

# DEVELOPING AND EVALUATING AN AUTOMATED BED ASSIGNMENT ALGORITHM IN A TERTIARY HOSPITAL: A CASE STUDY IN SINGAPORE

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## ABSTRACT

### OBJECTIVES

The primary aim of this quality improvement project was to develop, implement and evaluate an automated bed assignment algorithm (ABAA) which can offer objective and consistent bed assignment recommendations that comply with the unique operational constraints and prioritization rules of a tertiary hospital in Singapore.

### METHODS

Using the classical process improvement framework of Plan-Do-Study-Act (PDSA), the quality circle workgroup first developed and tested the ABAA prototype to confirm its feasibility and reliability to meet all hospital operational constraints and prioritization rules. PDSA framework was then also employed in the user interface design and integration of ABAA into existing system setup. The staff satisfaction level of the ABAA was subsequently assessed via an anonymized online survey.

### RESULTS

In the prototype development phase, the workgroup was able to conclude after nine rounds of review meetings that the ABAA prototype was able to perform bed assignments like hospital staff using data in 64 operational scenarios. Among the 10 eligible staff who completed the online survey, up to 90% of them reported that ABAA was able to generate bed assignment recommendations which met the hospital operational requirements. 90% of these staff also reported that ABAA was easy to use and navigate, while all respondents reported using ABAA before attempting to assign beds manually. 80% of staff felt ABAA was able to reduce human error, while 50% of staff felt ABAA had reduced their time taken for bed assignments by 30 minutes to 2 hours per shift.

### CONCLUSIONS

Evidently, the user-centric design of ABAA has enabled its high adoption and acceptance rate among staff. Overall, it has allowed the staff to make faster, consistent and objective bed assignment decisions which complied with hospital operational constraints and prioritization rules so that newly admitted patients received the most appropriate care at their point of admission.

### KEYWORDS

decision support, bed assignment, heuristic.

## INTRODUCTION

Ensuring timely patient care in the right location with the right clinical team is paramount in any acute hospital so that patients are not at risk receiving suboptimal care and potential harm. Inevitably, bed management is an important function of acute hospital since it has downstream impact [1] on patient care, patient flow, patient and staff satisfaction. A key challenge in bed management is optimizing the bed-assignment process in a complex and dynamic operating environment. To ensure patients are sited at the right locations with the right clinical teams, bed assignment decisions need to take into consideration of multiple factors relating to patients and bed resources. A patient bed assignment problem (PBAP) in a hospital entails assignment of available inpatient beds to newly admitted patients in the hospital with multiple goals in mind. These goals may include minimization of internal movements among patients and staff to optimize patient care and maximization of hospital bed utilization according to the patients' [2] acuity levels. Operational constraints which typically need to be accounted for in a PBAP include patients' gender, clinical needs and choice of bed class.

Due to its underlying complexity, the best solution to a PBAP is difficult and laborious to determine if it is addressed manually by hospital staff. Empirical evidence [3] has reported that human intuitive judgment and decision making can be far from optimal, and that they deteriorate in complex and (or) stressful situations. Clearly, hospital bed assignment practices that entail manual searches and manual interventions for bed assignments are prone to human errors and result in suboptimal care for patients.

Public hospital bed management in Singapore is characterized by a proactive and coordinated approach, leveraging technology, data, and community care services to optimize bed utilization, improve patient flow, and ensure timely access to healthcare services for the population. One key aspect of bed management among public hospitals in Singapore is adopting of IT systems that allow hospitals to share patient information, including bed availability, in real-time internally. This enables hospitals to coordinate and optimize the utilization of beds across the system, ensuring that patients are admitted to the most appropriate facility based on their medical condition and urgency of care, rather than their physical location within the hospital. This allows hospitals to flexibly manage bed

capacity and ensure that patients receive appropriate care in a timely manner, even during peak periods of high demand.

Overall, the Ministry of Health (MOH) in Singapore is responsible for overseeing and regulating the allocation and utilization of more than 9,500 hospital beds in the public healthcare sector. MOH conducts regular reviews of hospital bed capacity and utilization to ensure that resources are allocated optimally across the public healthcare system. This includes monitoring bed occupancy rates, patient flow, and admission patterns, and making adjustments as necessary to ensure that hospitals are operating efficiently and effectively. Overall, the public hospital bed management by MOH has helped Singapore achieve high standards of healthcare delivery and outcomes, with relatively short waiting times for hospital beds and efficient patient flow across the healthcare system. Over the years, public hospital bed demand in Singapore has been rising due to the duo effect of ageing population and post-pandemic where more patients with more complex needs are admitted to inpatient wards with longer length of stay [4]. To cope with this rising demand, the island state has not only made plan to build more tertiary hospitals. It has also been actively developing a network [5] of patient care outside of acute hospitals to mitigate the hospital bed demand in the coming years. Such network includes step-down care facilities, community hospitals and nursing homes, caregivers who can take care of patients at homes as well as community based programmes such as Healthier SG which aim to keep the resident population healthy [6].

Changi General Hospital (CGH) is a public hospital in Singapore with over 1,000 beds; it serves a community of 1.4 million people in the eastern part of the island state. In CGH, hospital beds are broadly classified in 4 dimensions, namely bed type, clinical specialty, class, and gender. Based on these bed classifications, and together with the account of patient acuity, current bed waiting time of patient, and patient's preferred choice of class, the PBAP in CGH has to account for the constraints listed in Table 1 before any bed assignment is performed by the Bed Management Unit (BMU) staff. A newly admitted patient cannot be assigned to an available bed if another bed of higher priority (in terms of clinical specialty and/or class) is available for the same patient.

