

## Achieving Economy of Scale in Critical Care, Planning Information Necessary to Support the Choice of Bed Numbers

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### Authors' contributions

*This work was carried out in collaboration between both authors. Author NB designed the study. Author RPJ performed the statistical analysis, wrote the first draft of the manuscript. Author RPJ managed the literature searches. Both authors read and approved the final manuscript.*

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### ABSTRACT

**Aims:** To investigate the need for additional critical care beds, the potential for economy of scale in larger units, including ratios to support the choice of bed numbers.

**Study Design:** Time trend analysis and construction of useful ratios to assist planning.

**Place and Duration of Study:** Operational data for English NHS hospitals (2011 to 2016) obtained from NHS agencies. Analysis of critical care data at King's College Hospital from April 2013 to February 2016.

**Methodology:** Analysis of time trends and/or calculation of averages and ratios of critical care beds per total hospital beds in different categories.

**Results:** In England, demand for critical care beds is growing at around 2.6% per annum. In 2015/16, the ratio of critical care beds to total hospital beds ranges from an average of 1:5 in tertiary/specialist hospitals to a minimum of 1:50 in general hospitals. Ratio of neonatal beds to maternity beds is around 1:5. Critical care units with more than 35 beds (adult, pediatric or

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neonatal) operate at around 85% annual average occupancy. Average monthly occupancy across the whole of England correlates with total monthly cancelled urgent operations.

**Conclusion:** Smaller units require far higher levels of flexibility in staffing and will suffer the unavoidable consequences of higher costs and the knock-on effects of periods of 100% occupancy. Smaller units must become part of a larger network in order to compensate for the higher volatility in CCU demand as size reduces.

*Keywords: Critical care; bed numbers; bed occupancy; economy of scale; turn-away.*

## 1. INTRODUCTION

The King's College hospital (KCH) is a large tertiary teaching hospital situated in the Denmark Hill area of London. The hospital contains around 1,000 beds and 65 critical care beds dedicated to the treatment of general surgical and medical admissions. There are around 40 other critical care beds dedicated to more specialized tertiary care located in separate critical care units within the hospital. In early 2012 planning began for a dedicated and large adult critical care facility, designed to service parts of London and wider afield.

In the UK, critical care beds are in short supply with high average occupancies of around 80% to 85% for adult and pediatric beds, around 70% for neonatal beds [1]. At such high occupancy levels, instances of 100% occupancy are reasonably common. For example, on the last Thursday of January and December in 2015 some 22% and 14% respectively of hospitals in England were at 100% occupancy for adult critical care [1]. The December 2015 figure needs to be understood in the context that nearly all elective surgery stops over the Christmas/New Year period.

Critical care is required to support both elective surgery (especially so in the larger specialist teaching hospitals), trauma, and general medical and surgical emergency admissions. Up to the present the accepted norm has been for every hospital to have a 24/7 critical care unit (CCU). An alternative arrangement could be for some hospitals to have a work day critical care unit staffed to support elective surgery and occasional emergency surgery, while larger nearby units could deliver the remaining critical care. Or in the case of KCH, to have a single large unit rather than a series of separate CCUs dedicated to particular patients. Obviously such an approach would not apply in sparsely populated areas. This second approach largely applies to Pediatric critical care in England,

where 76% of hospitals do not have any Pediatric CCU beds, and care is concentrated in just 41 hospitals which act in a hub and spoke arrangement with the 127 other nearby acute hospitals [1].

Supporting the notion regarding the benefit of size is the observation that in the field of surgery there is a well-recognized relationship between the volume of cases and the quality of the outcome [2-4]. This is an extension of the learning curve, a relationship describing the increased speed at which a technical task can be performed as the operator gains experience [5-7]. In addition, there is economy of scale to be achieved as the size of the critical care unit increases, larger units are able to operate at higher average occupancy without the undesirable consequences of having to turn potential patients away [8-10]. Larger and well-staffed units are also more likely to attract and retain high quality staff in what is called the 'magnet' effect [11].

With factors such as these in mind, the KCH embarked on a venture to build a large adult critical care unit, which would effectively expand the existing 65 bed unit to 90 beds. The critical care consultants were keen to gain the benefits of scale, to introduce a variety of care pathways along with the process efficiency which could be afforded by a larger unit. After discussion with relevant stake-holders a business case was presented in 2012, construction commenced in 2015 with completion in mid-2017.

However, it must be admitted that there was very little information available to guide the choice of the total number of beds in this new unit, or regarding the likely average occupancy expected for the larger unit, or the potential wider effects on whole hospital efficiency. This paper therefore examines trends in CCU bed demand and CCU capacity issues in English hospitals, the role of size and average occupancy in the CCU on wider hospital operational efficiency.

Queuing theory will be used to provide a context for the level of turn-away or bed non-availability associated with the various sized CCU units operating at different levels of average occupancy [8-10].

Throughout this study the term critical care beds refer to level 2 and 3 critical care plus high dependency beds. Available beds refer to beds which are staffed. All occupancy has been measured at midnight.

## 2. MATERIALS AND METHODS

### 2.1 Data Sources

All data is from mandatory NHS data collections with associated data definitions. Information regarding available and occupied high dependency and critical care beds (Levels 2 and 3 for adult, pediatric and neonatal), along with cancelled urgent operations at NHS hospitals in England was obtained from the NHS England website in the 'Critical Care' sub-section [1]. This website includes information on data definitions. The data on this website is a snapshot taken at midnight on the last Thursday of every month. Data is available from 2010/11 to 2015/16.

Available general acute beds in 2015 for Hospitals in England were obtained from the NHS England website in the 'Bed Availability and Occupancy' sub-section [12]. The data is the average number of available beds over a full year along with annual average occupancy. Trend data is also available from 2010/11 to 2015/16.

