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RESEARCH ARTICLE

Adding Resilience to Hospital Bed Allocation, using FRAM

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ABSTRACT

Modelling complex sociotechnical systems to better understand and optimise their operation has proved a challenge and many methodologies have been put forward to use in what has been called model-based system engineering (MBSE). The appropriateness and availability of the Functional Resonance Analysis Method as a suitable candidate has been tested here, in the context of developing a methodology that can be applied currently, and in an actual real system requiring taking life and death decisions on an informed understanding of the factors and risks involved.

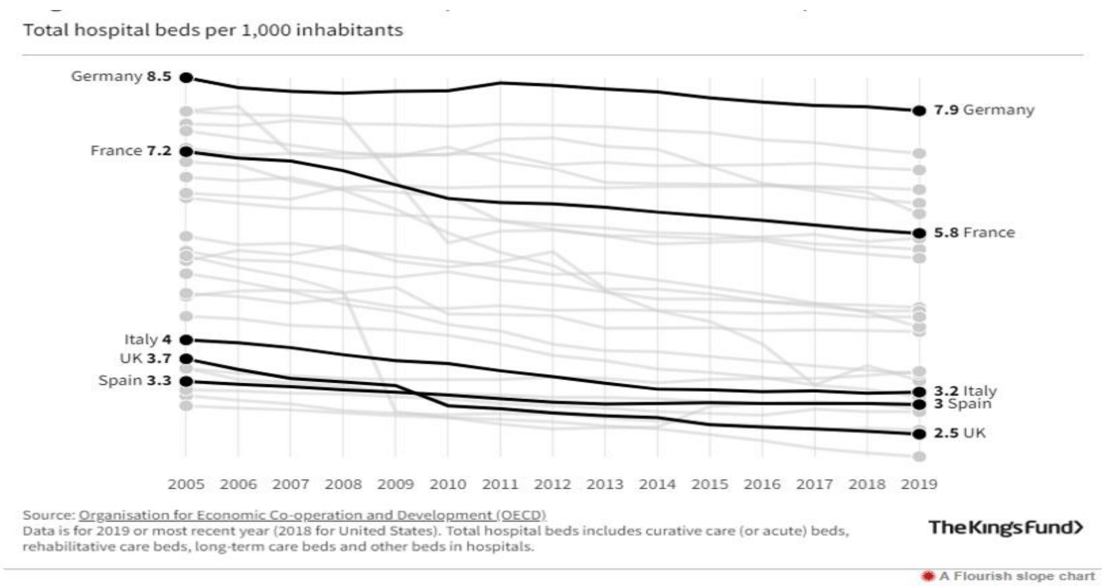
The allocation of scarce critical care beds in hospitals is a clear example of where a better understanding of the system and a way of feeding the decision makers with crucial information on numbers and trends could help optimise very challenging responsibilities. By building on recent developments by Hill of Hollnagel's paradigm shifting approach, this paper has laid out how FRAM system modelling can provide not only the prediction and correction mechanism provided by the new machine learning FRAM facility demonstrated by Nomoto but can add resilience to the critical decision making involved. It puts forward the case that it is certainly worth pursuing and developing further.

Background

In England, the National Health Service (NHS), has been facing bed allocation problems for a while now. The total number of NHS hospital beds in England has more than halved over the past 30 years, from around 299,000 in 1987/88 to 141,000 in 2019/20 (1).Most other advanced health care systems have also reduced bed numbers in recent years. Notwithstanding, the UK has fewer acute beds relative to its population than many comparable health systems.

How hospital beds are used depends on the availability of other services, yet national data does not provide a full picture of NHS bed capacity and requirements. While reductions in bed numbers have slowed in recent years, there are opportunities to make better use of existing beds by preventing avoidable admissions, reducing variations in length of stay and improving the discharge of patients. So, one of the major challenges in hospitals, particularly in the UK, is the management of bed availability. But realism is needed about what can be achieved in improving the use of hospital beds and moderating future demands for bed-based care
.

Currently there appears to be no sign of an imminent increase in bed capacity in UK hospitals, so the only options appear to be to accept the current supply (bed availability) and demand (number of patients requiring critical care) imbalance and use optimisation and efficiencies to make do and mend (i.e., manage it proactively). Also just increasing beds is not helpful if there are not the staffing levels available to manage / attend them.



Source: Organisation for Economic Co-operation and Development (OECD)
Data is for 2019 or most recent year (2018 for United States). Total hospital beds includes curative care (or acute) beds, rehabilitative care beds, long-term care beds and other beds in hospitals.

The King's Fund

A Flourish slope chart

Figure 1 – UK Hospital Bed provision compared to other countries(1)

However, research (next section) shows that initiatives to moderate demand for hospital care often struggle to succeed.

The Problem

The reality is that the staff at the front line have very little opportunity to moderate supply and thus have no option but to try to manage demand. But, as Cook (2) points out:- "with bed demands intense, beds are available for new patients only as old patients are discharged" His is one of a number of studies which provide valuable insights into the processes involved (3) and describes in detail, the sequence of an actual incident where: - "The ICU's (Intensive Care Units) were continuously working at capacity--- the units were full".

The incident details documented by Cook, lay out the basic issues and but for lack of space could usefully have been included here in full, but in summary:
"A patient undergoing surgery needed to go to an intensive care unit when the surgical procedure was complete. The surgical procedure was finished before the bed was available. But after a few hours in a recovery room the patient was eventually transferred to the ICU".

As Cook says, this description is far from complete, it omits the hectic to and froing of telephone calls and discussions, some disagreements and disputes, extra work, changes of plan, with accompanying levels of stress and inevitable "human error" as the investigation found – situation normal?

