Optimizing ICU Bed Allocation for Improved Patient Outcomes and Resource Utilization

Mitu Banerjee
Jyothsna Ravipalli
Aashi Sethiya

Advisor: George Shaw, PhD

BACKGROUND RESEARCH

Intensive Care Units (ICUs) face significant challenges in managing bed capacity effectively, particularly during public health emergencies. Inefficient bed allocation can lead to extended patient lengths of stay, increased healthcare costs, and suboptimal patient outcomes. Recent studies have explored various approaches to address this critical issue.

A study published in Nature Scientific Reports introduced a two-stage multi-objective optimization model for ICU bed allocation (Wan, 2023). This model considers three patient categories (emergency, elective, and current ICU patients) and aims to balance multiple objectives, including minimizing required ICU beds, maximizing resource utilization, and ensuring maximum patient admission.

Another approach, developed at MIT, combines optimization and simulation techniques to improve bed allocation in academic medical centers (Vanden Berg, 2018). This framework uses a network-flow inspired mixed integer program to approximate operational performance and search for optimal bed allocations, which are then evaluated through detailed simulations.

A recent study in China demonstrated the impact of an ICU bed capacity optimization method on reducing average length of stay and average cost of hospitalization following the implementation of an open COVID-19 policy (Zheng, 2024). This research employed difference-in-differences models to validate the practical impact of the optimization method.

BUSINESS INTELLIGENCE PROBLEM

The core business intelligence problem we aim to address is:

How can we develop a comprehensive ICU Bed Allocation Optimization Dashboard that leverages real-time data visualization to improve bed utilization, reduce patient length of stay, and optimize resource allocation in Intensive Care Units?

This BI solution should provide the following: real-time visibility into ICU bed occupancy and availability, identify patterns in patient flow and potential bottlenecks, analyze length-of-stay trends across different patient categories and disease groups, track and visualize resource utilization and associated costs, and offer actionable insights for healthcare administrators and clinicians to make informed decisions about bed allocation and patient management.

PROPOSED BI SOLUTION

Our proposed Business Intelligence solution is valuable because it addresses critical gaps in current ICU management practices by providing hospital-specific insights that tailor recommendations to each facility's unique characteristics. It is a comprehensive ICU Bed Allocation Optimization Dashboard, designed to enhance healthcare management through advanced data analytics. The dashboard also analyzes length of stay by patient category and disease group, evaluates resource utilization and costs, and provides key performance metrics such as average length of stay and bed turnover rates, helping optimize bed allocation, reduce inefficiencies, and improve overall hospital operations. By integrating multiple factors that influence ICU bed demand, such as disease severity and resource utilization patterns, the solution delivers a comprehensive approach to management. Additionally, it supports dynamic capacity planning, allowing hospitals to adjust resources in real-time to meet evolving needs.

By implementing this BI solution, hospitals can potentially reduce average length of stay, decrease healthcare costs, and improve patient outcomes. The integration of advanced visualization techniques will enable healthcare providers to make more informed decisions about resource allocation, ultimately leading to more efficient ICU operations and better patient care (Balaji, 2018).

AVAILABLE DATA DESCRIPTION (see Appendix 1 for detailed information)

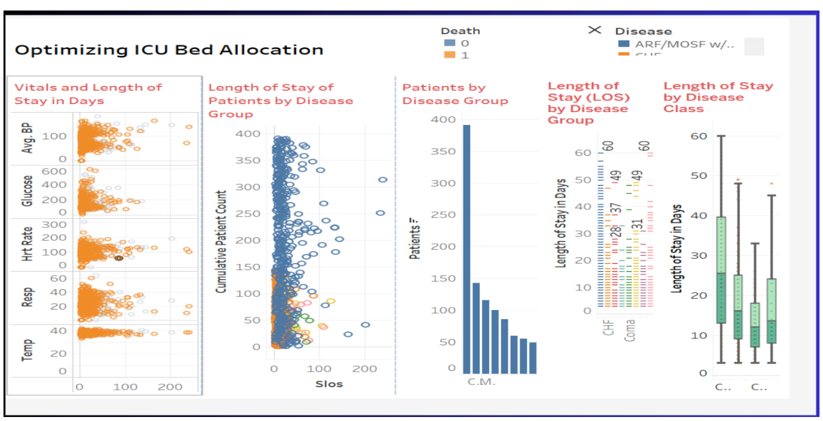
Our dataset includes rich patient-level information that can be leveraged for the BI solution including Patient Demographics, Clinical Indicators, Disease and Severity Metrics, Resource Utilization and Patient Outcomes.

