PROCESS-LED ICU DESIGN

Applying Discrete-Event Simulation and Process Improvement to Measure Design Performance

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AN IMPROVEMENT MINDSET

Design research and evidence-based design practice is bringing increased rigor to design process while advancing design performance in healthcare environments. Process improvement and operations research methodologies are being increasingly adopted into healthcare planning, bringing process-oriented and quantitative tools to demonstrate value and predict outcomes. In a highly dynamic and competitive environment, healthcare systems are moving towards an improvement and value-focused mindset, placing a premium on measuring and demonstrating operational planning and efficiencies. How do design teams take advantage of methodologies from design research as well as from systems and operations research within this improvement paradigm?

As designers partner with industrial and system engineers and researchers, complementary tools and approaches can be applied to better understand workflow dynamics, design operational and facility-focused improvements concurrently, test the performance of design options, and predict operational outcomes. Simulation modeling and process improvement methods can provide real-time decision support to the teams tasked with assessing the viability of different design options. Will we have sufficient rooms to meet future volumes? How will the new unit allow us to spend less time looking for supplies and more time at the patient bedside? Will one medication dispensing unit suffice or will we need two to support the unit without delays? In this ICU study, these tools were used to answer these questions and others.

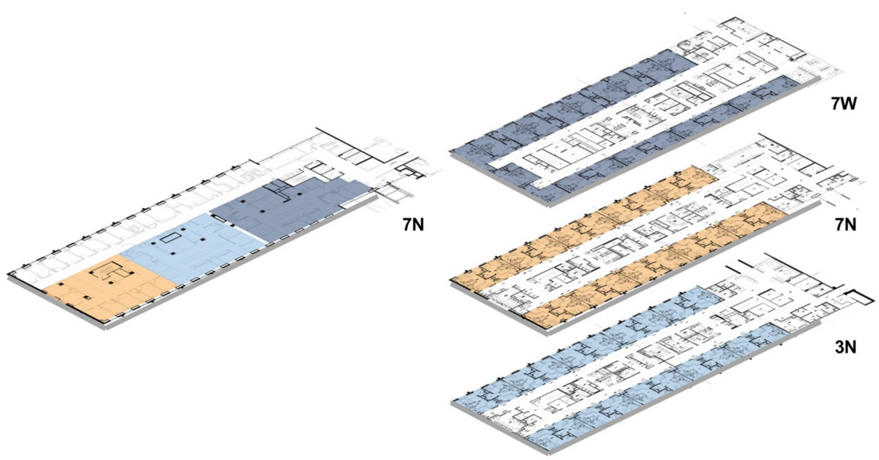
This study adopted a process-led framework, applying discrete-event simulation modeling, process mapping, extensive workflow observations, and collaborative stakeholder engagement in the re-design of three intensive care units. A primary objective was to test and predict outcomes for design options during design development. A secondary objective was to pilot novel approaches for measuring the performance of design innovations in the context of an active design project. The research approaches applied during this ICU redesign served as a “proof of concept” to further develop rigorous methods and metrics to test new and existing ICU designs.

Measuring Design Performance: Emerging Trends

- Growing awareness, and adoption of, continuous process improvement mindsets
- Recognition of the value of simulation modeling to inform high-risk/high cost design decisions
- More opportunities for cross-functional facilities design-operations-clinical collaboration
- Wider adoption of co-design approaches
- Greater emphasis on early testing and measuring of design performance
- Recognition that engagement by all stakeholders will improve design outcomes

THE SETTING

Following a merger with an urban academic medical center, this hospital began planning for the design of three new intensive care units. The redesign entailed a shift from three centralized pods of 10-12 beds sharing one floor, to three decentralized racetrack units of 20 beds each, each occupying a separate floor (See Figure 1). Two of the three original units were designed with a central team station and a combination of three-walled rooms with a curtain and private isolation rooms. The third unit was designed with a centralized team station and all single occupancy, private rooms. This third unit had adopted an ad hoc decentralized approach, with some nurses using workstations on wheels outside patient rooms. Occupancy levels in the current ICUs were consistently higher than the target utilization, requiring medical ICU patients to be split between two teams, each operating in physically separated units. In their current state, the ICU rooms were undersized for the needs of present ICU-level care. The lack of appropriate spaces for supplies and equipment in the units was negatively affecting workflow, causing inefficiencies and excessive movement for clinical teams as they went about their patient care activities. The future design envisioned three state-of-the-art ICUs designed to offer a healing environment for patients and families while also operating at high efficiency, safety, and reliability. The future ICUs were envisioned to support a highly engaged care team and foster a multidisciplinary and collaborative environment for practice.



- 3 centralized units
- 3 units on one floor
- 39 beds total

→

- 3 decentralized units
- 1 unit per floor
- 20 beds per unit

Figure 1: Redesign of 3 Intensive Care Units

THE ICU ENVIRONMENT

The ICU has been referred to as a "semi-autonomous mini-hospital" [1]. Between 2002 and 2009, ICU stays rose at three times the rate of general hospital stays, a trend which is expected to continue [2]. ICU utilization is expected to outpace other inpatient bed use (26.9% of hospital stays in 2011 took place in an ICU) and critical care is 2.5 times more costly than other stays [2]. Due primarily to increased demand for ICU based on experienced bed shortages, the number of critical care beds in the United States increased 15% from 2006 to 2011 [3]. Some have suggested that the need for additional critical care beds is real, and that there are opportunities for improving efficiency in bed use and allocation [4].

ICUs require a balance between functionality and cost, and are among the most expensive spaces to build. Critical care units care for very sick patients with multiple needs who require high levels of direct care (nurse to patient ratios are 1:1 or 1:2), Visibility of patients is critical. Access to supplies and equipment is more than a matter of efficiency, it can be a matter of life-or-death. The model of care in ICU has also been undergoing change, with an emphasis on humanization of care [5], given the long-term effects of ICU stays on patients and their families. There is continuing recognition of the importance of patient-centered and family-involved care even at times of crisis.

ICU Stays Trending Upward

- ICU stays rose at 3X the rate of general hospital stays from 2002 to 2009 [2]
- The number of critical care beds in the United States increased by 15% from 2006 to 2011 [3].