So, admitting a patient is a complicated business and requires an approach which can take in all these complex, conflicting demands and interactions. In Cook's work, as with subsequent studies by Woods and others, the understanding, insights and interpretations of what was happening and why, is developed from the point of view of joint cognitive systems (in the ED, Ward and surgical silos). Woods describes these interactions of locally adaptive strategies as "collisions*, (4), as these silos individually attempt to adapt to deal with the complexity of the system.

Woods observes that – "The Emergency Department continues to be one of the critical laboratories for studying or understanding resilience and adaptation in human systems".
Woods also indicates directions for future research, which should: -"Focus on how factors such as information availability, governance and work culture influence the behaviour of units ----- and what factors will result in the most resilient management ---in the context of actual work systems."

His work was done before Hollnagel had published a method that produced functional models of these interacting, interdependent processes in a complex system. Now with the added facility of being able to include the effect of information flows in a complex sociotechnical system, this paper looks at following up Woods and Cook's work to apply the Hollnagel's methodology to an individual case study, of a general challenge for hospital staffs worldwide.

The New Approach Ptoposed

The process of negotiating conflicting and competing requirements is clearly dynamic and complicated, but here, it seems to work, day after day. So, the first need is to understand quite how this is achieved. The aim of the paper is to explore whether a newer methodology can help to provide this insight and perhaps help to solve the problems. Since Cook and Woodsa newer methodology has emerged, which is proving useful in unscrambling and understanding what goes on in these complex sociotechnical decision processes. This is the Functional resonance Analysis Method (FRAM) developed by Hollnagel (5).

This FRAM method consists of identifying the critical Functions* needed to accomplish successfully, the design intent of the system. It can then allow exploration of how the intricate interactions and interdependencies of these functions combine to produce the required outputs.

*In this document, FRAM Functions will be spelt with an upper-case 'F', to distinguish them from the otherwise generic use of function, functioning etc., spelt with a lowercase 'f'. The system model is constructed as a mind map of Functions, which are represented as abstract hexagons to show and allow the definition of the different types of coupling Aspects necessary to link the Functions into an operating system. These Aspects are described below. (Figure 2)

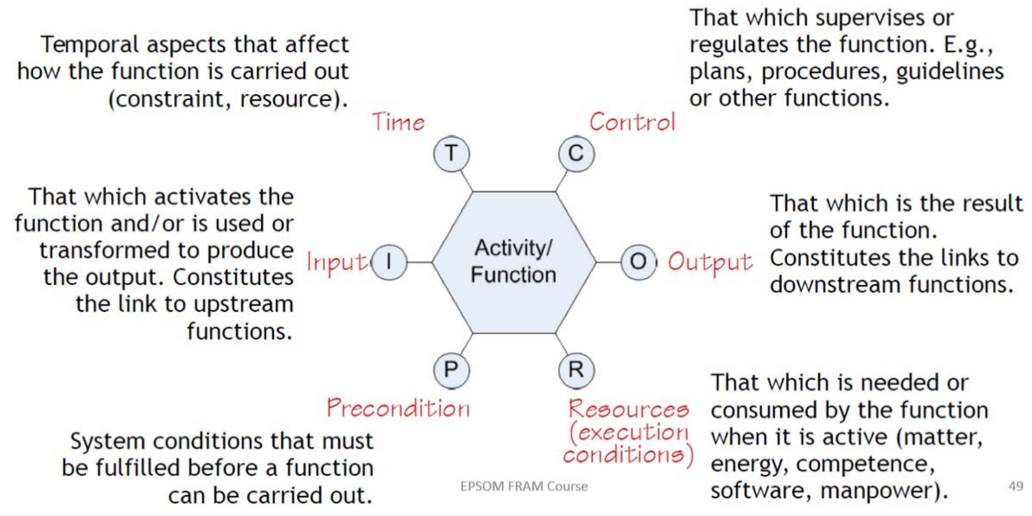


Figure 2 – The FRAM Function "hexagon" with its Aspects

The analysis generally consists of discovering what the system does, (or how the standard protocols and procedures imagine it is done!): how it normally does it successfully; and what variations in conditions and interactions in the real world can affect how it works in practice, often involving adapting to unexpected emergent developments by changing how the system operates as a work around. (i.e., how the work is actually done).

The model is then used as a basis for discussing, observing, improving and optimising approaches and applications for which normal conventional engineering and business process models find it difficult to cope with. Manuals on the method and comprehensive reviews of the applications of the method are available in the literature (6,7,8).

There is now a group working on further developing the power of the analysis and visualisation software to extend the usefulness and range of facilities available to analysts. The software authored by Hill (9), is open source and can be accessed on GitHub (10) through standard creative commons conditions. This serves as a community of practice repository for the various codes and applications.

These recent advances in the development of the FRAM Model Visualisation software – (11), has opened up the possibility of the dynamic Markovian tracking of Function properties (Metadata) as the process develops and outcomes emerge; and has made possible more rigorous and quantitative applications including critical timings (12) and now machine learning (13,14). The dynamic matching of supply and demand, inherent in the optimising of limited resources (beds) thus offers an ideal candidate to test out the promise of this new Model Based System / Resilience Engineering (15) approach.

The Process to be Modelled.

The following description of the process in one of the major children's hospitals is taken verbatim from a recent paper by Jacob Barnaby (16).

"When a child is identified as needing critical care, they are added to the C3PO, (Critical Care Consultants Post-Op list), the surgical list requiring critical care beds, postoperatively.

The list is then reviewed at bed meetings with, bed managers, operation managers, nurse leads, matrons, critical care consultants and some secretarial staff. The capacity levels and current staffing levels feedback into this decision and determine whether or not the surgery can proceed that day.

There is no current system for pre-emptively identifying if the bed will be available in the days before the surgery. Delays can occur here, and the patients have their codes updated to indicate the delay and are then placed back on the C3PO list. If the capacity and staffing are adequate the surgery is allowed to go ahead, and they are looked after post-operatively before being admitted to the critical care unit.