LIMITATIONS OF NON-VISUALIZATION SOLUTIONS

Traditional non-visualization approaches to ICU bed management face several limitations. The multidimensional and dynamic nature of ICU data makes it difficult for non-visual methods to effectively represent the interrelationships between factors affecting bed utilization. These approaches often lack real-time insights, as static reports or basic dashboards fail to capture the rapidly changing ICU environment, resulting in delayed decision-making. Additionally, raw data or text-heavy reports can overwhelm busy healthcare professionals, making it challenging to quickly extract actionable insights. Non-visual methods also struggle with recognizing trends, patterns, and anomalies in patient flow and resource utilization, as well as exploring "what-if" scenarios for capacity planning. Furthermore, without visual aids, complex data is harder to communicate effectively across various stakeholders, such as administrators, clinicians, and nurses.

OVERVIEW OF VISUALIZATION SOLUTIONS EXPLORED (see Appendix 2 for detailed information)

<u>First Version Of Our Visualization</u>



Our first version of our dashboard on ICU bed allocation could be improved in several ways. The dashboard has several layout and organization issues. The chart appears crowded, lacking sufficient spacing and a clear visual hierarchy to guide users effectively through the information.

Data visualization also poses challenges. Overlapping points in the scatter plots on the left obscure patterns, while the cumulative patient count graph in the center is difficult to interpret due to overlapping data. Similarly, the box plots on the right are unclear, with missing labels and insufficient context.

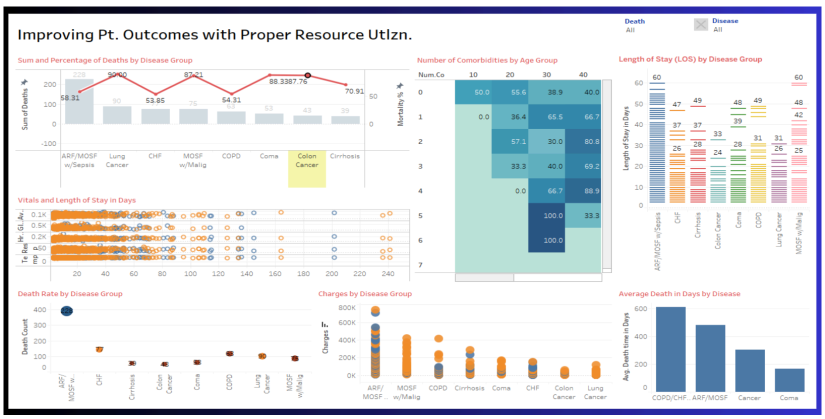
For the "Vitals and Length of Stay" section, heat maps or density plots could replace scatter plots for improved clarity, and adding trend lines would help highlight relationships. Breaking vital signs into individual charts with reference ranges for normal values would enhance readability. For "Length of Stay by

Disease," switching to a grouped box plot, adding proper labels, and including indicators for averages or medians would improve comprehension. Intuitive color coding could further aid interpretation.

The "Patient Distribution" section could benefit from clear bar chart labels, the inclusion of percentages alongside counts, consistent abbreviations or full names, and a legend explaining the disease categories.