Data on unscheduled admissions to all CCUs at KCH, and for all types of admissions (elective and unscheduled) to the surgical and medical CCU (April 2013 to February 2016) was obtained from the hospital information system. No patient identifiable features were available in these data extracts. Data on hospital mortality as the Summary Hospital-level Mortality Indicator (SHMI), which includes deaths within 30 days of discharge was obtained from the Health and Social Care Information Centre (HSCIC) website [13].

### 2.2 Methods

Total number of critical care and high dependency beds (adult + pediatric + neonatal) per total number of acute beds (adult + pediatric + maternity) was obtained by matching data from

the critical care data set and the acute beds data set [1,12]. Separate analysis was also performed on the ratio of neonatal CCU to maternity beds and on the ratio of pediatric CCU beds to occupied pediatric beds. Dates applicable to different analysis are given in each Table and Figure.

Average occupancy associated with critical care beds was determined by averaging monthly snapshot data based for units with the same number of beds. Separation between adult, pediatric or neonatal beds is not required since queuing theory indicates that the average occupancy is a function of size and not the type of occupant.

Monthly data was analyzed to determine the role of seasonality in demand, to investigate the role of average occupancy on operational efficiency. Seasonal factors for bed occupancy across England (May-11 to Feb-16) were determined using the Excel Solver function, a sophisticated simultaneous optimization technique, such that the seasonal factor for each month was determined by minimizing the sum of absolute differences between each seasonally-adjusted month in the time series. Default settings in Excel were used to run Solver.

Daily bed occupancy (midnight) at KCH was calculated using the start and end date for all CCU admissions. In this calculation the patient occupies a bed (at midnight) on the day of admission and all subsequent days, but not on the day of discharge, i.e. discharged before midnight.

## 3. RESULTS AND DISCUSSION

### 3.1 Results

#### 3.1.1 Growth in occupied critical care beds

As at May 2016 there were 3,998 adult; 1,421 neonatal, and 463 pediatric CCU beds in England servicing a population of 5 million persons (0.1 CCU beds per 1,000 persons), and around 695,000 births (2 neonatal CCU beds per 1,000 births), and 11 million children (0.04 pediatric beds per 1,000 children) [1].

Between August 2010 and February 2016 the number of occupied adult critical care beds in England grew by around 90 occupied beds per annum (2.6% per annum), while the total number of available critical care beds (adult + pediatric +

neonatal) grew by 118 beds per annum (2.5% per annum) – See Fig. A1 in the Appendix [1]. Since 2010 emergency admissions have grown by around 10% or 2.5% per annum [14-15], i.e. growth in critical care bed demand is incrementing parallel to growth in emergency admissions.

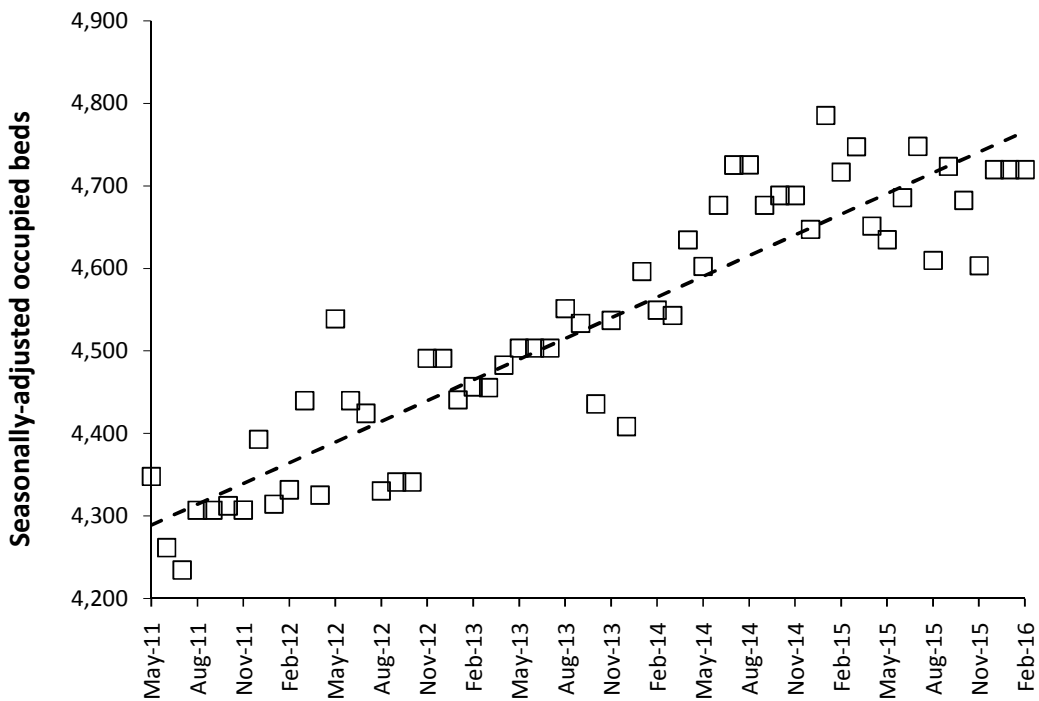
annum or around 6.4% per annum growth. Higher local growth presumably reflecting the more complex flows of non-elective and tertiary patients in London and surrounding areas, and an expansion in the general surgical and medical CCU beds occurring around February 2014 (see discussion).

Fig. 1 shows the trend for total (adult + pediatric + neonatal) critical care occupied beds after adjusting each month for the underlying seasonal profile in occupancy. Note that even after seasonal adjustment there is still wide variation in the number of occupied beds reflecting the contribution from the external environment. For example, the high number of occupied beds in Jan-15 occurred during an influenza outbreak which was possibly exaggerated by previous vaccination of the population with a poorly matched influenza antigen mix [16-19].