If a sudden emergency occurs the nurse team leader can step down from their coordination role to provide the team with a temporary increase in capacity and look after the patient from an improvised critical care bed, this is a last resort move as it requires an outlier bed being formed meaning staff are removed from the main critical care unit. Once the capacity of the ward opens up again the patients can be moved back to the critical care unit for the duration of their stay.

Critical care capacity is determined by a variety of factors the main one seeming to be admissions and discharges. It can be hard to predict the length of stay, so this does not seem to produce a monitorable impact on immediate capacity.

The admissions can come from the emergency department, escalations from medical wards, transfers from other facilities and emergency surgical admissions.

This is in addition to elective surgical admissions which seem to take a lower priority than the other admissions as they are not perceived to be immediately life-threatening. This results in on the day delays to surgery that could be improving the quality of life of certain paediatric patients and adding to the backlog of operations.

The main pathway for freeing up critical bed capacity is stepping down care from critical care to ward level care. But

- there is no established overall protocol for any of these processes with certain staff members even describing it as "the parts all falling into place when it needs to" implying the emergent property of all the meetings, handovers and communication was a functional system that no one truly understands from a global perspective.

- there are no firm guidelines or protocol for admission or discharge of patients, with clinical decision-making being the main tool used to make these decisions.
- A major point is the uncertainty around the bed meetings, when decisions are made nursing staff feel like they just have to work within the decisions made without having a say in the admissions process. The only intervention the critical care team seem to have is pausing elective operations.

This is not a procedure the nursing staff take lightly; instead, they will opt to set up temporary beds and allow their team leaders to step down from co-ordination to caring for extra patients".

The use of a coding system to prevent patients breaching a certain length of wating time seems to allow for triaging of the elective surgical patients that have experienced multiple delays and also provides a clear indicator of waiting times for the individual patients.

The FRAM Model

The initial model below, (figure 3) attempts to capture the complexity of the system as operated currently and will need validation against real world cases and further staff clarification to ensure it provides an accurate overview of the procedures in place. From the model the main aspects offering room for improvement seem to be around more clearly defining the actual and predicted capacity of the critical care units during the bed meetings.

Hill has set out clearly the process of assigning properties to a Function as Metadata (11). The data is assigned an identifying Key and the software allows the calculation of its value depending on the metadata of the Functions whose aspects initiate and enable the Function's functioning (such as activation, execution and output). Clearly in this application the key metadata will reflect how the number of beds in the hospital are distributed and vary during the day.

Metadata suggested for the bed allocation fram.

a) There must be a total number of beds in use on any given day – depending on staffing levels **Stl**, say - **Btl**

b) There seem to be three (/ four?) types of beds.
   Post-operative recovery Beds **- Bpo**
   Critical care beds - **Bcc**
   Ward Beds - **Bw**
   (Improvised beds (CC or W?) **Bim** ?

This is the supply side.

c) Of these a certain number will be occupied / blocked – **Bbl** (in each category?)
   Freed up by discharge from CC **– Bdcc**
   Freed up by discharge from the wards **– Bdw**

d) of these a certain number in each category will be

available / blocked each day (at 6 am – Actual) **Bpoa, Bcca, Bwa**

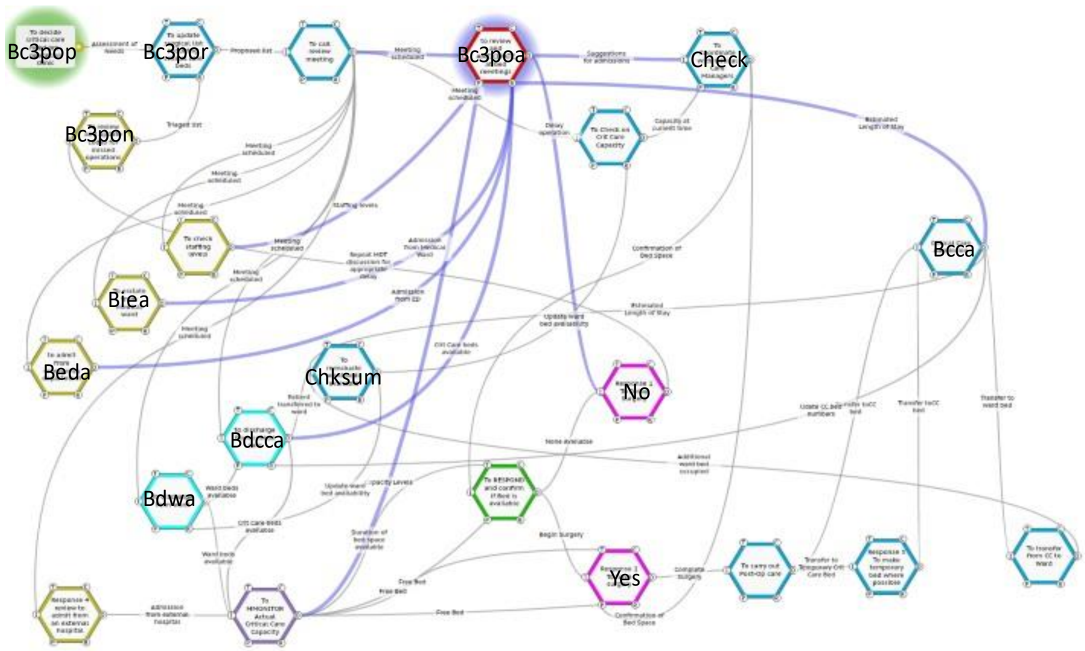


Figure 3 – The "Work as currently done" FRAM model.

An initial set of values obtained from the operating staff for a "typical day are given below and a subset (in Table 1) was utilised (see later), to test the practicality of the modelling scheme.