It is a major operational challenge for BMU staff to apply all relevant prioritization rules (see Tables 2 and 3) consistently

when BMU staff can be placed under stressful conditions whenever there is a surge in bed demand and a lack of available beds for assignments. Unfortunately, none of the approaches reported in the existing literature which aim to address PBAPs can be readily adopted in CGH. A quality circle [7] team was thus formed to embark on this quality improvement initiative which has two primary aims.

- Develop an automated bed assignment algorithm (ABAA) which can offer bed assignment

recommendations that comply with the unique operational constraints and prioritization rules of the CGH PBAP

- Integrate the abovementioned algorithm into existing CGH BMS so that BMU staff can operate the tool in the existing system using real-time hospital data on bed requests and statuses of beds in service.

**TABLE 1: OPERATING CONSTRAINTS WHICH BMU STAFF NEED TO CONSIDER IN ADDRESSING PBAP IN CGH**

Constraint	Description
Bed type	Patients with Vancomycin-resistant Enterococcus (VRE) are only to be assigned to either beds which are designated for such patients or to single-bed rooms in general wards. Patients with Methicillin-resistant Staphylococcus aureus (MRSA) are only to be assigned to either beds which are designated for such patients or to beds in general wards where other patients with MRSA are grouped together in proximity and are adequately distanced from other beds occupied by patients without MRSA and open wounds.
Clinical Specialty	All patients who require inpatient admission will be assigned to one of the nine broad clinical specialties in CGH. Similarly, all beds in CGH which are under BMU's purview in the PBAP, are categorized into one of the aforementioned nine clinical specialties. There is a matrix of bed assignment prioritization rules which BMU staff need to adhere to as shown in Table 2 and Table 3 based on clinical specialties and preferred choice of bed classes by patients.
Class	All newly admitted patients to CGH are allowed to indicate their preferred choice of class (i.e. four options: A, B1, B2, C) of beds which will determine the amount of government subsidies (if any) after accounting for the patients' eligibilities. Similarly, all CGH inpatient beds which are under BMU's purview are categorized into these four classes and there is a matrix of bed assignment prioritization rules which BMU staff need to adhere to as shown in Table 3 based on bed classes.
Gender	All beds in in a CGH ward cubicle or room are to be reserved to either female or male patients only. This means that if a current ward cubicle or room is occupied by at least one patient of a particular gender, only patients of the same gender can be assigned to an available bed in the same cubicle or room.
Patient Acuity	Every CGH Accident and Emergency (A&E) patient who requires inpatient admission will be assigned to an acuity level (one to five) based on patient's acuity assessed by the A&E physicians. Available beds will be assigned to patients based on the following descending prioritization:

	<ol style="list-style-type: none"> <li>1. Patients at acuity level of 1 or 2</li> <li>2. Patients with bed waiting time of <math>\geq 16</math> hours</li> <li>3. Patients at acuity level of 3 to 5</li> </ol>
Bed waiting time	Bed waiting time is defined as the duration between an A&E physician decides to admit an A&E patient till the instant when the patient has occupied a bed in the ward. Waiting time is considered together with patient acuity in prioritization of available beds to patients who are waiting to be assigned with beds (see above).

**TABLE 2: PRIORITIZATION OF BED ASSIGNMENTS TO PATIENTS BASED ON CLINICAL SPECIALTIES**

		Clinical Specialty of Bed Assigned								
		CVM	GAS	GRM	MED	OTO	PSY	RES	RMD	SUR
Clinical Specialty of Bed Requested	CVM	1	2		2	3		2		3
	GAS	2	1		1	3		1		3
	GRM	3	2	1	2	3		2		3
	MED	2	1		1	3		1		3
	OTO	3	3		3	1		3		2
	PSY	3	2		2	3	1	2		3
	RES	2	1		1	3		1		3
	RMD	3	2		2	3		2	1	3
	SUR	3	3		3	2		3		1

Numbers in the cells refer to the priority levels (1 to 3 in decreasing order) of bed assignments with reference to the clinical specialty of bed requested. Cells with white and blue background are bed assignment combinations which are considered by BMU staff only when there is bed-crunch situation while those with black background are prohibited bed assignments at all times. In non-bed-crunch situation, BMU staff will consider only bed assignments which correspond to cells with white background. Note that bed-crunch situation is defined based on hospital-imposed threshold on bed occupancy rate.

Abbreviation: CVM = cardiovascular medicine; GAS = gastroenterology; GRM = Geriatric Medicine; MED = general medicine, OTO = orthopedic; PSY = psychiatric medicine; RES = respiratory; RMD = rehabilitation; SUR = general surgery

**TABLE 3: PRIORITIZATION OF BED ASSIGNMENTS TO PATIENTS BASED ON BED CLASSES**

		Class of Bed Assigned			
		A1	B1	B2	C
Class of Bed Requested	A	1	2		
	B1*	2	1		
	B2		3	1	2
	C		3	2	1

Numbers in the cells refer to the priority levels (1 to 3 in decreasing order) of bed assignments with reference to the clinical specialty of bed requested. Cells with white and blue background are bed assignment combinations which are considered by

BMU staff only when there is bed-crunch situation while those with black background are prohibited bed assignments at all times. In non-bed-crunch situation, BMU staff will consider only bed assignments which correspond to cells with white background. Note that bed-crunch situation is defined based on hospital-imposed threshold on bed occupancy rate.

\*Only B1 CVM patients can be assigned to B2 CVM beds when there is not enough B1 beds for CVM patients who request for such beds.

