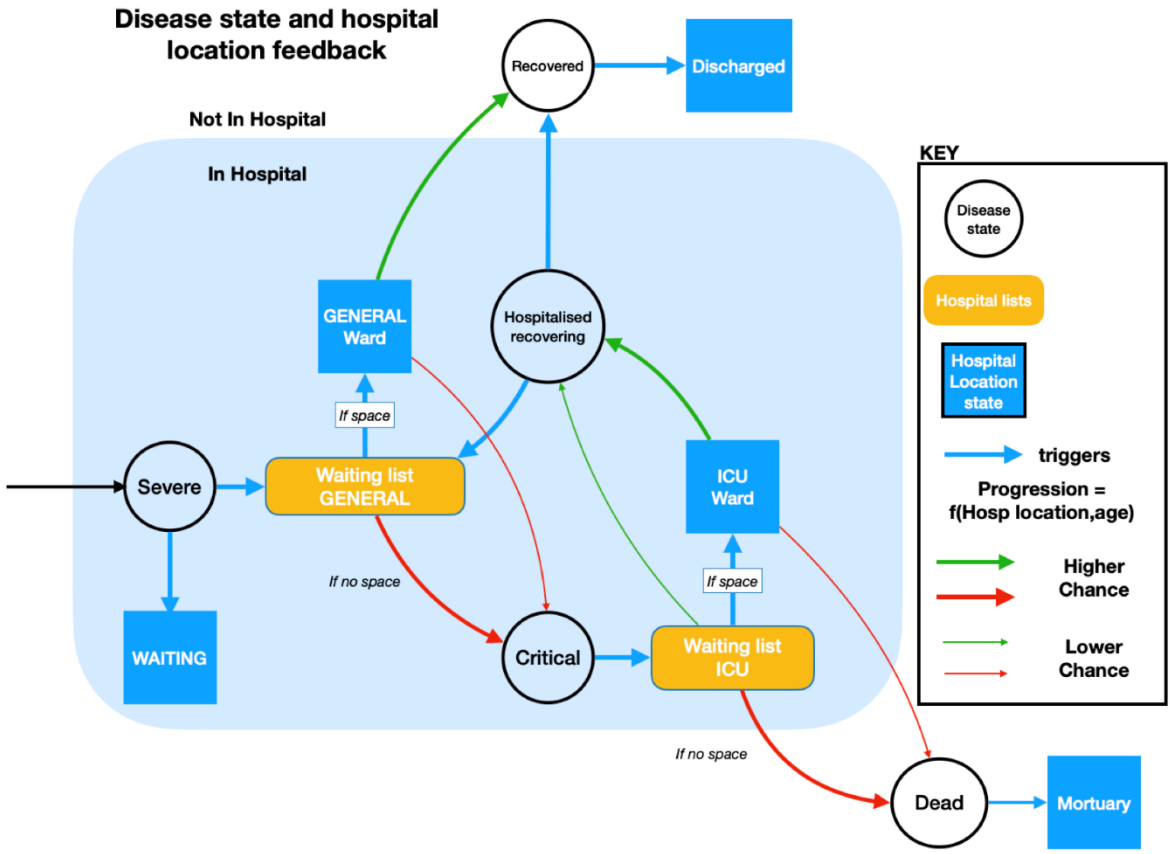

Figure 1. Diagram showing interlinking of disease states and hospital states in the simulation. As a person's disease progression advances, this triggers a change in their hospital state if they are able to move to their required ward (general if hospitalised or recovering, ICU if critical). If the wards are full, patients are added to a waiting list for that ward type and are moved in when space becomes available. However, failing to make it into a ward on the first attempt makes a progression to worse state more likely.

into doctors and nurses, in a hospital are added to a hospital-wide work network (whilst being removed from the generic, age-stratified work networks), which is static. Healthcare workers are then assigned to individual wards, where they form random interactions with the patients in those wards. HCW-patient networks are separated out based on the type of healthcare worker, i.e. there is a doctor-patient and a nurse-patient network in each ward. This allows a user to take into consideration the differing nature of interactions different types of workers can have with patients, and how this can impact the transmission. Healthcare workers remain in the same ward throughout the simulation unless severely ill or in quarantine, in which case they cannot form interactions with patients, and they are added back into the same ward upon recovery. and attempt to form a minimum number of required interactions with each patient. This means that a healthcare worker can form multiple connections with the same patient, representing a greater frequency of interactions with that patient. Doctors form a greater number of connections than nurses, but the strength of transmissions between doctors and patients is lower than for nurses, signifying the close contact and repeated interactions that a nurse typically has with a patient.

Name	Description	Value
n_hospitals	No. of hospitals.	1
n_covid_general_wards	No. of general wards per hosp.	40
n_beds_covid_general_ward	No. of beds per general ward.	30
n_doctors_covid_general_ward	No. of doctors per general ward.	5
n_patient_doctor_required_interactions_covid_general	No. of interactions patients in the general ward need from doctors.	1
n_nurses_covid_general_ward	No. of nurses per general ward	10
n_patient_nurse_required_interactions_covid_general_ward	No. of interactions patients in the general ward need from nurses.	3
n_covid_icu_wards	No. of ICU wards per hospital.	10
n_beds_covid_icu_ward	No. of beds per ICU ward.	10
n_doctors_icu_ward	No. of doctors per ICU ward.	3
n_patient_doctor_required_interactions_covid_icu_ward	No. of interactions patients in the ICU ward need from doctors.	3
n_nurses_covid_icu_ward	No. of nurses per ICU ward.	6
n_patient_nurse_required_interactions_covid_icu_ward	No. of interactions patients in the ICU ward need from nurses.	6
max_hcw_daily_interactions	No. of interactions a healthcare worker can form with patients.	20
waiting_infectivity_modifier	Infectivity of patients in the WAITING state.	1
general_infectivity_modifier	Infectivity of patients in the GENERAL state.	0.5
icu_infectivity_modifier	Infectivity of patients in the ICU state.	0.5
hospitalised_waiting_mod	Increase in chance a HOSPITALISED patient progresses to worse outcome when unable to enter a general ward.	1.3
critical_waiting_mod	Increase in chance a CRITICAL patient progresses to worse outcome when unable to enter an ICU ward.	2
relative_transmission_hospital_work	Transmission rate between healthcare workers.	1
relative_transmission_doctor_patient_general	Transmission rate between doctors and patients in the general ward.	0.9
relative_transmission_nurse_patient_general	Transmission rate between nurses and patients in the general ward.	0.8
relative_transmission_doctor_patient_icu	Transmission rate between doctors and patients in the ICU ward.	0.7
relative_transmission_nurse_patient_icu	Transmission rate between nurses and patients in the general ward.	0.8
hcw_mean_work_interactions	Mean no. of interactions in the healthcare worker work network.	20

Current Limitations and Future Plans:

Doctors and nurses from different wards are currently pooled together in the work network, which is likely to not reflect the actual working structure of hospitals during a pandemic, as workers treating

COVID patients can interact with patients who are not. Prediction of future disease state can only happen once for each patient and on the same time step when a patient transitions, therefore the length of time a patient waits in the ward cannot affect the progression of the disease state. Patients in the WAITING state also cannot currently interact with each other or with healthcare workers in the hospital.

In future, we aim to:

1. Include non COVID-19 patients in the hospital process.
2. Include a network for patient-patient interactions for patients in the waiting state.
3. Allow patients to be moved between hospitals in the event there is no space for them.
4. PPE for healthcare workers and ventilators for patients, which affect their likelihood to infect and be infected by other people, and disease outcomes, respectively.