The daily numbers for this hospital are typically:

- 25 scheduled elective cases requiring overnight beds*. (* noting overnight can mean between 1 and 3 days).
- There are 25 elective staffed beds (23 on wards and 2 in Critical Care) hospital keeps to this by re-allocating staff from around the hospital to ensure this number.
- (40-day case operations occur each day but rarely does a day case need an overnight bed, approximately 98-99% go home and don't take up a bed)
- 26 patients on average every day are admitted into a bed through ED (we are commissioned for 25 but this can spike as high as 40)
- Hospital needs to discharge 26 patients each day to be functional.

Bed Numbers are typically

- Elective surgery - 23 W (reserved) and 2 CC
- Emergency Dept – 25 W (+/- 10) and ? CC
- Long term blocks – 11W
- Total – 55W (+11) = 66?
- Post op beds - ?
- Critical Care beds – 5?
- Ward Beds – 50?
- Admissions from ED + IE = 26
- Discharged from Ward = 26
- Turnover ~ 40%?
- Blocked ~ 20%

On a specific day for example

There were 9 medical patients that came through ED and are still in the elective staffed beds. In fact, there are 11 long term patients that cannot be discharged out.

The timings of the meetings and the preparation of the relevant data also needs to be tailored to whatever procedure is agreed in sequence, timing and frequency.

A Simplified Application to Test its Viability

Before embarking on a full-scale application, which will require gathering actual day to day data from extensive observation and negotiations with data centres, it seemed sensible to test out the proposed approach with the above data on a simplified model. This is shown below in Figure 4