Abbreviation: A = air-conditioned single room; B1 = air-conditioned 4-bedded room; B2 = natural ventilated 4-6 bedded room; C = natural ventilated 8-bedded open ward

## METHODS

Using the classical process improvement framework of Plan-Do-Study-Act (PDSA) [8], the quality circle workgroup developed a ABAA prototype which could meet all hospital operational constraints and prioritization rules prior. PDSA framework was then also employed in the integration of ABAA into existing hospital BMS to realize manpower productivity gain via the adoption of the ABAA operationally. After ABAA was rolled-out at the hospital, the staff satisfaction level with ABAA was then assessed using an anonymized online survey in the post-implementation evaluation exercise. Staff participation in this online survey was entirely voluntary and no identifiable information of study participants were collected. The set of questions in this survey and their respective purposes are listed in Appendix A.

### DEVELOPMENT OF ABAA PROTOTYPE

The PDSA framework in this phase entailed planning for the algorithm to be tested; doing or developing the algorithm prototype; studying the operational validity of this algorithm prototype; acting to plan the next change cycle or full implementation. In the "Plan" phase, the team first performed a literature review of publications on PBAPs and assessed if any of the published solution frameworks could be adopted and adapted to address the PBAP in CGH. On the whole, PBAP has received a fair amount of attention in the literature [9-14] with the aim of reducing reliance on hospital staff to address it manually. The PBAPs in these studies can be characterized in terms of the operating constraints (e.g., gender policies, mandatory equipment, preferred equipment, age policies, etc.) being considered, whether these constraints are hard or soft, whether these PBAPs are solved offline or online and the techniques adopted to solve these problems. Techniques which have been reported include solving PBAP as a mixed-integer

linear programming (ILP) model [2] or using a heuristic which is based on solving a sequence of hierarchical optimization subproblems [15] or autonomous bat algorithm [14]. Apparently, there is no one size fit all solution to PBAPs as the operational constraints which need to be accounted for and prioritized usually vary across hospitals. After it was ascertained that it was necessary to develop a heuristic customized to suit CGH operational context, the team proceeded to the "Do" phase which involved algorithm prototype development using Microsoft Excel Visual Basic for Applications (VBA). A VBA program was developed so the CGH PBAP could be addressed with the following features:

- ABAA operates in a hierarchical manner so that available beds are prioritized at three tiers (from high to low) for assignments to bed requests according to acuity levels and bed awaiting time of admitting patients (see Table 1)
- At each aforementioned priority tier level of bed requests, ABAA assesses the operational feasibility of every possible assignment of available bed to each of the bed requests in the same priority tier level using a composite scoring mechanism.
- The composite scoring mechanism is calibrated according to a matrix of clinical specialty and bed class combinations (bed request versus bed assigned) as shown in Tables 2 and 3 so that a bed assignment which can better meet the operational constraints and priority rules will yield a higher score.
- ABAA offers the combination of bed assignments which yield the best total composite scores with these assignments meeting the operating constraints and prioritization rules as stated in Tables 1 to 3

The "Study" phase entailed experimentation and evaluation of the ABAA prototype using sampled and de-identified sets of retrospective operational data where 64 scenarios of hypothetical PBAPs were generated. Based on these sampled sets of data, the ABAA prototype was run to generate recommended bed assignments before the latter were reviewed by the BMU team (one team leader, one executive, two senior patient service associates and one senior manager). At this point, a qualitative approach [16] was iteratively employed by the quality circle team which met regularly to have focus group discussion on how to design ABAA that could better meet CGH operational constraints and prioritization rules as stated in Tables 1 to 3. Essentially, the topics covered in these discussions entailed BMU team highlighting how the specific bed assignment decisions proposed by the ABAA prototype in specific experimental scenarios were not in line with their current practice, what should be the correct bed assignment assignments in these scenarios. In each iteration, the algorithm developer then acted in response to the feedback collated by recalibrating the composite scoring mechanism in ABAA and/or refining the underlying algorithm based on feedback from the BMU staff before new bed assignments recommended by the revised ABAA were subject to next review by the BMU team. An overview of the key tasks and key outcomes in each of the steps in PDSA process of ABAA prototype development is available in Appendix A

### SYSTEM INTEGRATION OF ABAA IN BMS

In this project phase, the system integration effort also adopted the PDSA framework which entailed planning or coordinating with BMS vendor on system integration requirements; doing or translating the ABAA programme scripts into BMS platform with development of relevant user-interface; studying the operational functionality of ABAA and user-interface in the BMS. platform; acting to operationalize ABAA as part of a new workflow in BMU.

In the "Plan" phase, the project team worked closely with the BMS vendor to determine the system requirements which allowed ABAA to function seamlessly in the BMS platform. These requirements include:

1. On-demand feed of real-time data inputs are to be made available to ABAA before it generates the bed assignment recommendations.
2. A new function in BMS to allow users to execute ABAA to generate bed assignment recommendations.

3. An interface which allows users to review the bed assignments recommended by ABAA once the latter completes its run.

After the details of the abovementioned requirements were deliberated, the team then proceeded to the "Do" phase of building these requirements into the BMS platform. There were several iterations of the "Do" phase with the "Study" phase as every completion of building a requirement by the BMS vendor team was typically followed by a focus group discussion with the BMU team and algorithm developer to explore ways to enhance new BMS platform so that it better met the operational needs of BMU staff. Such discussion primarily entailed sharing by BMU team members and algorithm developer on (1) their user experiences; (2) ways to improve the user interface designs; (3) ABAA functional and data security related issues after running the ABAA in a testing environment. In the event that further rework was required, the BMS vendor would act by returning to the "Do" phase based on inputs gathered in the "Study" phase. An overview of the key tasks and key outcomes in each of the steps in PDSA process of integrating ABAA with BMS is available in Appendix B

## RESULTS

### DEVELOPMENT OF ABAA PROTOTYPE

After multiple rounds of ABAA refinement from nine review meetings among the algorithm developer and BMU team, the project team was able to conclude that the revised ABAA prototype was able to perform bed assignments like the BMU staff and in a more timely manner. The ABAA prototype was able generate multiple bed assignment recommendations concurrently in less than 10 seconds while a BMU staff typically took around 3 to 5 minutes before making one bed assignment decision for one newly admitted patient. Thus, the team went on the "Act" phase of the PDSA framework to seek hospital management approval for funding support which was necessary to embed ABAA function within the current CGH BMS. Backed by strong evidence that the proposed ABAA was operationally feasible, the project team was able to get the funding support approval by the hospital management to proceed with the next project phase of integrating ABAA with CGH BMS.