With national attention focused on clinician burnout, health systems and design teams are placing greater focus on the care team and creating environments that support and sustain teams, and reduce cognitive and emotional burden on staff. In the ICU setting, an increasing number of procedures are taking place at bedside, and mobile imaging is reducing the need for risky patient transfers. The adoption of interdisciplinary rounding practices and integrated care teams is increasing the number of team members actively caring for patients and collaborating with one another to coordinate care.

These shifts are bringing implications both for workflows as well as the designed environment, including the size of the patient rooms, supply and equipment decentralization strategies, and team station configurations. Guidelines specifying all private rooms and the wide adoption of room-side touchdowns for nurses are increasing the size of ICU units. While touchdowns bring nurses and team members closer to the point of care, studies are also showing an impact on community of practice, feelings of isolation, and longer walking distances [6, 7]. Flexibility in room use is increasingly recognized as an operational strategy to adapt rapidly to changing patient mix and acuity. All these changes have important design considerations and hold implications for clinical workflows, team interaction, and patient and family care.

SIMULATION MODELING AND PROCESS IMPROVEMENT AS APPLIED TO ICU DESIGN

How do we know if a design change is an improvement? Studies have confirmed the effect of the designed environment on outcomes such as nursing workflow efficiency, patient safety, and interdisciplinary care coordination[8-11]. Fewer have incorporated lean and process improvement methods and predictive modeling to inform stakeholder and decision-making during the design process. Discrete event simulation is still an underutilized research tool during design delivery to test performance of design options in these expensive environments.

Simulation modeling is a powerful tool to measure design performance and predict effects of design on efficiency as well as other workflow variables. Yet, it is not widely used in practice due to the expertise required and perceptions of significant investments of time and resources required. The Health Facilities Management/ASHE 2017 Hospital Construction Study reported that while 60% of hospitals report using evidence-based design to improve workflow during design, only 17% report using simulation modeling (See Figure 2). Time and motion studies were used even less frequently, with 15% hospitals reporting their use to improve workflow.

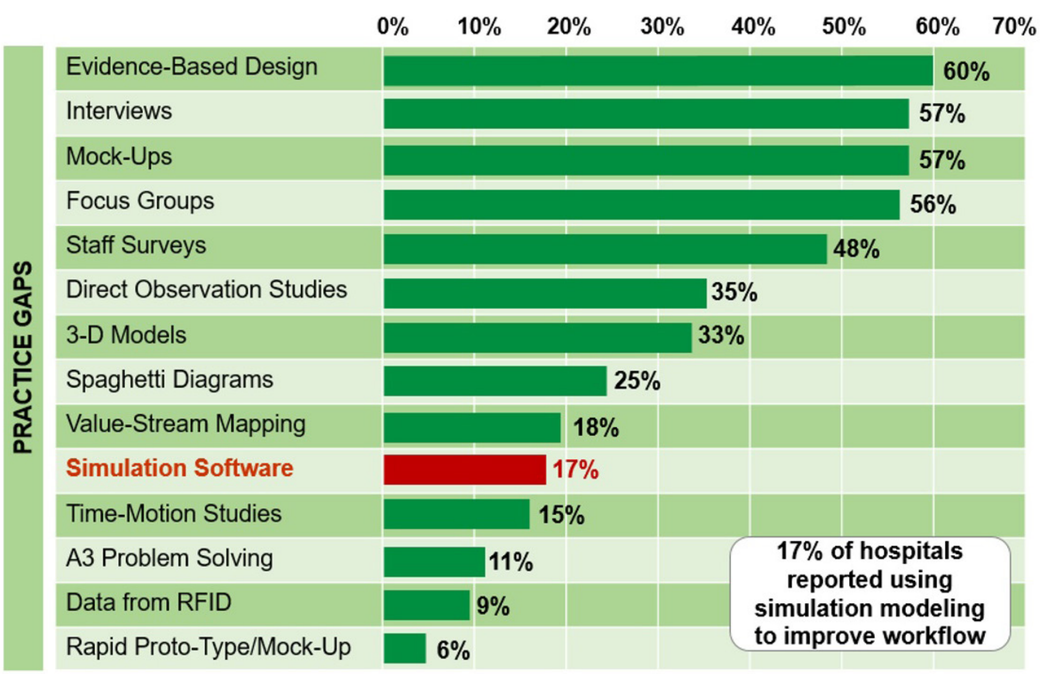


Figure 2: Methods Applied During Facility Planning and Design to Improve Workflow
Source: The Health Facilities Management/ASHE 2017 Hospital Construction Study

An internal systematic literature review of scholarly papers published between 2008 – 2018 related to ICU design found that few studies employed simulation modeling to optimize layout or test design concepts. And, while operational research literature has applied mathematical models to optimize layout in numerous studies, those studies have not fully considered architectural and design limitations encountered in practice. The ICU-related research and operational management literature is primarily focused on demand-capacity balancing as well as expediting patient discharge, while layout optimization has been "rarely touched in ICU literature since 1980," according to a 2018 literature review of operations research in ICU management [12]. This study set out to address the gap in both research and practice by applying simulation modeling to test and predict outcomes for design options during design development, and to develop an approach for measuring the performance of new design in the context of an active design project.

PROCESS-LED DESIGN FRAMEWORK

Process-led design is a framework for concurrent operational, experiential, and facility design, integrating principles and practices from conventional design, evidence-based design, process improvement (Lean), simulation modeling, human centered design, and operations research. It seeks to measure the performance of designs in terms of the predicted improvements in care delivery and increasing value-added activities in workflow to the benefit of patients as well as clinical team members. The main focus of this paper is on simulation modeling, process mapping, and workflow analysis research however, this work was conducted alongside and within a comprehensive design process.

The four elements: Define, Discover, Design and Test, and Align emphasized the interplay of operations, experience, and design, while applying evidence-based methodologies. Design was carried out in partnership with an interdisciplinary hospital team and as well the architectural programming, planning and design team. Researchers were embedded in this design team from visioning through design development. During the define phase, the team identified the scope of the study, as well as key metrics and measures of success for performance testing. Discovery entailed in-depth study of workflows, data analysis, as well as a current state simulation model to establish a baseline and identify opportunities for improvement. The simulation modeling was further utilized in the Design and Test and Align phases to provide real-time insights for team as design options were being developed and considered. Each phase was highly participatory and collaborative. During the Align phase, pre/post analyses were conducted to compare the new design to the previous design on key performance metrics and to shed light on opportunities for additional improvement.