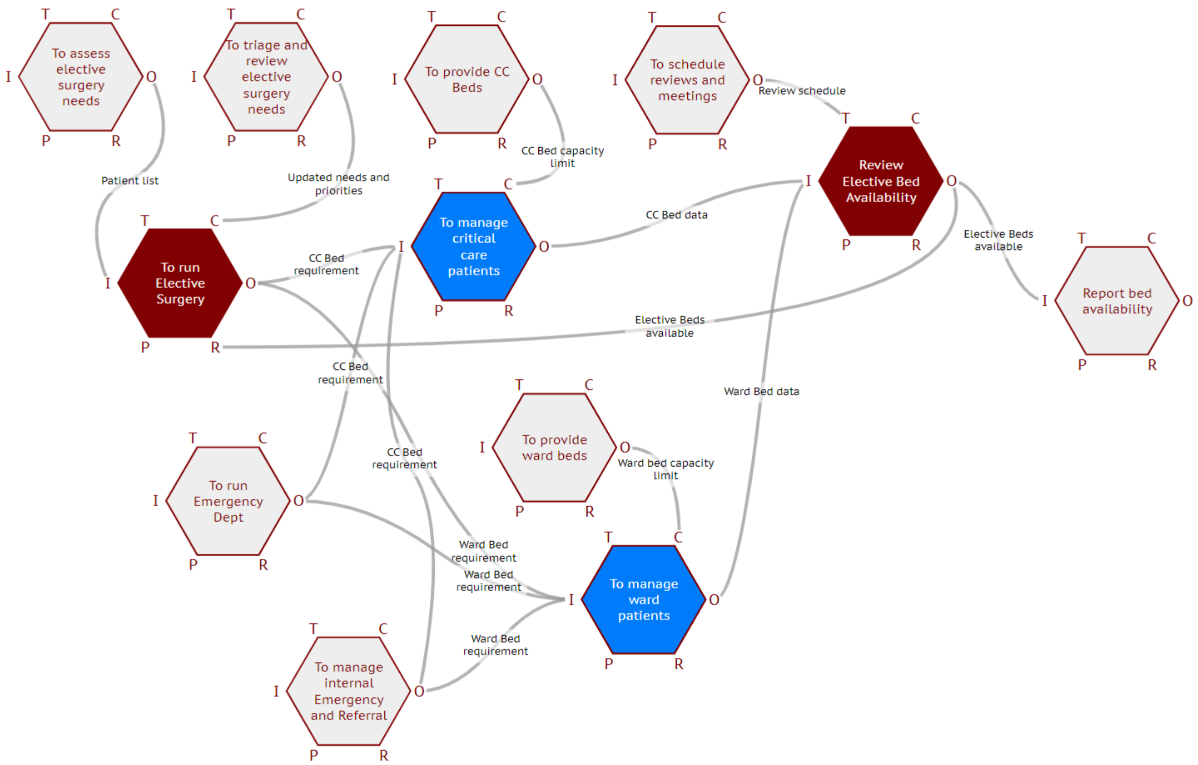


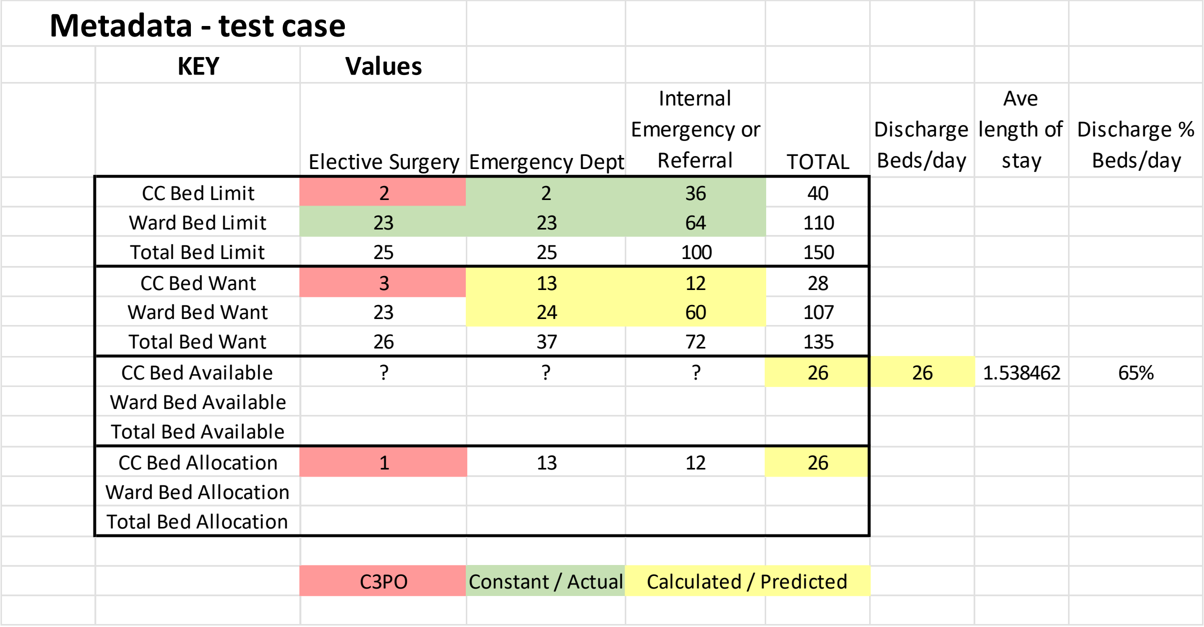
Figure 4 – A simplified test FRAM instantiation gives the results shown.

Table 1 – Initial test data set

Table 1.1 - Keys

Metadata	Test Run Key	Description
Btl	Bed-total	Hospital Beds in Total
Bcc	Bed_limit_CC	Total No. of Critical Care beds
Bw	Bed_limit_Ward	Total No. of Ward beds
Bdcc	Bed_ available_CC	No. of CC beds made available by discharging patients
Bwa	Bed_available_Ward	No. of Ward beds available
Bc3po	Bed_required_CC	No. of CC beds sought for elective surgery
Brw	Bed_required_Ward	No. of Ward beds required
Bc3poa	Bed_elective_CC	No. of CC beds assigned to elective surgery

Table 1.2 - Values



Metadata - test case

KEY	Values						
	Elective Surgery	Emergency Dept	Internal Emergency or Referral	TOTAL	Discharge Beds/day	Ave length of stay	Discharge % Beds/day
CC Bed Limit	2	2	36	40			
Ward Bed Limit	23	23	64	110			
Total Bed Limit	25	25	100	150			
CC Bed Want	3	13	12	28			
Ward Bed Want	23	24	60	107			
Total Bed Want	26	37	72	135			
CC Bed Available	?	?	?	26	26	1.538462	65%
Ward Bed Available							
Total Bed Available							
CC Bed Allocation	1	13	12	26			
Ward Bed Allocation							
Total Bed Allocation							
	C3PO	Constant / Actual	Calculated / Predicted				

Decisions on bed allocations

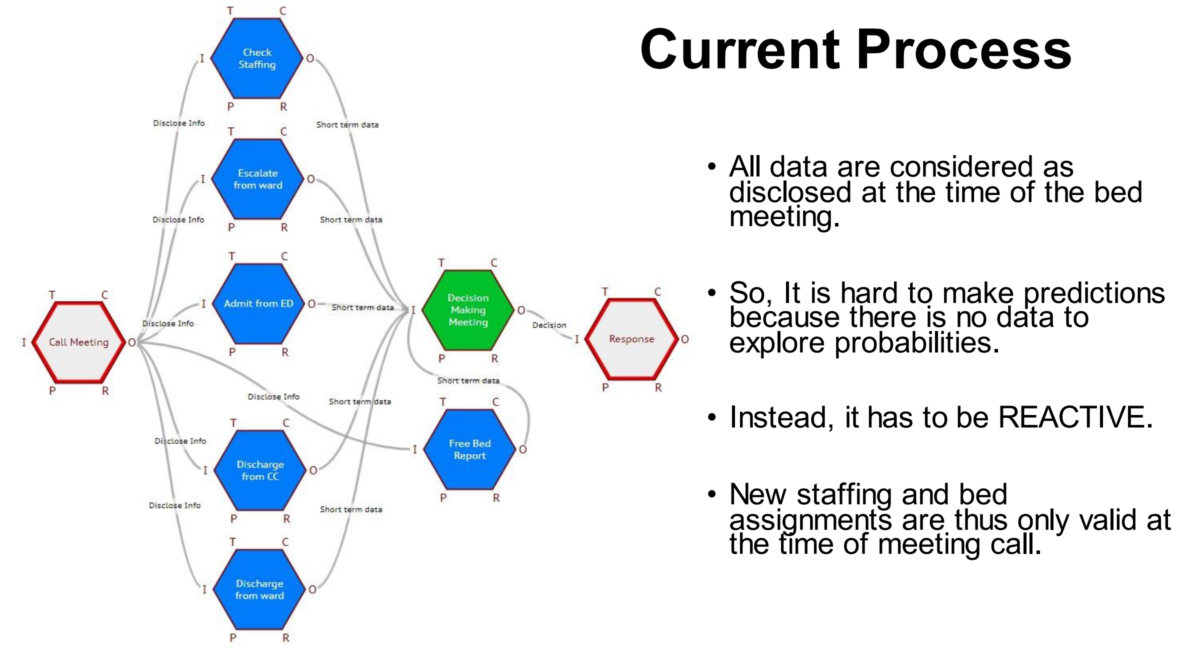
Currently the only available response is to adjust the number of children proposed for that day's elective surgery list to release, or reserve bed space, dependent on actual availability.

- (On the daily C3PO list requiring Critical Care beds, there are normally 0 – 3, but occasionally up to 5?)

There is an emergency response if needed to improvise another critical care bed.

In fact, the actual process (Work as done) is much more complicated. Reportedly (Barnaby), The Bed review meeting takes place at around 8:30 – 9 am each day.