## SYSTEM INTEGRATION OF ABAA IN BMS

Once it was established that the newly built-in features in BMS were ready to be operationalized as part of the new workflow (see Figure 1) for the BMU team for bed assignments, relevant training was then offered to the BMU team as part of the "Act" phase of PDSA cycle. This training entailed technical guidance to the BMU staff on how to operate ABAA function in the new BMS platform and what to follow up after the bed assignments recommendations become available (see Figures 2 and 3 for changes in BMS user interface due to introduction of ABAA). Once the training of BMU staff was completed, the project team then went on to the "Act" phase of the PDSA framework where the new bed assignment algorithm became operational in September 2020 in CGH.

To this end, it is also important to highlight the project team encountered one major setup issue during the initial operational roll out of ABAA which was not observed during the user acceptance testing of the ABAA in testing environment. The team realized the ABAA performance, particularly the speed at which the recommended bed assignment decisions were made available to users was not within the team's expectations once the BMU team started using ABAA in the production environment which required significantly more computing memory than what was required in the testing environment. As a result, the BMS vendor team needed to act swiftly to revise the system configuration setup so that speed at which ABAA generated the recommended bed assignment decisions was more acceptable to the BMU team.

FIGURE 1: PROCESS FLOW OF BED ASSIGNMENTS BY BMU STAFF WITHOUT ABAA AND WITH ABAA

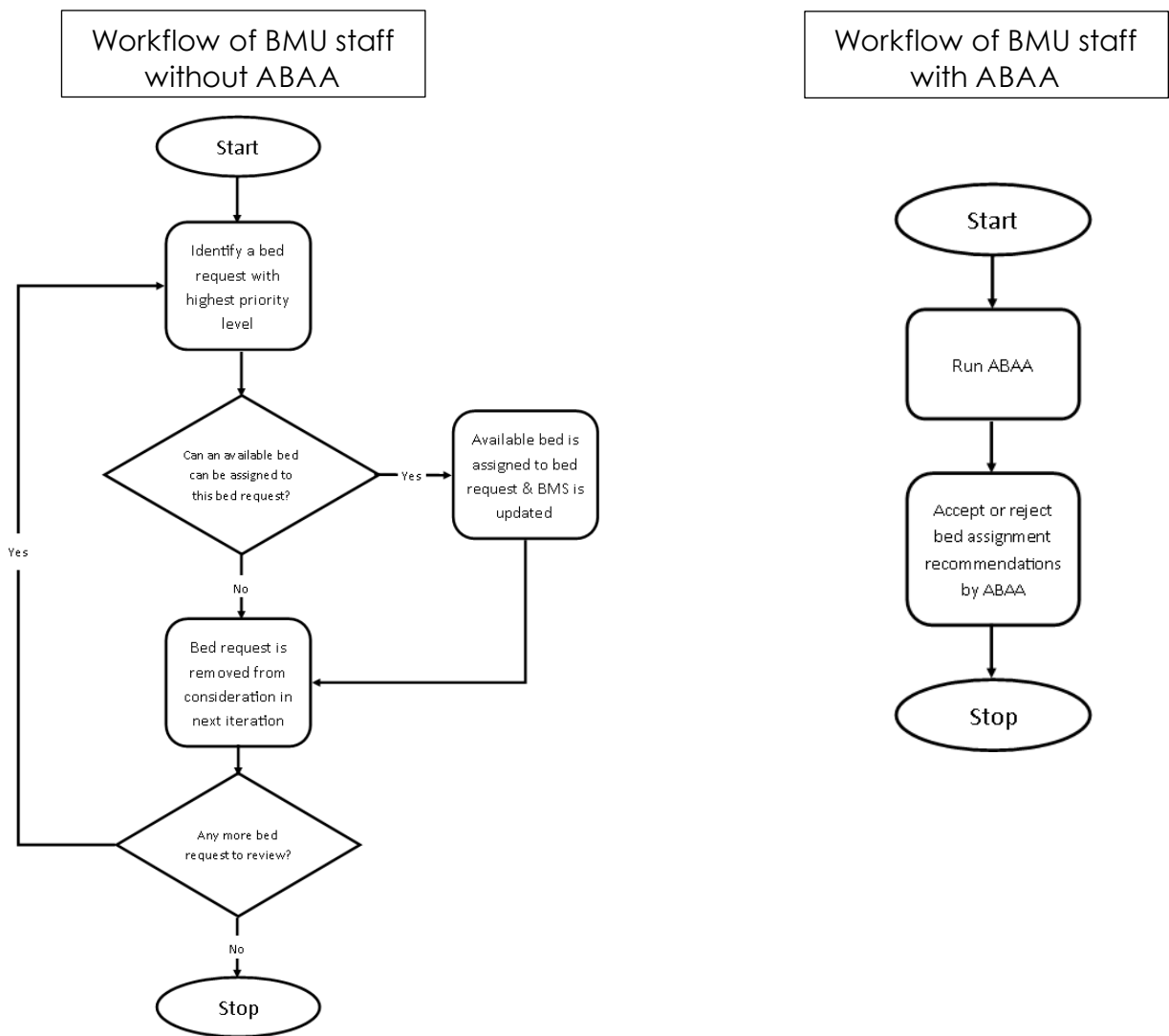
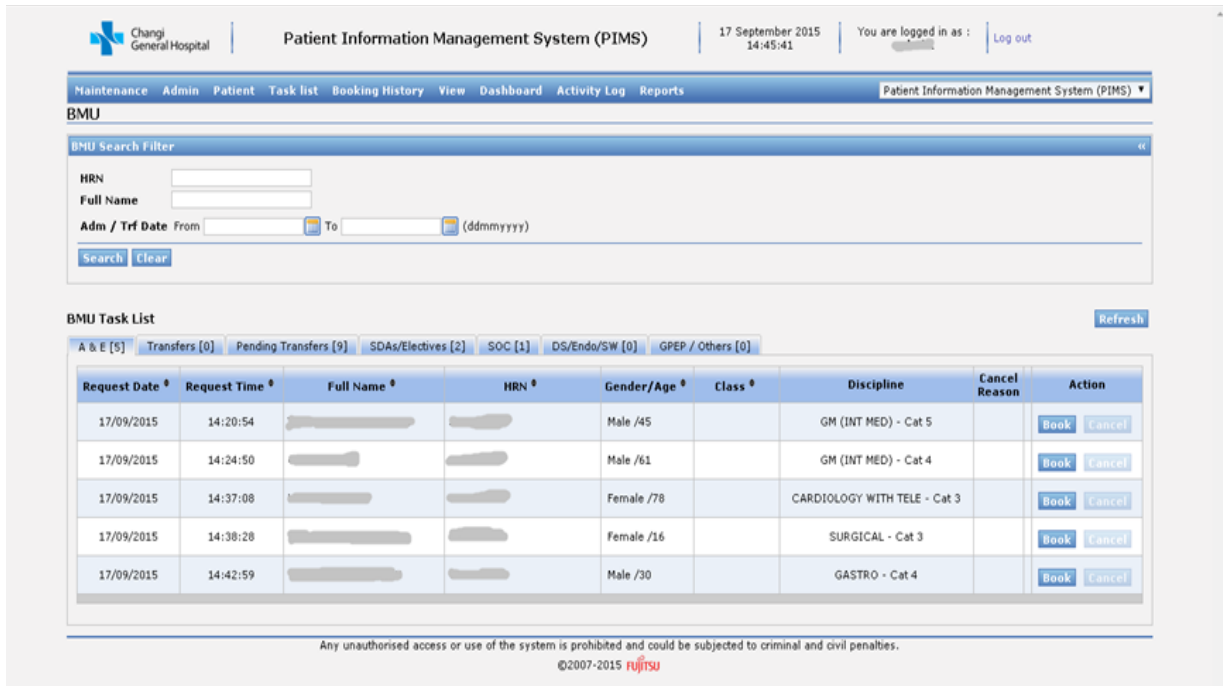