STAKEHOLDER AND DESIGN TEAM ENGAGEMENT

The steering committee for the ICU renovation project included representatives from the hospital facilities and planning and senior clinical and administrative leadership. The architectural design and research team for the ICU renovations included the project architect, project manager, interior designers, designers, architects, healthcare planners and two researchers. During the design process and period of the research study, over 90 staff members representing 25 hospital departments took part in 14 design workshops. The focus, variables of interest, and scenarios for the simulation studies were determined jointly by the user groups and designers. The research and analyses were carried out by the design research team members in consultation with the healthcare planning team who were very experienced with ICU and healthcare design. Clinical team members served as subject matter experts throughout the study and validated model findings to confirm representation of actual system flows.

DEFINE

The scope of the study was focused on real-time decision support to guide the optimal layout of the unit, test the effects of supply and nursing decentralization strategies, and predict expected bed utilization under expected patient volumes. As such, the variables of interest and “what-if” scenarios for the simulation model were determined based on the specific research questions of interest to the hospital design team members, as well as design variables that have been shown to have important effects on patient care and capacity and efficiency outcomes. A secondary, but important objective of the model was to provide a visual demonstration of the expected operation of the unit for the hospital design team.

High-level design guiding principles included operational efficiency, safety, high reliability, highly engaged care team, and fostering a multidisciplinary and collaborative environment for practice. Based on literature study and discussion with the project teams five design metrics were chosen. The design performance variables were grouped into three main categories: flow, capacity, and design (Table 1: Design Performance Metrics). Metrics included patient wait time to admission [13], bed occupancy [13, 14], nurse time in transit [15, 16], activity or task duration [15], congestion, and bumpability [17] (defined as opportunities for spontaneous interaction). The rationale for bumpability stemmed from studies reporting that the shift to individual, decentralized nurse touchdowns at room-side is associated with increased feelings of isolation and burnout among nurses [17]. Based on on-site study of circulation and acoustical sampling, it was also noted that congestion in ICU was associated with higher noise level as will be discussed later in this paper.

5 ICU workflows modeled

- Arrival and Handover
- Recurrent Monitoring
- Medication Administration
- Personal care
- Interdisciplinary rounds

		Capacity	Flow					Design
		Utilization	Proximity	Circulation	Queuing	Delays	Non-value added time	Centralized vs decentralized
Performance metrics	Patient wait time to admission	X						X
	Bed occupancy							X
	Time in transit						X	X
	Activity duration					X		X
	Congestion		X	X	X			X
	Bumpability			X				X

Table 1: Design Performance Metrics

Two novel simulation approaches were developed and programmed into Flexsim HC to evaluate congestion and bumpability. Nodes were coded at key intersections and at key resource locations to identify and quantify the number of staff passing on these nodes (Figure 3: Novel Modeling Metrics). Bumpability was modelled by quantifying incidents when a staff member met with another staff member on one of the pre-defined nodes. Five key patient care processes were included in the model: arrival and handover, medication administration, patient daily rounds, personal care, and routine monitoring. The five care processes were identified by the clinical team as being the most significant for the ICU workflow.

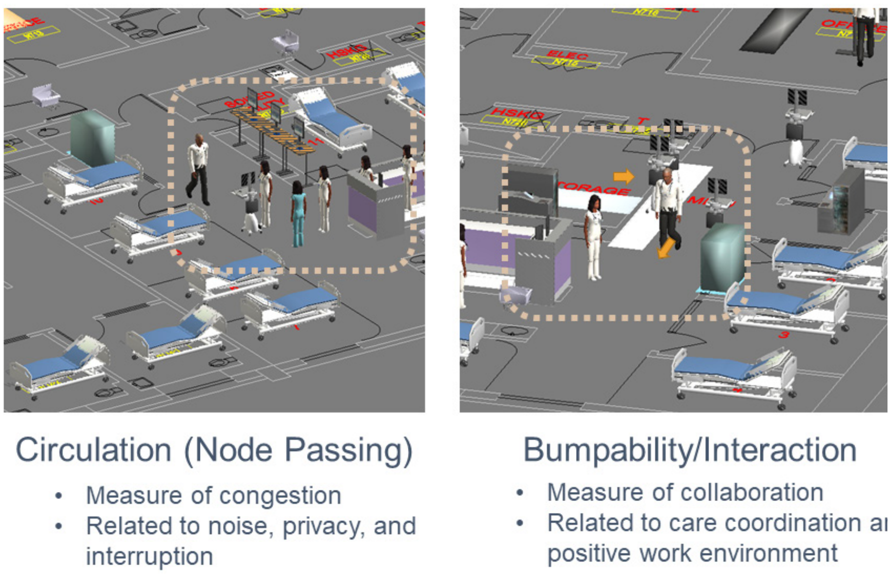


Figure 3: Novel Modeling Metrics

DISCOVERY

The Discovery phase was focused on gaining a deep understanding of the current state design and operations in the existing ICUs. The team applied a mixed-method approach which took place concurrent to programming, schematic, and design development. In the pre-design stage, an electronic survey was distributed to ICU nursing and medicine teams to understand key challenges and vision for future state ICUs.

During design workshops, five primary workflows were mapped: patient arrival and handover, medication administration, regular monitoring, personal care activities, and daily interdisciplinary rounds. The team created process maps for each workflow, including location, team members involved, process duration, and required supplies and equipment for each. Figure 4 shows a simplified version of the swimlane diagrams of ICU workflow developed by the teams.