At the meeting the C3PO list is presented as the indication of the number of critical care beds the surgeons will need that day. The Nurses (Ward sisters and Nursing coordinators), then have to look at their individual current beds in terms of planned discharges and expected demands from the Emergency, Internal Escalation and planned referrals from other hospitals. As these are mostly cases involving a potential threat to life, they have priority over the elective requests. As is common in sociotechnical systems the different requirements, are negotiated adaptively, and compromises agreed (ETTO's) to accommodate the expected numbers in each category. These are individual case by case and bed by bed considerations and discussions to maximise the availability against very real constraints of beds and staffing levels



Current Process

- All data are considered as disclosed at the time of the bed meeting.
- So, It is hard to make predictions because there is no data to explore probabilities.
- Instead, it has to be REACTIVE.
- New staffing and bed assignments are thus only valid at the time of meeting call.

Figure 5 - The decision making at the morning bed review meeting.

This is on the assumption that this "work as imagined" decision meeting is the last word. In reality the bed availability picture at 9 am will probably be out of date by 10! The variability and uncertainties, not just in lengths of stay in occupancy levels and the unexpected emergencies requiring admissions force a constant round of individual adjustments and awareness of both surgical, emergency and internal escalations and bed blocking. This is to ignore the unscripted possibility of a major alert or road traffic accident spike in demand. In this case inevitably the elective surgery is cancelled but for those in surgery, emergency / improvised beds are the standby.

It is also unclear where all the information / data is recorded, collated and disseminated. Presumably this is part of the HIVE database, an Electronic Patient Record (EPR) solution used by Manchester University NHS Foundation Trust (MFT) hospitals. which provides a single trust-wide hospital record for every patient, (HIVE stands for Hospital Information and Virtual Environment).

But the NHS staff seem to respond best to these unscripted pressure situations (e.g., the Arena response) and the system copes day after day. To an outside observer, it seems to be designed to throw up anomalies and discrepancies and the occasional misreading of information, or situations. This would provide an unfortunate opportunity for recrimination and retribution on the operators, rather than "blaming" the designers and regulators of such an imagined system.

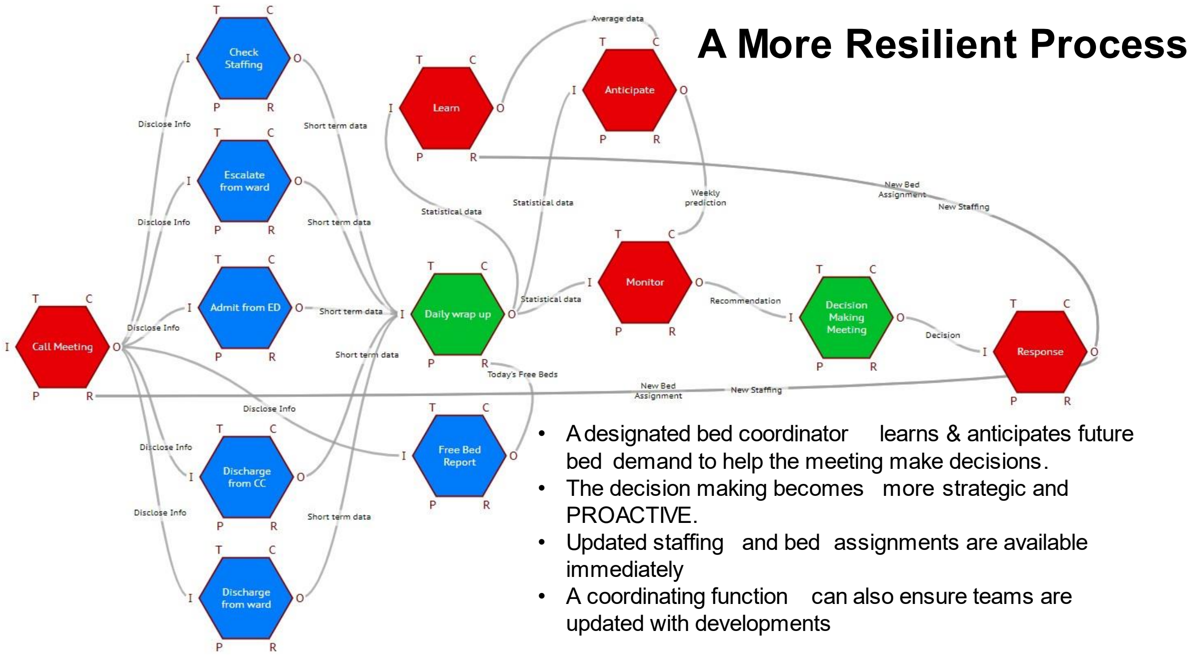
SO HOW CAN THE FRAM APPROACH HELP?

Support the decision process.

We can expand this analysis now by ensuring the FRAM includes and identifies the systemic potentials necessary for optimising and adding resilience to the model. (17) The first attempt represents the current "Work as Imagined". The system MONITORS (number of available beds) and then RESPONDS to current actual numbers to negotiate that day's assignment numbers.

But because we can now view the problem / process systemically, we can start to add Functions to improve / optimise the effectiveness of the decisions. So, to add resilience to the decision process we can now add two more Functions which can significantly help to operate the bed assignment process.

We can add a LEARNING Function (17), to uncover patterns and trends in previous system behaviour and outcomes to predict the distribution and probabilities of bed demands and supply say for that next day and a longer-term trend for forward planning. This information can then allow the decision makers to ANTICIPATE (17) daily constraints and now adjust expectations in bids and bed / staff capacities. For example, we could formalise the organisation of the available data – a bed coordinator.