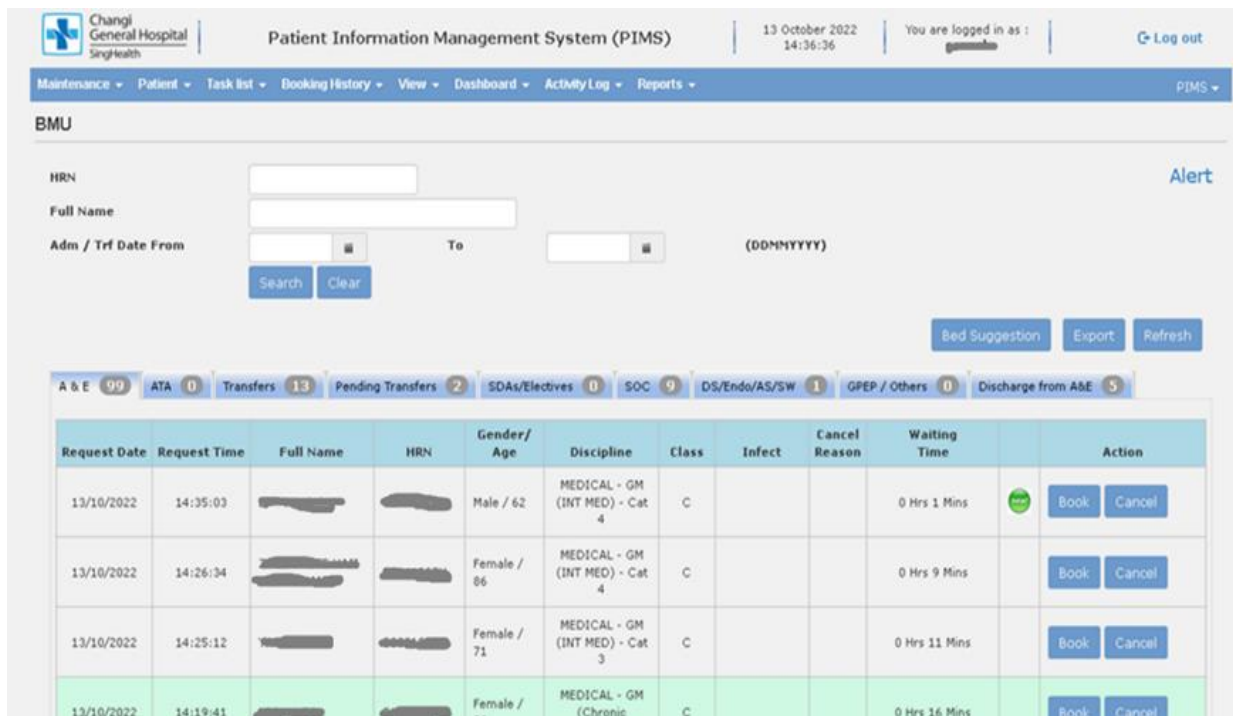
FIGURE 2: CGH BMS PLATFORM USER INTERFACE: BEFORE AND AFTER THE ROLLOUT OF ABAA

Before rollout of ABAA



BMU staff need to click on "Book" icon before entering the details of an available bed which has been assigned to patient