**3.1.2 Seasonal patterns of bed demand**

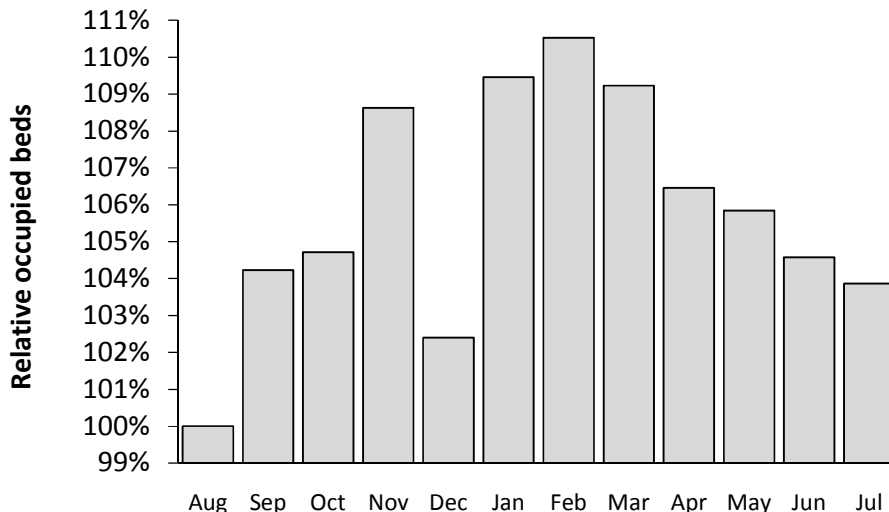
It is well known that demand for beds in the NHS is seasonal with lower elective demand typically occurring during the summer holidays (mostly August) and during the Christmas/New Year period (usually last week of December and first few days of January). Non-elective medical admissions typically peak in January and February [20]. Fig. 2 demonstrates how these respective patterns for elective and non-elective demand impact on the relative level of occupied critical care beds in England (as measured on the last Thursday of each month). As can be seen bed occupancy is typically 10% higher in February than in August, and around 9% higher in January and March.

This national growth is also reflected at KCH, and between 2011/12 and 2015/16 the total number of occupied critical care beds grew from 60.8 to 86.4, i.e. 3.9 extra occupied beds per



**Fig. 1. Monthly trend in seasonally adjusted occupied critical care beds in England, May-11 to Feb-16**

Data from <https://www.england.nhs.uk/statistics/tag/critical-care-2/>



**Fig. 2. Relative number of occupied adult critical care beds by month, England**

Data covers August 2010 to March 2015 and is from the England Time Series spreadsheet at <https://www.england.nhs.uk/statistics/statistical-work-areas/critical-care-capacity/critical-care-bed-capacity-and-urgent-operations-cancelled-2014-15-data/>

While this pattern is relatively clear using aggregate national data, the situation becomes more volatile as the total shifts from national to single hospital level. This is illustrated in Fig. A2 using daily bed occupancy data from KCH. As can be seen the size of the CCU was expanded on the 24<sup>th</sup> of February 2014 from 48 to 65 beds. Intake of patients does not stabilize until around the beginning of April, i.e. about 5 weeks after the new beds become available. As can be seen in the running 28-day average chart bed occupancy also shows a minimum in August and December although this also depends on environmental conditions (weather and infectious outbreaks) prevalent at the time, i.e. the spike on 5<sup>th</sup> of January 2015 corresponds with start of a national influenza outbreak [16].

### **3.1.3 Ratio of critical care to total beds**

The usual ratio of beds per 1,000 population is subject to variation due to the population age structure, and uncertainty regarding the exact population size serviced by a particular hospital. This study attempts to address this issue by giving the ratio of CCU beds to general acute beds. As demonstrated in Fig. 3 the range of critical care and high dependency beds per bed in 150 English NHS hospitals/hospital groups varies widely from a minimum of 2% for a range of small to large general hospitals (DGH) to a DGH maximum of around 6.3%.

Teaching hospitals range from 6% to 14.7%, while specialist hospitals can reach as high as 33% at the Liverpool Women’s Hospital and the Royal Brompton & Harefield Hospital, next highest is 22% at the Liverpool Heart & Chest Hospital. Children’s hospitals range from 9% at Sheffield to 21% at Alder Hey, and 15% at Great Ormond Street. There is clearly a degree of latitude in the proportion of critical care beds, which will partly depend on the range of tertiary activities, the mix of elective and emergency activities and financial pressures.

### **3.1.4 Adult, pediatric and neonatal**

While the ratio of CCU beds per total beds is useful, the ratio is highly likely to vary between adult/pediatric/neonatal patients. Table 1 therefore presents the ratio of CCU beds per total beds split by adult, pediatric and neonatal patient types for all NHS hospitals in England in 2014/15.

Neonatal CCU beds have been set against maternity beds since births are the primary driving force behind neonatal CCU bed demand. The ratio is presented in two ways as either against available or occupied beds. The difference in the ratios between available and occupied beds is determined by the occupancy level in the larger total bed pool and the CCU occupancy. Note that occupied beds are

determined at midnight. There is no direct count of available pediatric beds however this was estimated from a count of occupied pediatric beds assuming 70% occupancy.