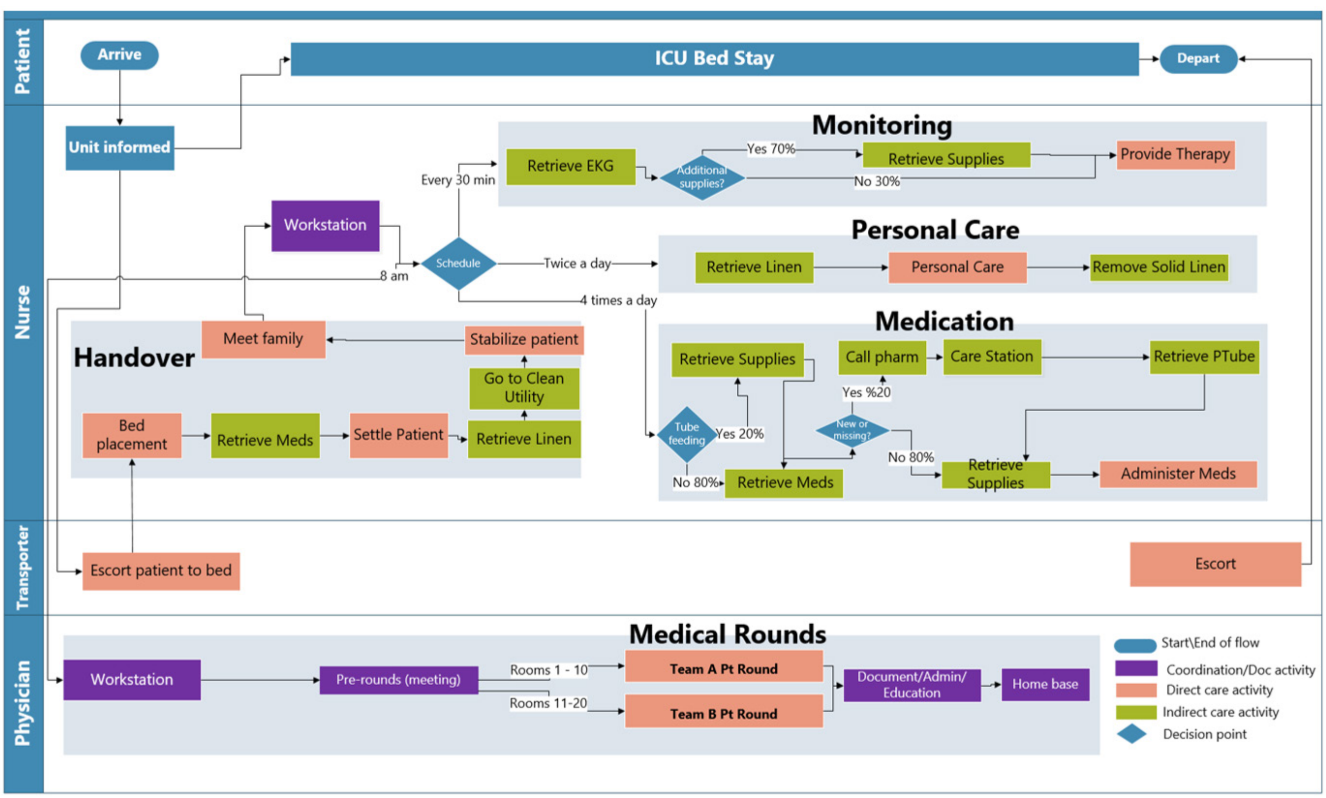


Figure 4: Simplified ICU workflow process map

Time and Motion Studies

On-site time and motion studies were conducted over a two-week period (9 days total) in the three ICU units to gather additional process times and observe and record workflows. Clinical team members were repeatedly shadowed for one-hour periods over nine days. Using a tablet-based observation application (DOTT or Detailed Observation Time and Task), the researchers documented each person's pathways and activities onto the electronic floor plan, with timestamps collected to record duration of each task. The time and motion studies added details to the process maps and provided empirically-established process times for tasks to account for individual variability and more accurately represent operations as carried out. Samples of acoustical readings were also gathered during peak hours at nursing team stations using the DecibelX application. Three months of historical arrivals and one year of census, length of stay, and arrivals data for the three ICUs was also collected and analyzed. The process maps, together with onsite observations, served as a foundation for the current state simulation model as well as to identify the workarounds and inefficiencies imposed by the layout of the existing ICU units.

Current State Simulation Model

A discrete-event simulation model was built to represent the current state for the three ICUs using Flexsim for Healthcare. Patient arrivals, length of stay, and departures as well as the five key clinical workflows were modeled. Probability distributions were generated for the patient interarrival times and process durations using ExpertFit based on historical and empirical data. The model verification and validation process was carried out in partnership with the clinical design team members in a workshop setting. Videos of the models and dashboards were shared with the team to verify flows and pathways. Historical and model-generated census were compared, and statistical testing was conducted to ensure validity. Figure 5 shows a comparison between daily census from simulation and from historical data obtained from running the simulation for 35 days.

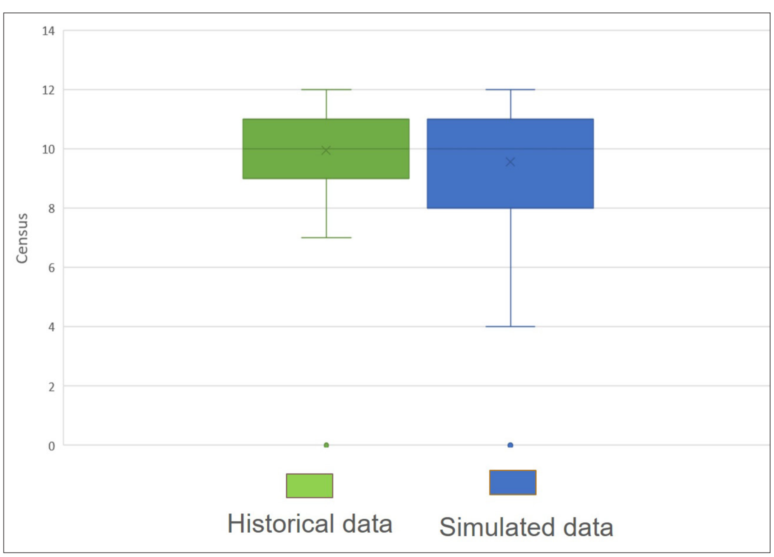
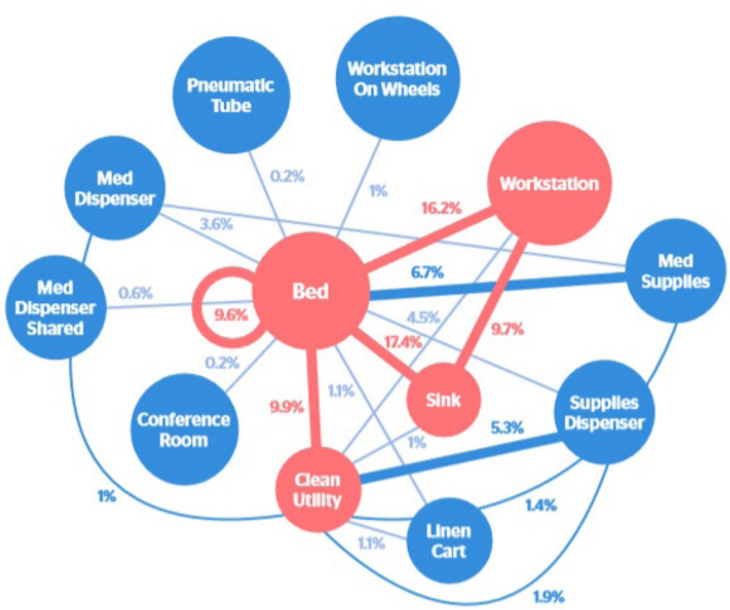