After rollout of ABAA



BMU staff have the option of clicking on "Bed Suggestion" icon to activate ABAA. Refer to Figure 3 for sample of bed assignment recommendations offered by ABAA in BMS Figure 3: Screenshot of sample bed assignment recommendations made by ABAA in BMS platform



FIGURE 3: SCREENSHOT OF SAMPLE BED ASSIGNMENT RECOMMENDATIONS MADE BY ABAA IN BMS PLATFORM

Name	HRN	Gender	Discipline	C.O.C	Infection	Category	B2 Only	Scheduler Time	Adm. Remarks	Remarks	Suggested Bed	Curr. Bed Status	Request From	Action
[REDACTED]	[REDACTED]	F	MOTO	C		CAT 4	N				WA36B26	Ready	A & E	Approve Reject
[REDACTED]	[REDACTED]	F	MSUR	C		CAT 5	N			PT GOING FOR OP	WA36B25	Ready	A & E	Approve Reject
[REDACTED]	[REDACTED]	F	MSUR	B2		CAT 4	N			OPEN FOR C CLASS AS PER SPOUSE   PT FOR OP	WA36B24	Ready	A & E	Approve Reject
[REDACTED]	[REDACTED]	F	MSUR	B2		CAT 4	Y				WA36B15	Ready	A & E	Approve Reject
[REDACTED]	[REDACTED]	F	MSUR	C		CAT 3	N				WA36B14	Ready	A & E	Approve Reject
[REDACTED]	[REDACTED]	F	MOTO	B2		CAT 5	N			PT OK W C	WA36B12A	Ready	A & E	Approve Reject

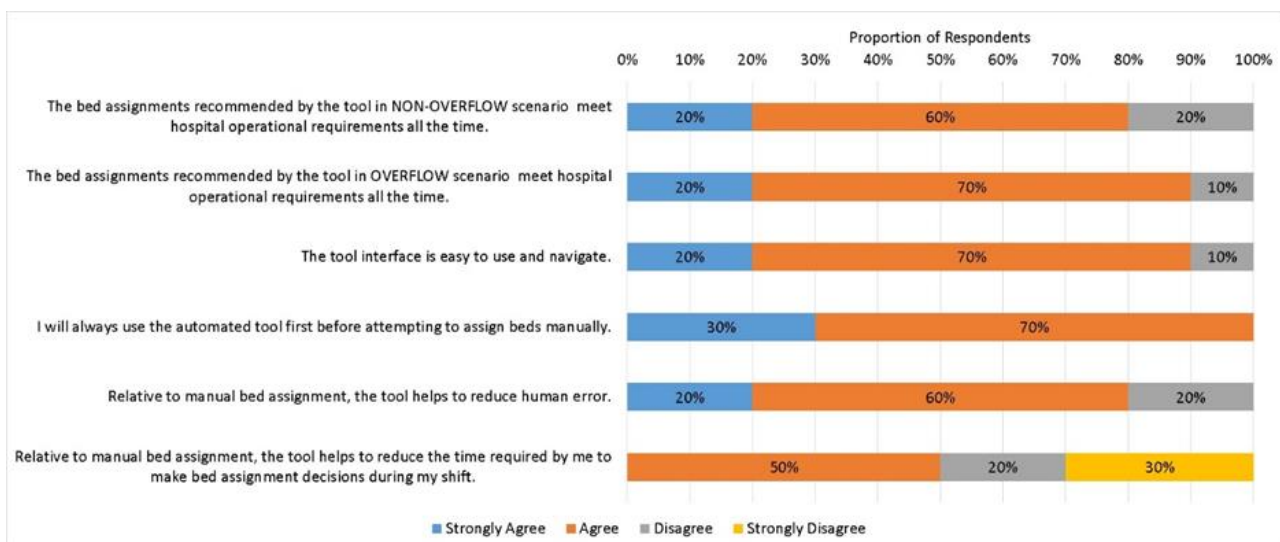
Note: BMU staff have the option of to either "Approve" or "Reject" any bed assignment recommendation made by ABAA

**POST-IMPLEMENTATION EVALUATION EXERCISE**

Due to operational exigencies during the COVID-19 pandemic, the project team was only able to perform a formal evaluation of the new operational ABAA in June 2022 where BMU staff who had at least six-month experience of using ABAA were invited to complete an online survey which has questions pertinent to staff's perception on the reliability, acceptability and benefits of the new tool. In total, all the 10 BMU staff who satisfied the inclusion criteria completed the anonymous online survey where the list of key questions administered in this survey is shown in Figure 4. The mean (standard deviation) years of bed assignment experience in BMU of these 10 staff was 7