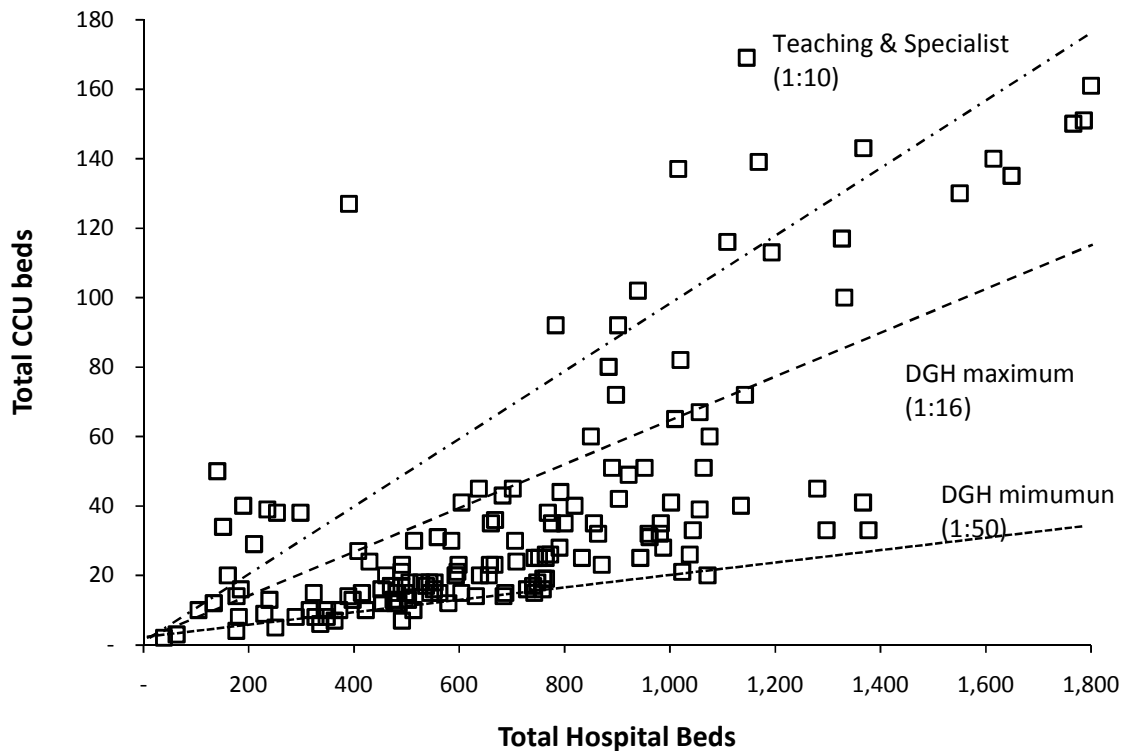
Due to the preponderance of adult beds, and the absence of pediatric intensive care beds in 76% of hospitals the situation for adult critical care beds is very similar to Fig. 3.

There are five dedicated Pediatric hospitals in England with a combined total of 1,150 beds. Table 1 has presented the ratio of pediatric intensive care beds per occupied pediatric bed in English Hospitals. Available pediatric beds are not counted as a separate entity so in this case the ratio has been estimated using reported data on occupied pediatric beds covering a range of pediatric specialties from general pediatrics' through to different types of pediatric surgery. As mentioned some 76% of general hospitals have no pediatric intensive care beds, and hence many of the larger teaching hospitals such as Imperial College or Central Manchester have a ratio of 47%, Alder Hey Children's Hospital 50%, and Great Ormond Street 96%. The England

average is 1:13 or 7.6% per occupied bed. Average occupancy in the larger pediatric hospitals is around 75% although there is considerable variation between hospitals.

**3.1.5 Growth in the ratio of CCU to total beds**

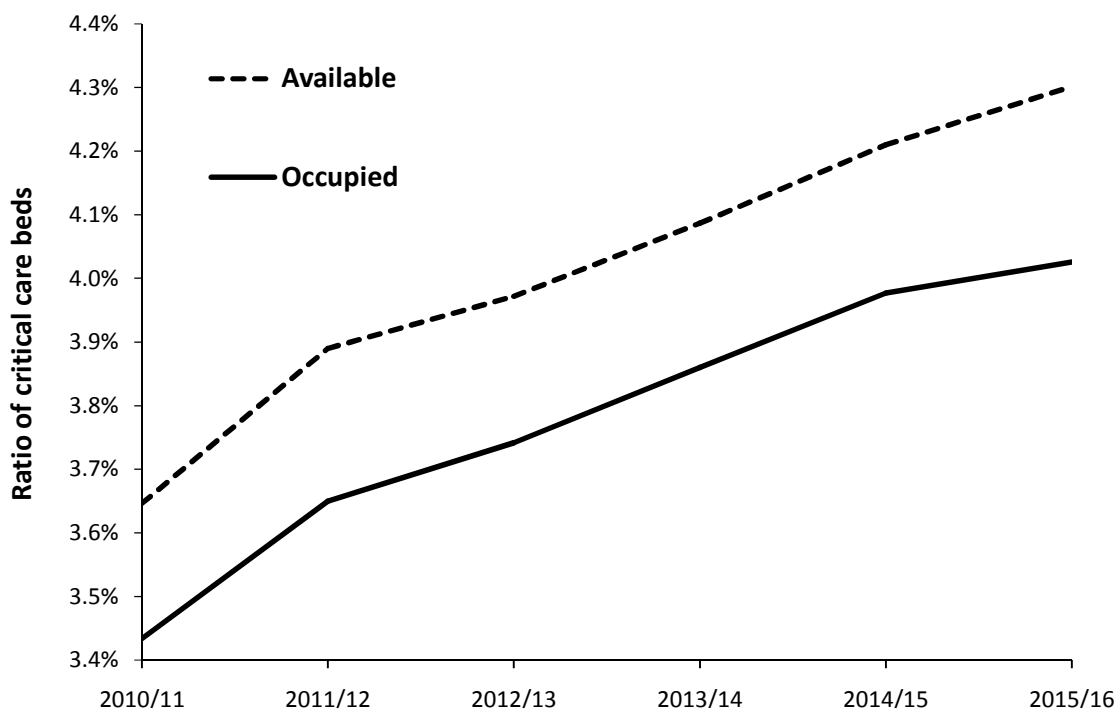
Given that improvements in health care have led to an increase in life expectancy, along with higher levels of multi-morbidity [15,21], it would be expected that the ratio of critical care beds to total inpatient beds may be increasing over time. This possibility is implied by Fig. 1, however, this trend can be derived for England over the period 2010/11 to 2015/16 when both CCU and total bed data are both available. Due to the fact that pediatric beds are not counted separately, the ratio can be determined by adding pediatric and adult CCU beds and dividing by total 'general and acute' bed numbers (available/occupied). The results of this comparison are presented in Fig. 4, where it can be seen that the ratio of available CCU to available total or occupied CCU to occupied total is indeed increasing over time, although the rate of increase in the ratio appears to be declining with time.