Figure 5: Model validation results (census comparison)

Frequency and Flow Studies

The current state model provided an opportunity to measure and create simulations of workflow dynamics not possible with floor plan measurements of distance. The current state model was run one shift with 30 replications and the output analyzed to create flow and frequency diagrams (Figure 6: Simulation Model Generated Flow and Frequency Diagrams). Accounting for the five nursing and rounding workflows, the diagram mapped all key locations with the frequency of flow between locations. This provided a data-driven map to identify key adjacencies. Travel paths for tasks were found to be highly interconnected and have significant effects on overall efficiency. The frequent flows between the patient bed and sink confirm existing guidelines which require that each patient room include a sink for infection control purposes. This design also promotes efficiency. The need to locate clean utility as close as possible to patient rooms prompted the team to reconsider the inclusion of nurse servers and increased decentralization of supplies at the patient room. This emerged as scenario test request later in design. Contrary to expectation, the location of the pneumatic tube and need to obtain medications from a remote medication dispensing machine were not significant in frequency however, they were identified in cause-and-effect diagrams as contributing to multiple trips, increased potential for distraction, and time away from the patient visibility zone. Having more than one point of reference (simulation, mapping and observations of workflows) for design decision making ensured a more holistic approach. These diagrams provided input to the design team during later design phases to identify opportunities to streamline operations as well as in determining locations and extent of decentralization for key support resources, including medication dispensing, linens, and equipment. The model gave visibility to, and quantified, most frequent flows, and provided a data-driven and captured workflow in a more dynamic fashion. It allowed the design and clinical team to understand interactions between flows, travel distances, and unit layout. It also provided direction to focus future state simulation scenario testing.



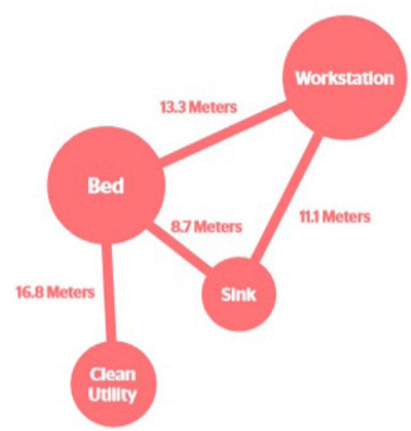


Figure 6: Simulation Model Generated Flow and Frequency Diagrams

Opportunities to Improve Workflow

Based on the shadowing sessions with the nursing team in the three existing ICUs, the layout and design of the units were implicated in excessive motion, workarounds, and considerable non-value-added activities in daily care processes. On average, it was found that nurses in the ICU were visiting up to five rooms to accomplish a single task such as medication administration (Figure 7: Time and Motion Study: Nurse Steps During Medication Administration). Overall, 85% of process durations were spent retrieving supplies and equipment, sometimes requiring trips outside the unit to retrieve medications, send and receive laboratory samples using the pneumatic tube, or seeking family members. Cause-and-effect diagrams were developed to identify key contributors to inefficiency (Figure 8: Cause-and-effect diagram). For medication administration, poor design was responsible for adding non-value-added steps and time in transit as well as contributing to rework when nurses could not find an item, or were interrupted along the route and forgot an item.

Figure 7: Time and Motion Study: Nurse Steps During Medication Administration

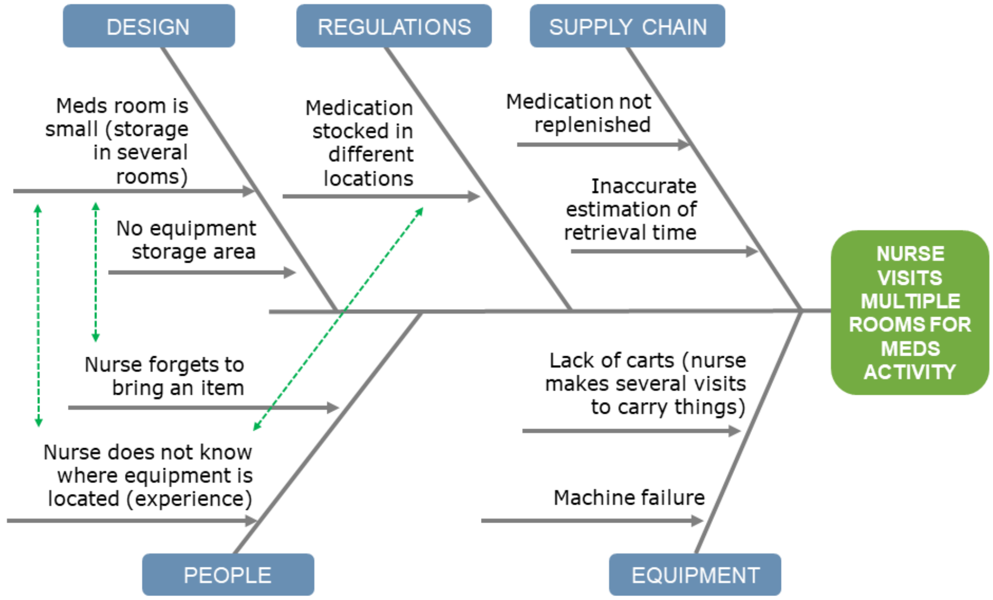


Figure 8:
Cause-and-Effect Diagram for Medication Administration

Congestion, Decentralization, and Acoustical Environment

Congestion in the small, centralized pods was identified as both a source of distraction and impediment to accessing supplies in the ICU units. Results from the shadowing sessions showed that congestion was much higher in the two smaller centralized ICU pods (Figure 9: Nurse Travel Paths in the ICUs) as compared to the ad hoc decentralized unit. The unit with private rooms had adopted an ad hoc decentralized means of documenting using workstations on wheels located outside the patient rooms.