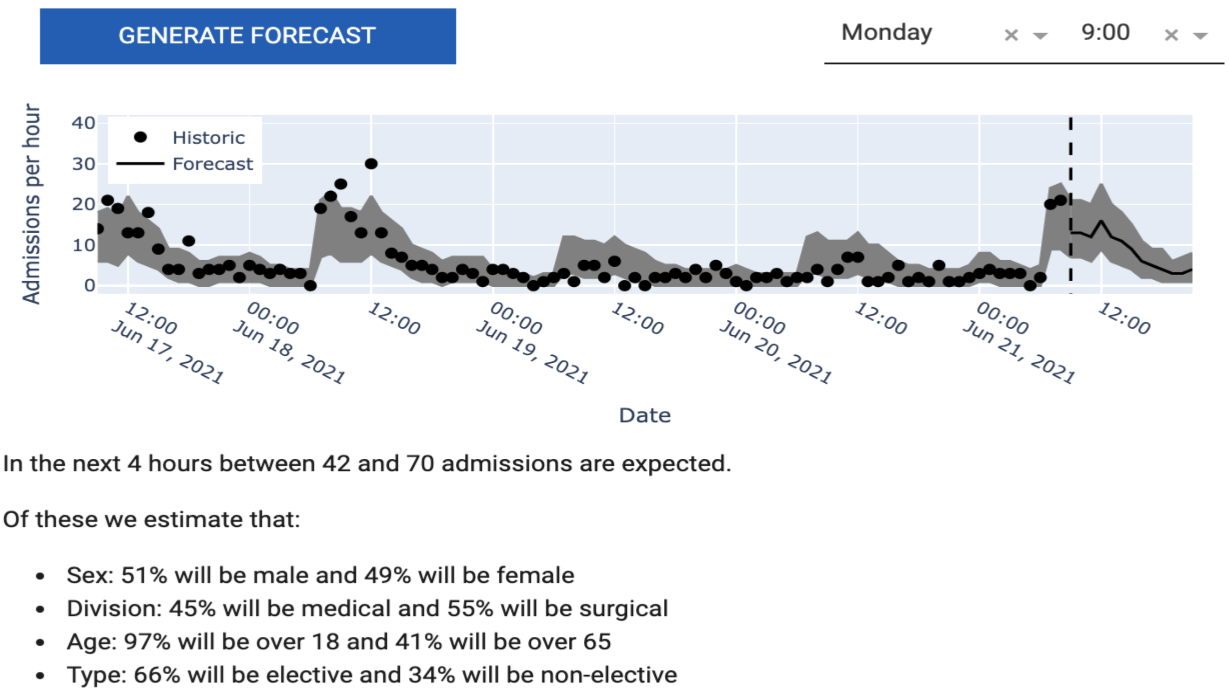


A More Resilient Process

- A designated bed coordinator learns & anticipates future bed demand to help the meeting make decisions.
- The decision making becomes more strategic and PROACTIVE.
- Updated staffing and bed assignments are available immediately
- A coordinating function can also ensure teams are updated with developments

Figure 6 – The decision making as a more resilient process.

But it is quite clear that we need to provide this feedback almost hourly to the decision makers individually with a facility to coordinate and involve all the key decision makers more frequently than once a day. A previous proposal to incorporate a facility to learn and predict demands on beds (18) was able to produce day ahead and week ahead forecast demands on an hourly basis.



In the next 4 hours between 42 and 70 admissions are expected.

Of these we estimate that:

- Sex: 51% will be male and 49% will be female
- Division: 45% will be medical and 55% will be surgical
- Age: 97% will be over 18 and 41% will be over 65
- Type: 66% will be elective and 34% will be non-elective

Figure 7 - Machine learned predictions from the Skunkworks project (15).

So, a natural step forward is to incorporate this feature to allow the bed coordinator to update and circulate these predicted demands and trends on an hourly basis. Again, presumably the HIVE database could acquire and redistribute this information. This type of data is referred to below as ML (Machine Learning).

Implementation

We now need to update our FRAM model with these LEARNING and ANTICIPATE Functions. It is proposed initially to utilise the simplified algorithms used by Nomoto, to demonstrate how this could be deployed.

For that we will need yet more Metadata Keys and Values. A suggested range is set out below.

1. Now from the ML (external database access?), we can also
   - have a predicted availability (at 6 am) from ML **Bpop1, Bccp1, Bwp1**
   - have a predicted availability for 6pm that day, **Bpop2, Bccp2, Bwp2**
   - have a longer-term forecast (7days, month?), **Bpopn, Bccpn, Bwpn**

2. So, looking at the actual requests for that day there will be the demand side requests at 6 am for the number of beds needed for that day
   - Bcc ideally needed for the elective list (C3PO) – **Bc3po**
   - Bcc needed for internal escalation – **Biea**
   - Bcc and Bw needed for overnight ED – **Beda**
   - Bcc needed for external referrals – **Bera**

3. From the ML there will be a comparable set of predicted bed demand numbers.
   - **Bc3pop, Biep, Bedp, and Bedp**
   - For 1 day, 1 week and 1 month

All of these data need to be made available from the MONITOR and LEARN Function.

From this database, the review and ANTICIPATE Function needs to estimate the delta between supply and demand in each category and suggest a response to the committee.

4. For example, the matching of the number of critical care beds **Bcca -Bc3po** - determines the possible recommendations for a C3PO response.
   - If **+ve** – (Twist) – fit in more patients,
   - If **0** (or close) - (Stick} – proceed with list, or
   - If **-ve** – (Bust) – delay patients and retriage the codes.

Or perhaps look at the probability of the likely estimated bed occupancy predictions, and decide to add patients if beds are likely to become more available, or if demand looks too high, defer further patients

5. The review meeting can then decide whether or not, to augment the bed availability with the improvised units for emergencies? **Bima** – informed by the actual staff availability – **Stla**

But these decisions can be helped by a more accurate picture of future supply and demand configurations.