General recommendations include adopting a consistent color scheme, adding tooltips for interactive exploration, and incorporating summary statistics. Filters for time periods or patient subgroups would improve interactivity, while better legend placement and explanatory text or annotations could enhance usability.

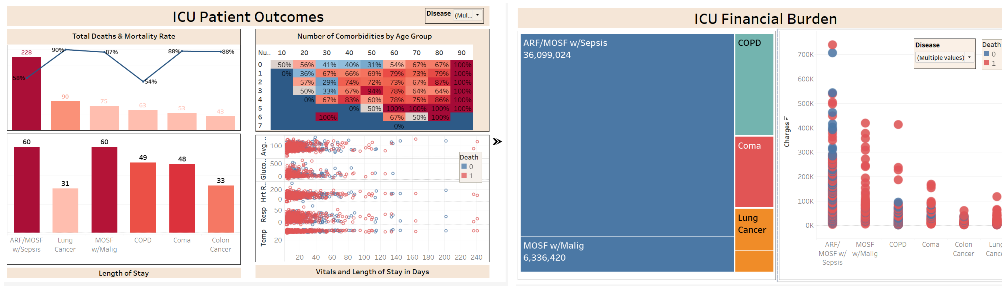
Second Version Of Our Visualization



This Tableau visualization provides a comprehensive overview of patient outcomes and resource utilization across various disease groups, but it suffers from clutter and a lack of clarity. The inclusion of multiple metrics like death rates, length of stay (LOS), and charges is valuable; however, the layout is overcrowded and makes interpretation challenging. Moreover, the color schemes across the charts lack consistency and accessibility, with some colors being difficult to differentiate, especially for individuals with color vision deficiencies. Additionally, the relationships between key metrics, such as comorbidities and LOS, are not clearly highlighted, leaving users to piece together insights on their own.

To improve the visualization, it should focus on simplifying content and organizing metrics into distinct, well-aligned sections. Key findings could be emphasized through annotations or a summary section, while interactive elements like filters and drill-downs would enhance user engagement. Consistent color schemes, larger font sizes, and a clean, structured layout with adequate white space would improve readability and aesthetics. Incorporating benchmarks or comparative goals would also provide context, making the data more actionable. Overall, the dashboard should aim to present critical insights more clearly while maintaining accessibility and ease of navigation.

<u>Final Dashboard</u>*



*** enlarged versions - Appendix 3**

CONCLUSION

The proposed ICU Bed Allocation Optimization Dashboard addresses critical challenges in ICU resource management by providing real-time, intuitive visualizations that enhance decision-making and improve patient outcomes.

Key benefits of the dashboard include enhanced decision-making, as it enables healthcare professionals to make informed and timely choices in the fast-paced ICU environment. It improves resource utilization by visualizing bed occupancy and patient flow, helping to identify inefficiencies and optimize bed turnover. By integrating clinical indicators, the dashboard supports data-driven patient care, allowing clinicians to quickly assess risks and outcomes for personalized care strategies. Cost management is also facilitated through transparent cost analysis visualizations, promoting cost-effective decisions without compromising care quality. Additionally, the dashboard provides easy access to key performance indicators for continuous monitoring and improvement of ICU operations. Its adaptability allows it to respond quickly to changing healthcare environments and incorporate new data sources. Finally, visual representations simplify complex data, improving communication among hospital staff.

By implementing this BI solution, hospitals can expect improved ICU bed utilization, reduced lengths of stay, and optimized resource allocation. These improvements will lead to better patient outcomes and increased efficiency in ICU operations.

In summary, the ICU Bed Allocation Optimization Dashboard is a valuable tool that transforms complex healthcare data into actionable insights, ultimately supporting high-quality critical care delivery.