During the on-site observations, noise levels were sampled at the central team stations in each of the three ICU units during peak hours. Noise in all three units exceeded the WHO Benchmark of 35-45 decibels. However, in the ad hoc decentralized unit, noise levels were significantly lower ($p < 0.05$) (Figure 10: Layout Impacts Acoustic Environment). Acoustics have implications for patients as well as team members. A study of nursing unit configurations showed that during periods of lower noise, staff members observed many positive outcomes, including improved speech intelligibility, lower perceived work demand, and lower perceived pressure [18]. This study provided further evidence of the positive impact of decentralized team touchdowns proposed for the future state.

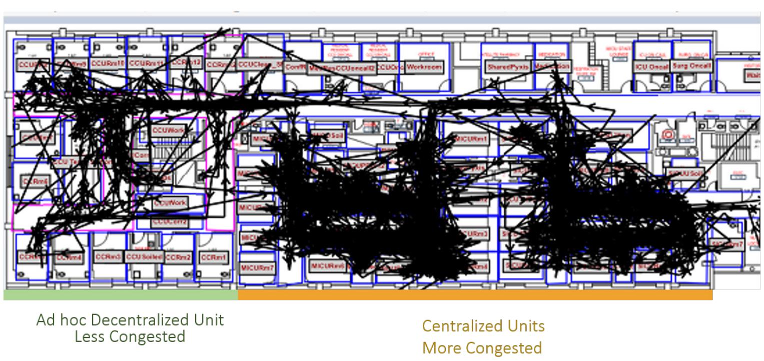


Figure 9:
Nurse Travel Paths in the ICUs: DOTT On-Site Shadowing Output

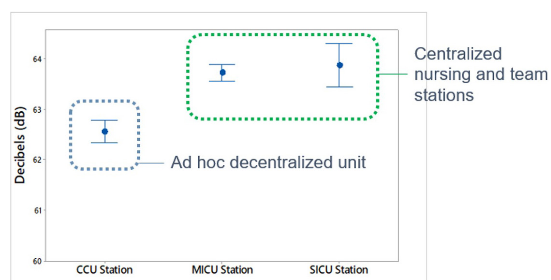


Figure 10:
Layout Impacts Acoustic Environment

DESIGN AND TEST

Building on the discovery phase, new workflows and ICU design options were developed and tested. The simulation modeling was further utilized in the Design and Test phases to provide real-time insights. A series of 3P-inspired stakeholder workshops were held with the participation of the clinical and support teams as well as design and facilities, including representation from 25 hospital departments and service lines.

Cross-functional teams concurrently mapped future ideal operations; streamlining processes based on current state process maps. Lean techniques were used to identify non-value-added activities and group supplies to streamline processes. The teams generated multiple layout scenarios based on a racetrack configuration with a central support core (Figure 11: Proposed ICU Plan).

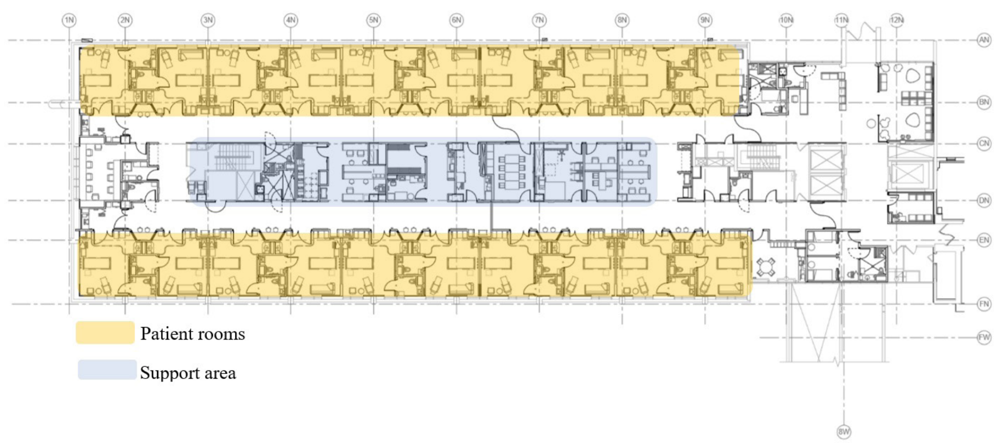


Figure 11: Proposed ICU Plan

Future State Simulation Model

A future state simulation model was developed based on the preferred design scenario developed by the workshop teams (Figure 12: Future State Simulation Model).

The model included the same five key workflows, but adapted nursing workflows according to future state maps and was based on the proposed racetrack layout. The model used similar demand patterns as in current design and it simulated the improved workflow as envisioned during the 3P workshops.

During the workshops, several questions arose regarding supply and equipment decentralization strategies, particularly with reference to medication dispensing and linens. These became the basis for testing "what if" scenarios.

Simulation Modeling Challenges

- Designs schemes are highly reiterative and changeable which requires quick modeling approaches to constantly test scenarios
- Data may be missing during early stages which requires frequent communication with ICU staff
- Lack of data can be a persistent challenge, particularly with respect to projections