**Fig. 3. Ratio of total critical care (CCU) beds to total hospital beds for English hospitals**

**Table 1. Ratio of CCU (available/occupied) beds per total beds (available/occupied) dedicated to adult, pediatric or maternity/neonatal patients for all English NHS hospitals (2014/15)**

Type	Total beds		Critical care beds		Ratio CCU: Total	
	Available	Occupied	Available	Occupied	Available	Occupied
Adult	98,153	88,580	3,967	3,357	4.0%	3.8%
Pediatric	6,500	4,548	439	346	6.7%	7.6%
Maternity/Neonate	7,804	4,572	1,377	992	17.6%	21.7%



**Fig. 4. Ratio of CCU to total beds in England, 2010/11 to 2015/16**

The slope of the ‘available’ line in Fig. 4 is increasing faster than the ‘occupied’ line due to the fact that total available beds in England are being closed in an attempt to contain rising acute costs, while the number of occupied beds *per se* is not decreasing over time [22-24].

[8-10], and units above 35 beds operate around 85% occupancy. It is only around a size of 60 beds that units are able to operate at 3% turn-away or less. Turn-away implies that a bed is not immediately available and so the patient must either:

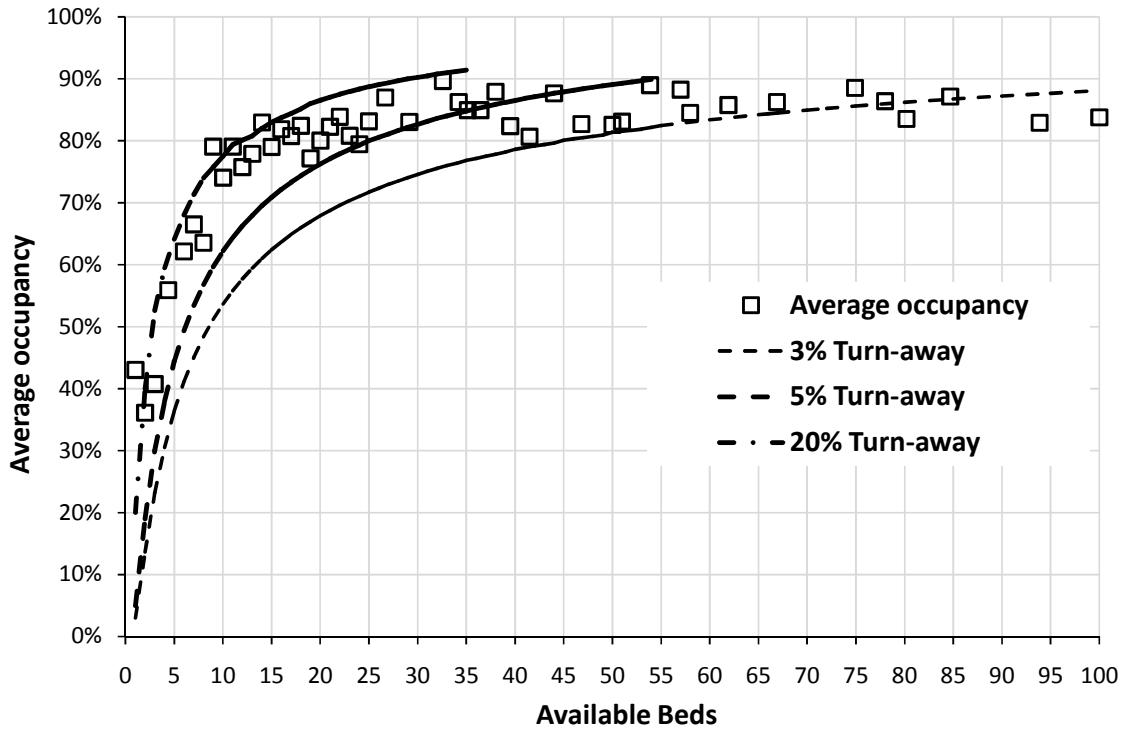
**3.1.6 Average occupancy and size**

Fig. 5 examines the average occupancy in English CCUs over a one-year period in 2015.

Some 2,700 occupancy measurements were made at midnight on the last Thursday of each month for adult, pediatric and neonatal units. In order to turn these point measurements into an approximate average occupancy, units of similar size were then grouped and the average occupancy calculated. As can be seen smaller units all operate above the 3% turn-away line calculated from queuing theory using Erlang-B

- Wait until one becomes free.
- Be transferred to another CCU.
- Another CCU patient must be prematurely discharged to allow entry to the waiting patient.
- An impending elective operation (requiring CCU care post-surgery) will be cancelled.
- The threshold to entry is raised to the point where supply and demand are matched.

As can be seen in Fig. 5 typical average occupancy in units with fewer than 35 beds are associated with turn-away levels of up to 20%.



**Fig. 5. Average occupancy versus number of available beds in English CCU (adult, paediatric and neonatal) in 2015**

In theory, up to 88% average occupancy is achievable at 100 beds [8-10], however this is in the absence of any seasonal profiles as noted in Figs. 2 and A2. Somewhere around 85% (annual average) therefore appears to be an achievable benchmark for the larger 100 bed unit at KCH, and attempts to push occupancy above this level would result in escalating turn-away.

**3.1.7 Average occupancy and cancelled urgent operations**

As average occupancy increases, so too does the proportion of time when a bed is not immediately available for the next prospective patient. Fig. A3 demonstrates this relationship between CCU occupancy and the level of cancelled urgent operations using monthly data for the whole of England, while Fig. A4 shows the relationship for adult CCUs having more than 50 beds. An 'urgent' operation is classified as being potentially life threatening or having serious consequences if delayed. Operational efficiency and patient safety is clearly hindered as CCU average occupancy increases both on a national level and for individual hospitals – even for those hospitals having a large CCU.