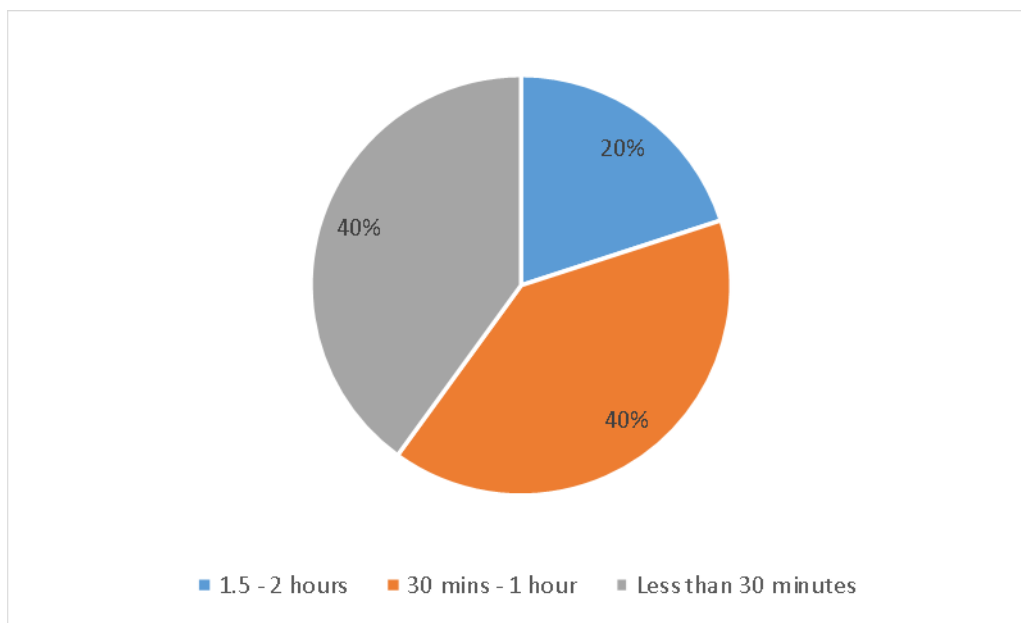
(5.2). Overall, up to 90% of survey respondents reported that ABAA was able to generate bed assignment recommendations which met the hospital's operational requirements. 90% of these respondents also reported that ABAA was easy to use and navigate while all respondents always reported using ABAA before attempting to assign beds manually. Relative to manual bed assignment, 80% of respondents reported that ABAA was able to reduce human error while 50% of respondents reported ABAA had reduced their time taken for bed assignments. Among these latter respondents, 60% of them indicated that ABAA had reduced their time taken for bed assignments per shift by 30 minutes to 2 hours (see Figure 5).

FIGURE 4: KEY QUESTIONS AND RESULTS OF THE ANONYMOUS SURVEY COMPLETED BY RESPONDENTS



Note: The tool used in this survey refers to ABAA while non-overflow and overflow scenarios refer to non-bed-crunch and bed-crunch situations respectively

**FIGURE 5: DISTRIBUTION OF TIME-SAVING PER SHIFT AMONG RESPONDENTS WHO REPORTED THAT ABAA HAD REDUCED THEIR TIME TAKEN FOR BED ASSIGNMENTS**



## DISCUSSION

ABAA had enabled BMU staff to harness two major benefits. Firstly, ABAA had reduced the time taken by 50% of BMU staff to make bed assignment decisions and this allowed them to spend more time on other value-adding tasks which included patient, next of kin engagement and care coordination with other hospital staff. This time saving was made possible due to ABAA's ability to make multiple bed assignment recommendations concurrently when BMU staff could only assign an available bed to one bed request at a time when they were making bed assignment decisions manually. The second notable benefit of the ABAA was reduction of human error in bed assignment. Relative to manual practice, ABAA also enabled BMU staff to make bed assignment decisions in a consistent and objective manner which in turn lowered the risk of BMU staff making unintended errors in their bed assignment decision-making processes and compromising inpatient care.

Two user-centric factors are crucial to the successful development and subsequent rollout of ABAA in CGH. First, all stakeholders of this project team were able to believe that the proposed ABAA was both technically and operationally possible to develop before they were engaged extensively in the algorithm development work. Due to the inherent complexity of the operational constraints and prioritization rules which BMU staff needed to account for in their bed assignment decision-making processes, some members of the project team were initially

sceptical that an ABAA that suited CGH requirements was possible to develop. Once the ABAA prototype in the VBA platform was made available for the project team to test run prototype using their respective corporate notebooks, the team members were progressively more convinced that there was a good chance that ABAA might work after all. Another crucial factor for the successful roll out of the ABAA was the extensive engagement of all key stakeholders including the ABAA users in development of the system interface which allowed ABAA to function seamlessly in the BMS platform. Usability and acceptability of ABBA was evident in the post-implementation evaluation survey where all respondents reported that they would always use ABAA first before attempting to manually make bed assignment decisions.

## LIMITATIONS

50% of respondents in the post-implementation evaluation survey did not agree that ABAA had reduced their time taken for bed assignments. Among these respondents, almost all of them had suggested that the current platform (BMS) where ABAA was residing needed to be upgraded. It must also be highlighted that the BMS hardware was set up more than one decade ago primarily to allow users to electronically record and track all bed assignment decisions and bed statuses, not to offer bed assignment recommendations. With added role of offering bed assignment recommendations that requires more computing resources, it is inevitable that the current BMS hardware would need to be enhanced to support this added role. Therefore, it is crucial that the computational

needs of a decision support tool like ABAA (which is to be customized according to individual hospital operational needs) have to be taken in consideration in planning for system upgrade or setting up the BMS in a new hospital.

## CONCLUSIONS

The user-centric design of ABAA has enabled its high adoption and acceptance rate among staff as a decision-support tool. It is also evident from this study that hierarchical heuristic approach offers tremendous potential as a decision-support tool for hospital providers in addressing their respective unique PBAPs. As the computing hardware continues to evolve, it is highly probable that significantly more time saving can be harnessed in the near future with abovementioned decision-support tool for PBAPs. Potentially, better bed assignment decisions can also be made by the tool by embedding relevant predictive elements in the hierarchical heuristic setup where these decisions also take into consideration of future bed demand and supply.