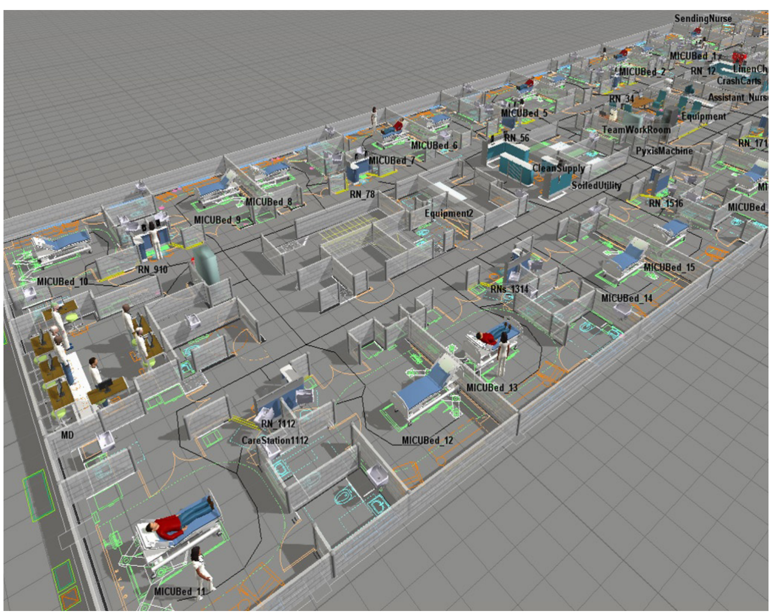


Figure 12: Future State Simulation Model

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What-if Scenarios

To provide guidance to the team as the support core areas were further defined, five "what-if" scenarios were developed and tested using the simulation model (Table 2: Model Scenarios and Figure 12: Scenarios 1,2 and 3 Mapped onto the Floor Plan). The key questions under consideration included:

1. Would one or two medication dispensing units be optimal with respect to walking distances and potential queuing/wait time for nurses?
2. Would the two-corridor access to a medication pod decrease non-value-added time compared to single corridor access?
3. What level of decentralization of linens and other supplies would be optimal? Would putting linens in the patient room (nurse server) improve efficiency significantly as compared to locating them centrally or decentralized in the core?

Five scenarios related to the optimal location of medication dispensing and linens were tested. Metrics included walking distance and time in transit (considered non-value-added time).

Scenario	Description
Scenario 1	Single-sided access to MedDispenser 2 decentralized linen carts
Scenario 2	2-sided access to MedDispenser 2 decentralized linen carts
Scenario 3	2-sided access to MedDispenser Linen in patient room
Scenario 4	Adding a second MedDispenser 2 decentralized linen carts
Scenario 5	Adding a second MedDispenser 1 centralized linen cart

Table 2: Model What If Scenarios

1

2

3

Figure 13: Scenarios 1, 2 and 3 Mapped onto the Floor Plan

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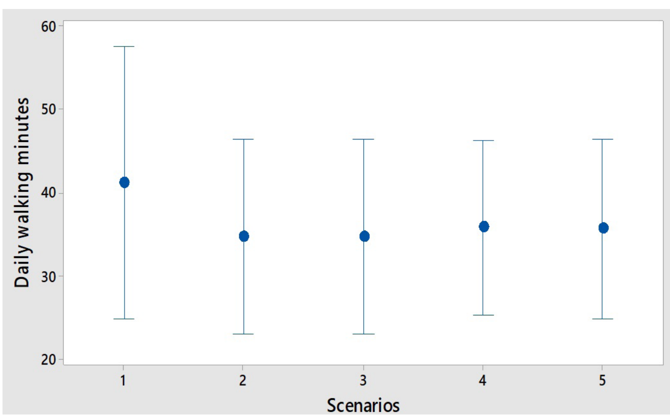
Scenario Testing Results

The results showed that Scenario 2: A centralized medication dispenser device with a dual entry corridor would offer the most efficient and cost-effective option (see Figure 14: Interval Plots for Design Scenarios). Statistical tests were applied with 95% confidence. Although walking distance would not improve for all nurses, the overall average reduction for nurse would be 15%, saving an estimated 390 hours of non-value-added time annually. Scenario 2 also minimizes the risk of high daily walking distance. Scenarios 4 and 5, which added an additional medication dispensing, did not have the expected positive effect on nurse travel distance, and as such, would not be needed (a cost savings for the project). Under Scenario 2, foot traffic by the team station was predicted to decline by 5.6% and time spent in touchdown station would increase by 2%, which would be expected to translate into a more direct care spent with patients.



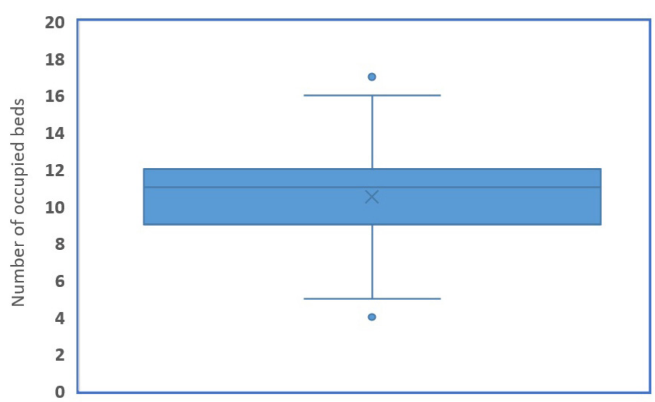


Figure 14: Interval Plots for Design Scenarios

Figure 15: Average Occupied Beds

Projection of Bed Capacity

The future state simulation model was also used to predict future state bed utilization. While the existing ICUs were often over capacity, particularly the medical ICU, it was assumed that in the near future, some ICU beds could be utilized for step-down patients as well as overflow for medical – surgical patients. The study demonstrated that under current volumes, up to three ICU beds would be available in each unit for flexible use (see Figure 15: Average Occupied Beds). Alternatively, the hospital could choose to shell those spaces at an estimated cost-savings of approximately $1M.

ALIGN

The aim of this phase was to ensure that the new design would perform as expected and to determine where additional opportunities for improvement might be identified. A pre-post simulation study was conducted to compare current design with a suggested future design with decentralized nurse stations using the performance metrics established for the project. T-tests were used to compare the results for each metric. Based on the comparisons, the new ICU layout is expected to result in a 31% reduction in indirect care activities for medication administration activities, a 56% reduction in indirect care for monitoring activities, a 10% in indirect care for arrival activities, and a 48.8% reduction of overall flow by patient rooms (noise reduction benefit). The new design also has excess capacity of 3 beds to handle unexpected surges. A summary of study results is shown in Table 3.