**3.2 Discussion**

The UK National Health Service provides both primary and secondary medical care which is free of charge to all UK residents. In theory, patients are free to receive outpatient and inpatient care at any hospital in the UK, but in practice most receive care from the hospital nearest to their home address. Due to high population density in England the average distance travelled for an emergency admission is only 16.1 km (13.9 km in urban areas), while only 10% of patients travel further than 23.6 km [25]. While most emergency care is delivered via the closest hospital to the patient's home address around 15% of emergency care is delivered by other hospitals due to the patient being away from home due to work, holidays or recreation at the time they require such care. In addition, large tertiary hospitals such as KCH also receive critically ill patients via transfers from other hospitals.

Funding is via general taxation and is set by parliament as part of the annual budget. In 2012 total NHS funding was set at 9.4% of GDP which is well below US expenditure and lower than



OECD or European Union average [26]. Capital expenditure is tightly regulated, and the UK therefore has a very low ratio of beds per head of population [27]. In addition, very high population density and small size compared with the US [28] allows the average hospital size to be in excess of 600 beds [12], compared to an average around 100 in the US [29]. While all NHS hospitals are effectively state-funded, they are run as 'independent' NHS Trusts with the management given freedom to set bed numbers and staffing levels – within a national framework of targets relating to waiting time for outpatient appointments and time spent in the emergency department. These targets are set by government and implemented by NHS England. There are no specific targets for CCU bed numbers, other than via an indirect effect upon whole-hospital mortality if CCU bed numbers were to fall dramatically short requirements [30,31].

It is worth noting that the rate of growth in both CCU bed numbers and emergency medical admissions is well above that implied by demographic change [15,21]. This is seemingly due to larger than expected growth in a number of conditions associated with multi-morbidity in the elderly [21], i.e. patient complexity/acuity is increasing, and this was reflected in the growth in the ratio of CCU to total beds in England seen in Fig. 4.

As was demonstrated in Fig. 3 the ratio of critical care and high dependency beds covering adult, pediatric and neonatal patients to total acute beds in the UK ranges from a minimum of 2% in a number of DGH to an average of 10% in Teaching & Specialist hospitals. A recent like-for-like study on critical and intermediate care beds in Europe identified an average ratio of 2.8% (range 5.1% in Germany to 1.3% in the Czech Republic) [32]. In that study the UK was ranked in the middle of the 31 countries studied, although the UK ranked as the 8th lowest country in terms of number of critical care beds per head of population. Germany had 4.4-times the number of critical and intermediate care beds per capita than the UK. There was a weak association between GDP and total critical and intermediate care beds [32], indicating that relative health care austerity plays a role in CCU bed numbers.

Hence by UK standards, current critical care beds at KCH (10%) are roughly average for a large teaching hospital, but are lower than the

upper limit and probably lower than the equivalent in half of European countries. The planned expansion in beds is probably needed, as per the trends in CCU occupied beds in Figs. 1 and A1 (and the higher local growth experienced at KCH), and will almost certainly afford increased operational efficiency.

The application of queuing theory into understanding hospital operational performance was appreciated by a number of early researchers. In 1987 queuing theory was advocated to aid in psychiatric hospital bed availability calculations [33], while in 1995 its utility was demonstrated in the critical care setting [34]. Several reviews have presented queuing theory for non-mathematicians [8-10], and it effectively explains why smaller units cost more to run [10], i.e. the issue of economy of scale. The larger the unit the higher the average occupancy before beds are unavailable for the next prospective patient. Indeed, queuing theory allows average occupancy to be calculated in adult, pediatric and neonatal units irrespective of the type of patient, simply because the average occupancy is highly dependent on the number of beds or the size of the CCU.

Hence the lines of turn-away in Fig. 5 are a useful aid to visualize the adverse effects of inappropriate average occupancy in the context of the size of the CCU. However, Fig. 5 also begs the question as to how so many CCUs in England operate around 85% average occupancy. The answer to this question lies in the range of *tolerable* turn-away before the service becomes unsuited to patient care. Hence in the context of the English NHS with its particular capital and operational cost constraints, a level of turn-away between 3% and 5% appears to be tolerable [20,35], which may not be considered tolerable in places such as Germany or the US. Indeed, a roughly similar range appears to apply to mental hospitals [35], although routinely exceeded in England due to poor funding of mental health services.

As was demonstrated in Figs. A3 and A4 high occupancy in general leads to the deleterious consequences of turn-way as cancelled urgent operations and general queues to admission such as patients stacking in the emergency department [36], unplanned discharges from the CCU [37], and cancelled elective operations [38]. Indeed, too few critical care beds leave any health care system open to shock demand due to influenza and other infectious outbreaks [39].

This was amply demonstrated in Figs. 1 and A2 where an influenza outbreak in January of 2015 led to the highest ever number of occupied critical care beds in England.

Finally, as a unit gets larger the volatility associated with the arriving demand reduces due to the effect of size in Poisson statistics (the basis of queuing theory). By way of explanation, in Poisson statistics the standard deviation associated with the arrival rate is, by definition, equal to the square root of the average arrival rate. Hence the volatility in demand (and the proportion of times at 100% occupancy) rapidly diminishes as size increases. Larger units can therefore minimize staffing costs by flexing staff levels to match seasonal demand (as in Fig. 2), and daily demand (as in Fig. A2). This will hopefully minimize unhelpful intervention by management relating to bed closures [40].

Regarding the increase in general surgical and medical critical care beds at the KCH in February 2014 from 47 to 65 beds it is of interest to note that the average length of stay in the unit increased from  $7.0 \pm 0.4$  (95% confidence interval, standard error of the mean) to  $7.8 \pm 0.3$  days (data not shown). It is possible that this increase arose from fewer premature discharges from the unit due to the poor availability of beds before the expansion in bed numbers. Given the higher proportion of critical care patients who die, the increase in critical care beds was associated with a small change in total hospital mortality as measured by the Summary Hospital-level Mortality Indicator (SHMI), which includes deaths within 30 days of discharge, from 90.2% for the 12 month ending March 2014 to 89.8% for the 12 months ending March 2015, however this change was not statistically significant [13].