## IMPLICATIONS

This study value adds on to existing literature on hospital bed management practice by offering empirical evidence on operational feasibility of customizing a hierarchical heuristic that offer bed assignment recommendations which can meet multiple unique and conflicting hospital operational requirements. The favorable results from this study suggest that similar hierarchical heuristic can potentially be adapted to address PBAPs of other hospitals.

## CONFLICT OF INTEREST DECLARATION:

The authors declare that they have NO affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

## ETHICAL CONSIDERATIONS:

This quality improvement project did not require local research ethics board review as per organizational policy since the project did not involve identifiable data.

## ACKNOWLEDGEMENTS:

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## APPENDIX A: OVERVIEW OF PDSA PROCESS IN ABAA PROTOTYPE DEVELOPMENT.

Step	Description	Key Tasks	Key Outcomes or Findings
Plan	Plan for the change to be tested/implemented	Literature review to understand the research landscape in this domain of patient bed assignment problem (PBAP)	<p>There is no one size fit all solution to PBAPs as the operational constraints which need to be accounted for and prioritized usually vary across hospitals.</p> <p>None of the approaches reported in the existing literature which aim to address PBAPs can be readily adopted in CGH.</p> <p>The project team decided to develop a ABAA prototype that can meet the unique operational constraints and prioritization rules of the CGH PBAP</p>
Do	Carry out the change	Develop the algorithm prototype development using Microsoft Excel Visual Basic for Applications (VBA)	A prototype was developed and was ready to be assessed in terms of its ability to make bed assignment decisions like existing BMU staff.
Study	Study the relevant data before and after the change is introduced and reflect on what is learnt	Experiment and evaluate the ABAA prototype using sampled and de-identified sets of retrospective operational data	After each cycle of experiment and feedback from BMU team on the existing gaps in the ABAA prototype, the developer revise the prototype to address these gaps.
Act	Plan the next change cycle or full implementation	Recalibrate the composite scoring mechanism in ABAA and/or refine the underlying algorithm based on feedback from the BMU staff before new bed assignments recommended by the revised	After multiple iterations between the Study and Act phases, the project team was able to conclude that the revised ABAA prototype was able to perform bed assignments like the BMU

		<p>ABAA were subject to next review in the Study phase.</p> <p>Seek hospital management approval for funding support which was necessary to embed ABAA function within the current CGH BMS</p>	<p>staff and in a more timely manner.</p> <p>Hospital management granted approval for the project team to proceed with the next project phase of integrating ABAA with CGH BMS</p>
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## APPENDIX B: OVERVIEW OF PDSA PROCESS IN ABAA PROTOTYPE IMPLEMENTATION.

Step	Description	Key Tasks	Key Outcomes
Plan	Plan for the change to be tested/implemented	Worked closely with the BMS vendor to determine the system requirements which allowed ABAA to function seamlessly in the BMS platform	The vendor understood the system setup requirements before they commence the next step of the PDSA cycle.
Do	Carry out the change	Build these requirements into the BMS platform	New system setup and user interface which BMU staff execute the ABAA
Study	Study the relevant data before and after the change is introduced and reflect on what is learnt	BMU team and algorithm developer reviewed the system setup and interface and offered inputs that can potentially enhance new BMS platform so that it better met the operational needs of BMU staff.	The BMS vendor team revised the system setup and user interface design in response to collated comments from the BMU team and algorithm developer.  New system setup and user interface were operationally ready for full implementation.
Act	Plan the next change cycle or full implementation	Conduct relevant training for BMU team so that they understand how to operate ABAA function in the new BMS platform and what to follow up after the bed assignments recommendations	The BMU team was ready to adopt ABAA as part of their new workflow

## APPENDIX C: SET OF QUESTIONS ADMINISTERED TO ELIGIBLE BMU STAFF AFTER IMPLEMENTATION OF ABAA

Questions	Response Options	Purpose
The bed assignments recommended by the tool in non-overflow scenario meet CGH operational requirements all the time	Strong Disagree, Disagree, Agree, Strongly Agree	Assess if the assignment algorithm meets the operational requirements in CGH
The bed assignments recommended by the tool in overflow scenario meet CGH operational requirements all the time	Strong Disagree, Disagree, Agree, Strongly Agree	Assess if the assignment algorithm meets the operational requirements in CGH
The tool interface is easy to use and navigate	Strong Disagree, Disagree, Agree, Strongly Agree	Assess users' acceptability of tool
I will always use the automated tool first before attempting to assign beds manually	Strong Disagree, Disagree, Agree, Strongly Agree	Assess users' acceptability of tool
Relative to manual bed assignment, the tool helps to reduce human error	Strong Disagree, Disagree, Agree, Strongly Agree	Assess the benefit of tool
*Relative to manual bed assignment, the tool helps to reduce the time required by me to make bed assignment decisions during my shift	Strong Disagree, Disagree, Agree, Strongly Agree	Assess the benefit of tool
if the response to previous question* is Agree or Strongly Agree: how is the time saving per shift?	<30min, 30min-1 hour; 1-1.5hr; 1.5-2, >2hr (to track by shift)	Assess the benefit of tool
if the response to previous question* is Agree or Strongly Agree: The time saving is significant enough to allow me to perform other job tasks.	Strong Disagree, Disagree, Agree, Strongly Agree	Assess the benefit of tool
What you like most of the tool?	Free text	Assess users' acceptability of tool
What improvement do you recommend for the current tool version?	Free text	To look out for improvement opportunity