Measure		Current	Future	Improvement
Bed capacity		74.1%	56.5%	Excess capacity of 3 Beds*
Indirect care duration	Arrival activity	24.13 min	21.7 min	Reduced by 10%*
	Meds activities	14.7 min	10.17 min	Reduced by 31%*
	Personal care activity	3.47 min	2.58 min	No statistical difference
	Monitoring activity	6.4 min	2.8 min	Reduced by 56%*
Circulation node passing		137.1	70.2	Traffic reduced by 48.8%*
Bumpability		12.9	13.9	No statistical difference

* Statistically significant at 95% CI

Table 3: Summary of Current and Future State ICU Metrics

Measuring Congestion

While previous research has found that the shift to a decentralized nurse station leads to less team interaction [17], our research suggests that decentralizing nurse stations may not negatively impact opportunities for spontaneous interaction of clinical team members. With respect to congestion, the future state design significantly outperforms the current state. Figure 16 shows two heat maps of daily traffic measured at key nodes on the unit.

Decentralizing the unit will distribute circulation more evenly throughout the unit. With greatly reduced foot traffic outside patient rooms the new unit is expected to reduce noise and improve patient experience in the future ICU.

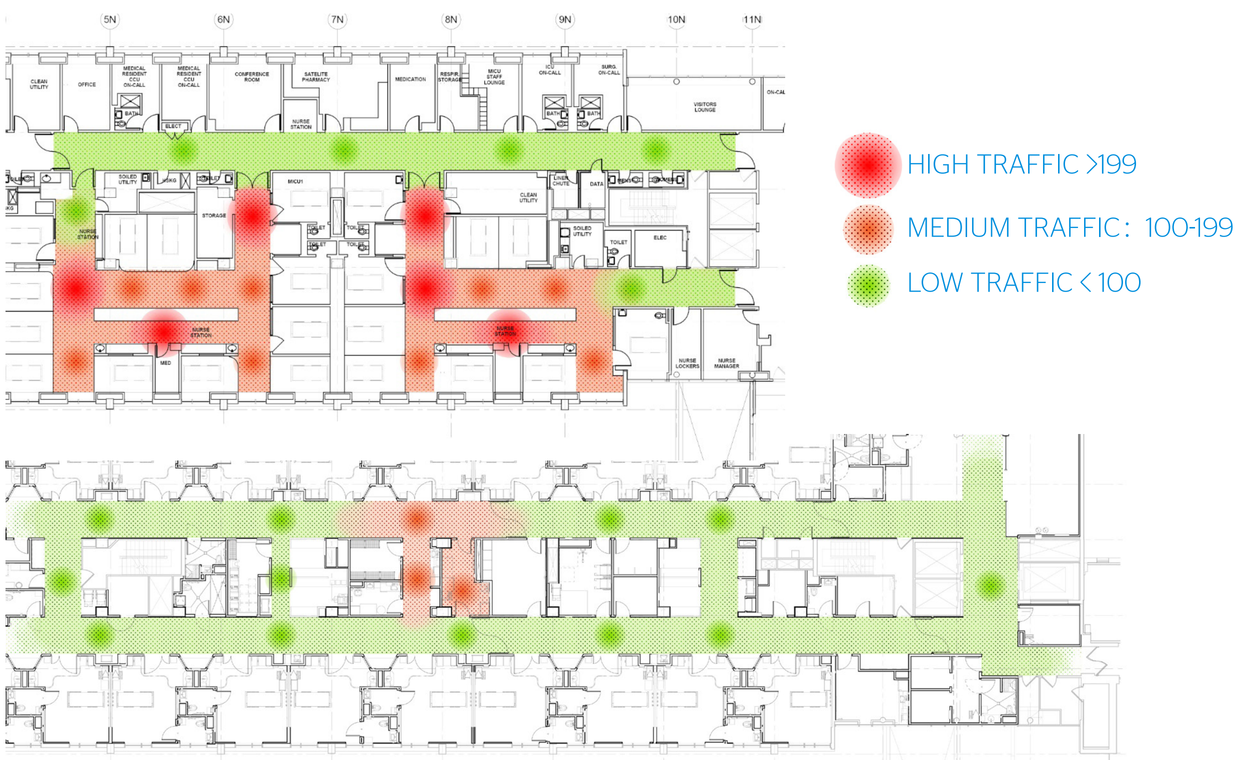


Figure 16: Comparing Congestion in the Current and Future State

LIMITATIONS AND LESSONS LEARNED

Simulation modeling of ICU is highly dependent on staff movement which is highly variable and patient-dependent. With the lack of actual tracking data of staff movement, it was still possible to simulate staff movement after interviewing several nurses and physicians and conducting shadowing sessions to learn the main staff activities. Future research should consider ways to utilize real-time technologies which can help to learn significant patient tracks and reduce the time required for data observation and collection. It was the team's experience that applying simulation modeling during early design phases was informative to the design teams as it provided an early "proof of concept"; however, the level of fidelity such models can have in early stages is dependent on accurate data and understanding of the basic healthcare processes at such stages. The project team overcame this drawback by maintaining frequent communication with the nurse and physician managers on the clinical team. The period of on-site observations provided an opportunity to build rapport with the teams which contributed to the overall success of the simulation efforts.

CONCLUSION

This research study shows how simulation modeling served as a useful evidence-based tool to predict performance of a future ICU layout within the context of the process-led design. Applied together with process improvement tools such as workflow mapping, cause-and-effect diagrams, and participatory design techniques; operational and design planning can take place concurrently. Simulation modeling can allow the team to test and verify operational and design improvements in tandem. In earlier design stages, simulation modeling can be used to understand workflow dynamic and generate data-driven adjacency diagrams as well as test scenarios based on stakeholder needs. In later stages of design, modeling can be used to demonstrate performance and quantify the extent to which various metrics will improve. This study demonstrates how engaging with the cross-functional team to design space and workflows concurrently make it possible discover problems with current flows and design and had a positive effect on streamlining those processes. The clinical and support team were able to visualize new layout because of 3D modeling environment. In this research, novel modeling approaches were developed to use modeling to measure circulation, congestion, and bumpability. To the knowledge of the authors, this is the first time these metrics were applied in simulation to evaluate designs. They are important metrics for ICU design given their role in team collaboration and in fostering a more positive healing environment for patients and for staff. Finally, this process-led approach served as a proof of concept to apply mixed methods during design development to provide insights to stakeholders and designers about advantages and trade-offs of multiple design and operational scenarios.

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