At this point it is worth noting that a study of high-risk general surgical admissions in England between 2000 and 2009 established that lower whole-hospital mortality was associated with a 50% higher ratio of CCU beds per 1000 hospital beds (low versus high mortality outlier hospitals) [31].

The increase in average length of stay at KCH noted above is significant. Hospital administrators generally consider lower length of stay an indicator of efficiency; however, it can also be a sign of a distressed hospital or health care system [29]. Length of stay comparisons

between CCUs can therefore be of questionable value unless placed in the correct context.

Some comments are required regarding the options available to smaller hospitals. The ratios presented in Table 1 are the result of a policy decision in England to run pediatric and neonatal critical care in networks. Hospitals in the spokes have a minimum number of CCU beds which are supplemented by a larger hub bed pool at the teaching/specialist hospital at the hub. This is especially the case for pediatric intensive care. This hub and spoke system mimics the benefits of economy of scale in that beds in each hub and spoke system can run at the higher occupancy of the entire system. In the US this can be replicated within chains of hospitals under common ownership, however, the far larger distances in rural USA and the generally smaller hospitals supporting these rural communities do present unique difficulties.

Due to increasing demand (as per Fig. 1), in February of 2014 the size of the existing surgical/medical CCU was expanded from 47 to 65 beds. One of the major contributors was the need to keep pace with expanding tertiary elective operations and emergency admissions, with consequent CCU aftercare. As was demonstrated in Fig. A2 this expansion led to the inflow of additional patients from a number of areas as both emergency and elective flows expanded. Given an overall relative under-supply of critical care beds in England a similar situation is expected in mid-2017 as the new unit opens and staffing levels are expanded to match the increased arrivals. Should the new general surgical and medical CCU not achieve the expected inflow of patients the KCH is in the somewhat enviable position of being able to move one or more of the specialist CCUs to become part of the larger unit, thereby freeing space for more general acute beds.

As a final point, the issue of suppressed demand is clearly implied in Figs. 1 and 4, and in the increase in LOS following the previous expansion of beds at KCH. Discussion with one Chief Executive of a large acute hospital lying on the 1:50 line in Fig. 3 showed that they were aware that this was sub-optimal provision, however, their local Clinical Commissioning Group was unwilling to fund any extra CCU beds. A somewhat common issue in the English NHS with its unique set of capital and revenue constraints. Indeed, a comparison between Figs. 1 and A1 shows that Fig. A1 exhibits higher

scatter due to step-like increases in available beds, i.e. growth in occupied beds continues to the point that turn-away rises to an unacceptable level and hospitals are forced to increase available bed numbers in a retrospective rather than prospective manner.

This study has several limitations. Firstly, the effect of deprivation on CCU bed demand has not been studied. Several studies have shown that hospital and CCU mortality is around 20% higher in the most deprived quintile [31,41], and by extension it can be assumed that the ratio of CCU beds to total beds may need to be higher in more deprived communities. It is also recognized that different hospitals operate at different average occupancy due to size and complexity [8,9], and for this reason Table 1 and Fig. 4 gave values for the ratio of CCU to total beds calculated based on total or occupied beds. Other limitations relating to the English NHS have already been discussed.

#### 4. CONCLUSION

As in any process, economy of scale can be achieved in critical care provided there is sufficient local demand (as in large and densely populated cities), or where there is sufficient scope for a hub and spoke arrangement. Average annual occupancy of around 85% can be achieved along with a reduction in the undesirable effects of turn-away such as premature discharge from the CCU, delays to admission from the emergency department, a reduction in cancelled urgent and routine elective surgery. Planning guidelines have been provided for the ratio of CCU beds to total (available or occupied) beds.

It would be highly desirable to have the equivalent to Fig. 3 and/or Table 1 available from a variety of other countries to arrive at some consensus on the ratio of critical care beds per total hospital beds – with England being an example of provision in a highly capital and operating cost constrained environment. The suspicion is that the USA would form the other extreme due to high levels of futile CCU intervention toward the end of life [42-45].

Finally, the results of Fig. 4 clearly show that international comparisons need to be conducted at the same point in time, and that the 'optimum' ratio of CCU beds varies with the age

structure and relative deprivation of the population.

#### CONSENT

It is not applicable.

#### ETHICAL APPROVAL

It is not applicable.