REFERENCES:

Balaji, Ramachandran; Brownlee, Mark. 2018. Bed Management Optimization. Infosys BPO, Viewpoint.https://www.infosys.com/industries/healthcare/documents/hospital-bed-management.pdf

Harrel, Frank. UC Irvine Machine Learning Repository. https://archive.ics.uci.edu/dataset/880/support2

Vanden Berg, Andrew. Optimization-Simulation Framework to Optimize Hospital Bed Allocation in Academic Medical Centers. September 2018. Optimization-Simulation Framework to Optimize Hospital Bed PDF

Wan, F., Fondrevelle, J., Wang, T. et al. Two-stage multi-objective optimization for ICU bed allocation under multiple sources of uncertainty. Sci Rep 13, 18925 (2023). https://doi.org/10.1038/s41598-023-45777-x

Zheng Q, Zeng Z, Tang X, Ma L. Impact of an ICU bed capacity optimisation method on the average length of stay and average cost of hospitalisation following implementation of China's open policy with respect to COVID-19: a difference-in-differences analysis based on information management system data from a tertiary hospital in southwest China. BMJ Open. 2024 Apr 19;14(4):e078069. doi: 10.1136/bmjopen-2023-078069. PMID: 38643008; PMCID: PMC11033667.

APPENDIX 1: AVAILABLE DATA DESCRIPTION

Our dataset includes rich patient-level information that can be leveraged for the BI solution:

- Patient Demographics:
  - Age (continuous variable)
  - Sex (binomial variable: male/female)
  - Race (categorical variable)

- Clinical Indicators:
  - Mean blood pressure (meanbp)
  - White blood cell count (wblc)
  - Heart rate (hrt)
  - Respiratory rate (resp)

- Disease and Severity Metrics:
  - Disease group (dzgroup, categorical)
  - Disease class (dzclass, categorical)
  - Number of comorbidities (num.co, discrete)

- Resource Utilization:
  - Length of stay (slos, continuous)
  - Hospital charges (charges, continuous)
  - Total cost (totcst, continuous)
  - Total medical cost (totmcst, continuous)

- Patient Outcomes:
  - Death indicator (death, binary)
  - Days until death (d.time, continuous)
  - Hospital death indicator (hospdead, binary)

APPENDIX 2:

OVERVIEW OF VISUALIZATION SOLUTIONS EXPLORED

Our ICU Bed Allocation Optimization Dashboard will include the following visualizations, leveraging the available data attributes:

1. **Bed Occupancy and Patient Flow:**
   - Stacked area chart showing daily ICU occupancy by disease group (dzgroup)
   - Sankey diagram illustrating patient flow from admission to discharge or death
2. **Length of Stay (LOS) Analysis:**
   - Box plots of LOS (slos) by disease group and disease class (dzclass)
   - Scatter plot of age vs. LOS, colored by number of comorbidities (num.co)
3. **Resource Utilization Insights:**
   - Treemap of total costs (totcst) by disease group and class
   - Scatter plot of charges vs. LOS, with disease group as color
4. **Patient Outcome Visualization:**
   - Heat map of mortality rate (death) by age group and number of comorbidities
   - Bar chart of average days until death (d.time) by disease class
5. **Clinical Indicators Dashboard:**
   - Parallel coordinates plot for vital signs (meanbp, wblc, hrt, resp, temp) by disease group
   - Scatter plot matrix of clinical indicators to identify correlations
6. **Cost Analysis:**
   - Stacked bar chart showing breakdown of total costs (totcst, totmcst) by disease group
   - Bubble chart of average charges by disease group, sized by patient count
7. **Performance Metrics:**
   - Bullet charts comparing current metrics (e.g., average LOS, mortality rate) to targets
   - Line chart showing trends in key performance indicators over time
8. **Demographic Insights:**
   - Grouped bar chart of patient distribution by age group, sex, and race
   - Heatmap of patient outcomes by education level (edu) and income category

These visualizations will provide a comprehensive view of ICU operations, patient outcomes, and resource utilization, enabling data-driven decision-making for bed allocation and resource optimization.

APPENDIX 3:

FINAL DASHBOARD