6. So, with a set of longer term predicted metadata of demand, perhaps staffing levels could be rescheduled in the light of likely peaks and troughs?

Again, this way of presenting a structured view of actual and anticipated system behaviour, may give the review meeting, more confidence in their daily decisions and forward planning.

7. But looking at the FRAM, the degrees of freedom in making choices on how to respond seem to be limited, and boil down to:
   - To delay elective surgery
   - To agree extra C3PO surgeries
   - To discharge more people from the wards, or finally,
   - improvise beds and / or increase staffing levels.

From the ML and Bayesian predictions it should be possible to give the review meeting a better feel for the likelihood of effectiveness of these or other options and suggest priorities in the responses, perhaps even a – "What if?" - interrogation facility?

Finally, by continuously monitoring and updating / calibrating the ML algorithms and with the availability of data on the observed "GAP" between actual and predicted values, together with the "TRENDS" observed in the patterns of supply and demand; this will allow a more informed forecasting of future issues and allow a more strategic approach to this quintessential problem of bed availability in hospitals.

An initial attempt is shown above (Figure 7). But this needs to be further developed by:-

- Improving the FRAM with feedback and editing from the people involved (actual Work as Done"!)
  - Exploring extra degrees of freedom possible if the demand side can be predicted more accurately / sensitively?

For example,

- could we utilise the HIVE data to indicate probability of escalation and discharge numbers more accurately?
- Also are there signals from the emergency department (ED), (e.g., average waiting times?) that could better predict ED demand?

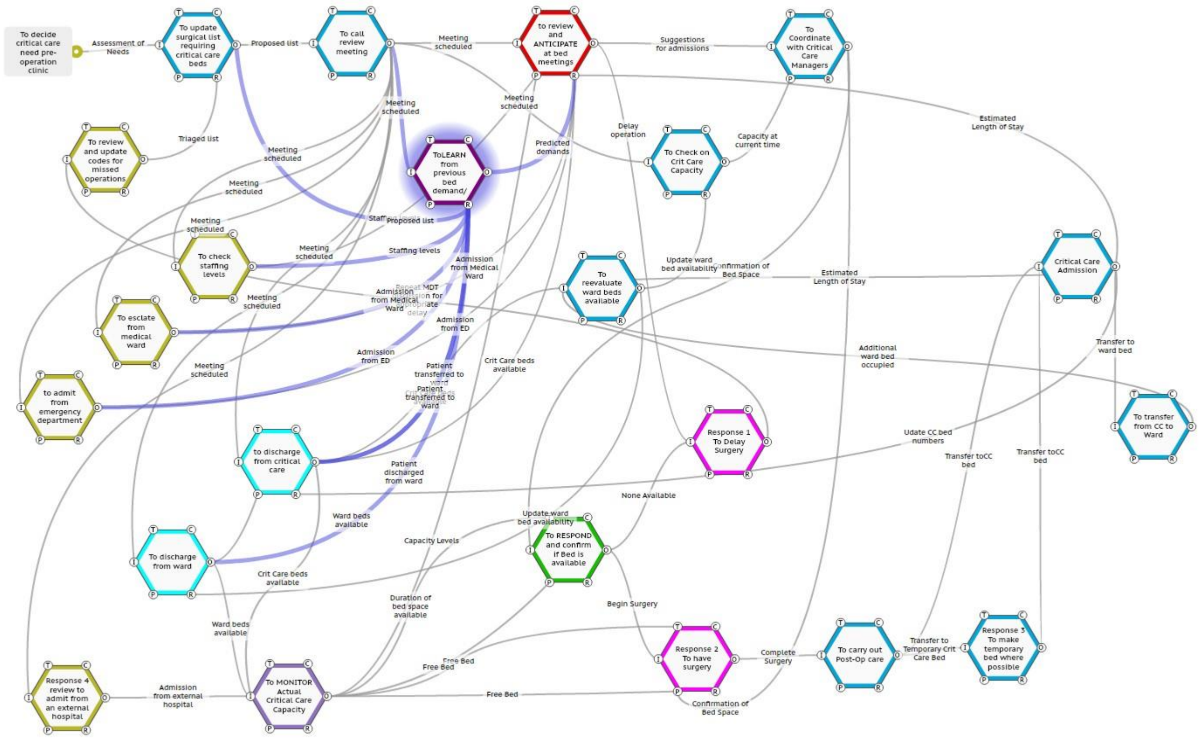


Figure 8 – The suggested decision support FRAM

Conclusion

Providing inputs help to hard pressed hospital staff with bed allocation in stressful, under-resourced conditions, from the outside, has proved difficult Previous studies have provided plenty of insights, and suggestions for solving the problems, but making practical contributions that really assist them has proved a challenge. The appropriateness and availability of the Functional Resonance Analysis Method as a way of modelling complex sociotechnical systems to better understand and optimise their operation has been identified as a more appropriate approach to be applied (in the context of methodologies that are available and can be applied currently), Accordingly, this model based system engineering approach was applied to an actual real-world system requiring taking life and death decisions on understanding and managing its operation. This paper puts forward the case that the Functional Resonance Analysis Method, with the new advances in its capabilities, is certainly worth pursuing and developing further.

The conclusion of this study therefore is that the approach suggested could provide much needed support to an increasingly stressed and stretched system. It looks as though much of the data needed is already logged routinely and available. The scheme outlined in the paper offers a way of utilising it much more effectively to better optimise the more efficient use of scarce resources.

If these conclusions are agreed, the next step should be to build and test the approach in close collaboration with the real teams and real data. If it still looks feasible, the proposal would be to build a test system to run in parallel with the "normal" system to compare, contrast and learn?

But as with all AI assisted applications it is important to realise that such a tool is only ever a decision aid! It will only enable the decision makers to make much more informed, appropriate, and safer choices.

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