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

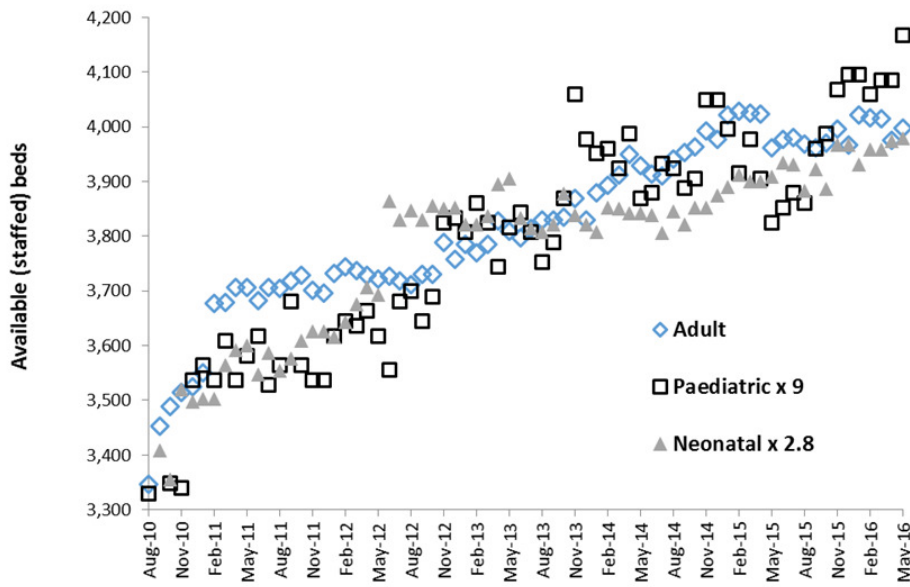
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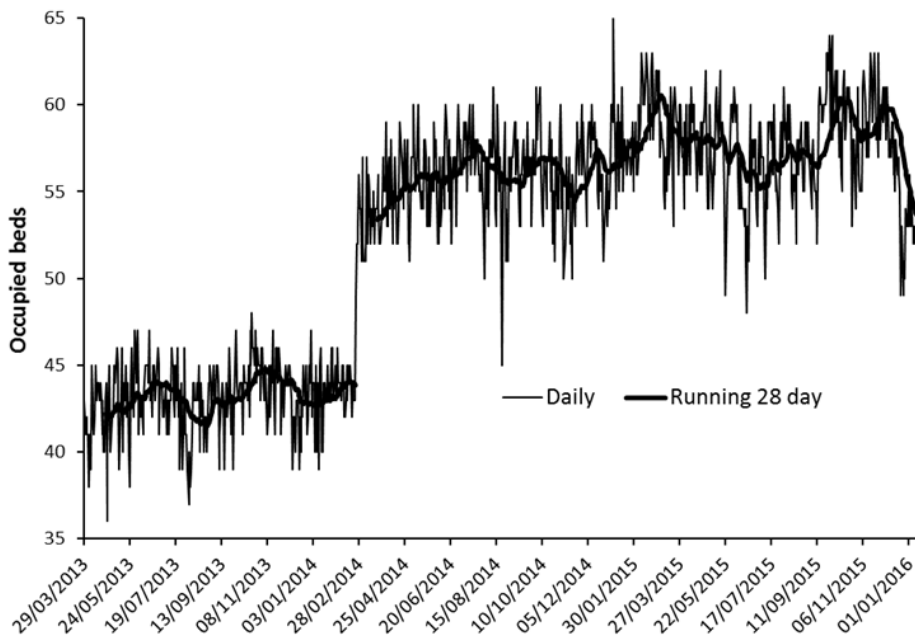
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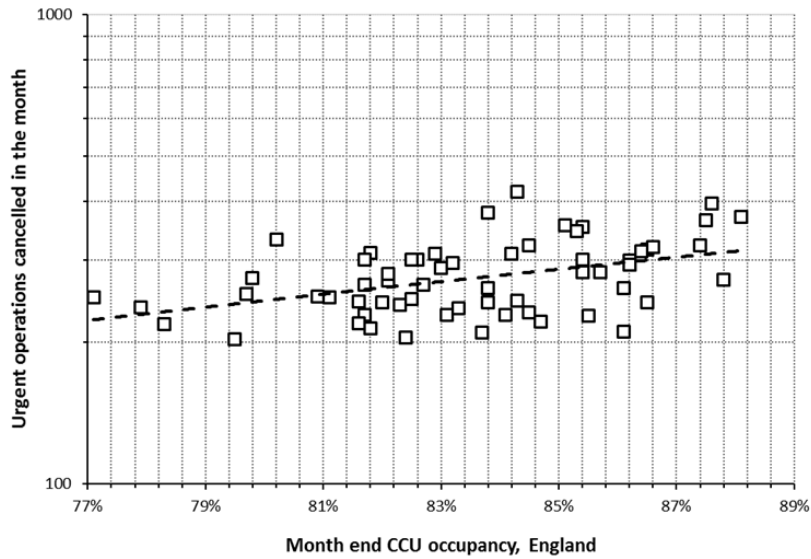
**APPENDIX**



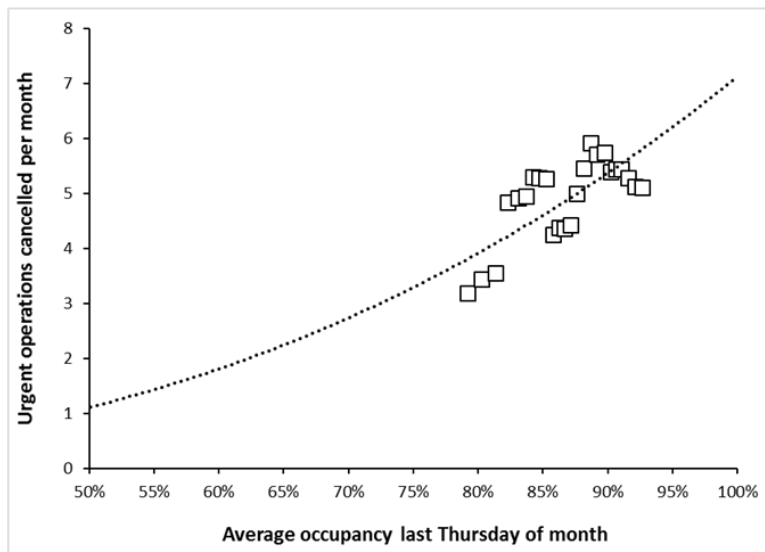
**Fig. A1. Growth in available (staffed) CCU beds in England. Paediatric (x 9) and neonatal (x 2.8) bed numbers have been factored up to adult-equivalent numbers**



**Fig. A2. Daily and running 28-day average (midnight) occupancy at KCH**



**Fig. A3. Monthly cancelled urgent operations and average adult critical care occupancy, England (November 2010 to February 2016)**  
*The Y-axis is a log scale*



**Fig. A4. Cancelled urgent operations and average month end occupancy in English CCU (adult) with more than 50 beds**

*Each data point is a running average of 25 data points from 16 hospitals each with three data points during April-June 2015, with data ranked by average month end occupancy*

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