Redesign of Bedside Supply Carts Using Human-Centered Design to Improve Emergency Department Workflows

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Submitted to: JMIR Human Factors
on: August 07, 2025

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Abstract

Background: Emergency departments are often chaotic environments where delays can significantly impact patient care. Key items are stored in supply carts in or near patient rooms to promote efficiency and enable nurses to spend more time assisting patients. However, disorganization, lack of standardization, and lack of stocking can cause significant delays and negatively impact quality of care.

Objective: This study utilized human-centered design to improve the workflow for supply acquisition in an emergency department.

Methods: Using a mixed-methods, human-centered design approach following the Double Diamond framework, the team worked with nursing staff and physicians in an urban emergency department to understand the root causes of frustrations with the current supply carts. Qualitative findings about bedside nursing workflows were integrated with quantitative observations of inventory and supply usage to drive a rapid-cycle prototyping process to optimize supply management in the bedside cart.

Results: A lack of clinical staffing exacerbates preexisting challenges with restocking the medical supplies in the bedside carts. This problem is compounded by misallocation of supplies, with high-frequency items underrepresented and low-frequency items overrepresented in the bedside carts. This leads to wastage of the seldom-used supplies, and lack of access to the most commonly used supplies. Reorganization of the cart through co-design with nursing staff sped up supply acquisition by approximately 20% overall, tripled the availability of the most important supplies, and reduced the need for restocking from once per shift to once per three shifts, thus producing tangible improvements even within institutional limitations.

Conclusions: A human-centered design process, using human factors principles in tandem with extensive input from end-users, enables improvements to stocking.

(JMIR Preprints 07/08/2025:80861)
DOI: https://doi.org/10.2196/preprints.80861

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Implications for Practice:

- Lack of easy access to appropriate supplies negatively impacts patient care and contributes to nurse burnout and frustration.
- Human factors engineering can improve access to patient care supplies through redesigning the layout of hospital supply carts to better align with workflows.
- Co-design with frequent collaboration from stakeholders and end-users ensures that solutions address the issues that matter most in a sustainable way.

Keywords: medical supply cart, patient care, inventory, cluster analysis, ergonomic workflow, human centered design, emergency department

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1 | Introduction

In a busy emergency department, every second counts. Medical professionals need to have access to key supplies and medication in an efficient and timely manner[1,2]. These key items are often stored supply carts in or near patient rooms in order to promote efficiency[3-6]. However, disorganization and lack of standardization can delay patient care and negatively impact outcomes [1-3,7-9]. Lack of supplies is also a frequent cause of operational failures and studies have shown that access to supplies as a leading factor in 'time wasted' in an emergency setting[3,9,10], and lack of familiarity with a cart system has been identified as one of the most common factors adversely affecting the quality of care in a high-stakes medical setting[11].

Human-factors engineering has emerged as a dominant method to address challenges in stocking[1,2,4,7,8,12-15]. For instance, Maul, Latham, and Westgate described that reorganizing and standardizing the contents of a resuscitation cart in a children's hospital according to the 5S Lean design method reduced the time needed to acquire supplies by 46%[7]. Similarly, the reorganization of a hospital medication cart based on usability testing and simulation reduced the number of wasteful actions taken while searching for the proper supply[12]. While groups vary in the methods they used, one thing remained true in each case: they began by understanding who is most affected by the challenges caused by the existing system.

The burden of a disorganized supply system often falls heavily on nursing staff, who are already struggling with staffing shortages and heavy workloads[16,17]. Nurses report frequently having to leave rooms to search for supplies, increasing job frustration, delaying patient care, and reducing the time available to spend with patients[9,18]. One study even reported that more than one third of nurses' time is spent looking for equipment, with an annual estimated cost of $1 million in lost time per year[10].

Given that nurses are most affected by supply layout, any redesign, therefore, should be done with nurse feedback and input at every step[14,15]. This is critical not only for ensuring optimization of the new system based on a nurse's lived experience[17], but also for ensuring nurses' approval and uptake of a new system[1,19,20]. It also gives nurses a voice in their workplace, increasing satisfaction, improving work performance, and helping to provide an environment for safe, quality patient care[14,21].

Here, we discuss the use of a human-centered human factors approach to redesigning the bedside cart supply in the emergency department of a low-resourced urban community hospital. The aim of this mixed-methods co-design intervention was to understand the challenges associated with restocking and access to patient care supplies, and implement a strategy to improve reliable and efficient access to supplies for nurses in an ED. Our novel approach, which combined the use of the double-diamond design framework with human-centered and participatory design, allowed us to reduce the time needed to access needed supplies by reorganizing the carts to hold more of the most crucial supplies and minimizing wasted space.

2 | Methods

In this paper, we report on the use of a data-driven and human-centered design approach to addressing the problem of supply shortage in the bedside carts in the ED. Our approach followed the double diamond design framework[22]. The double diamond design framework is a human-centered framework that breaks design into two main phases, each composed of a divergent step of discovery and ideation, followed by a convergent step distilling findings into a concise and workable next step. In addition, we relied heavily on principles of co-design[23], working closely with stakeholders at every step of the process to ensure any solutions fit within the constraints of the setting and appropriately addressed their concerns.

Following this framework, the design process was broken into three main phases. In the first phase of the double diamond, the team immersed themselves in the clinical environment and engaged with stakeholders to gather information. Based on these observations, they performed a root cause analysis to discover and define the true problems affecting supply accessibility. Finally, in the second half of the double diamond, they underwent co-design process with hospital staff to develop and deliver a new bedside cart prototype that successfully addressed the issue. Results are organized according to the SQUIRE reporting guidelines for quality improvement in health care[24].

2.1 | Study Background and Location

This study was conducted in a low-resourced, urban emergency department in Eastern Pennsylvania. The ED serves approximately 48,000+ patients every year and has inpatient medical and psychiatric services, with very little specialty coverage. Children and injured patients are generally sent to other hospitals in the region, and admission rate for patients is 10-13%. The department is split into a 23-bed high acuity area staffed with a 1:4 nursing to patient ratio, and a 10-bed low acuity area staffed with 1-2 nurses.

The ED utilizes a lockable 5-drawer Harloff ‘‘bedside” cart positioned in the hallway outside each patient room. Drawers have varied heights; the top three are each approximately 2.5” tall, the fourth drawer is 5.5” tall, and the bottom drawer is 8.5” tall. Supplies are separated by thin, ⅛” acrylic dividers in compartments that often fail to accommodate longer items like needles and syringes (Figure 1). In addition, heavy items like IV bags have deformed many of the carts over the years. Carts are often understocked given limitations in staff availability, causing nurses to search three or four carts to find necessary supplies. In addition, the underutilized supplies may linger in the cart for years well past their expiration dates. The research team was embedded within the ED from January 2025 to May 2025; the full process can be seen in Supplemental Figure 1.The team members included multiple engineers with specialties in mechanical design, product design, data science, human factors, and systems engineering, and two emergency medicine physicians.

a) b)

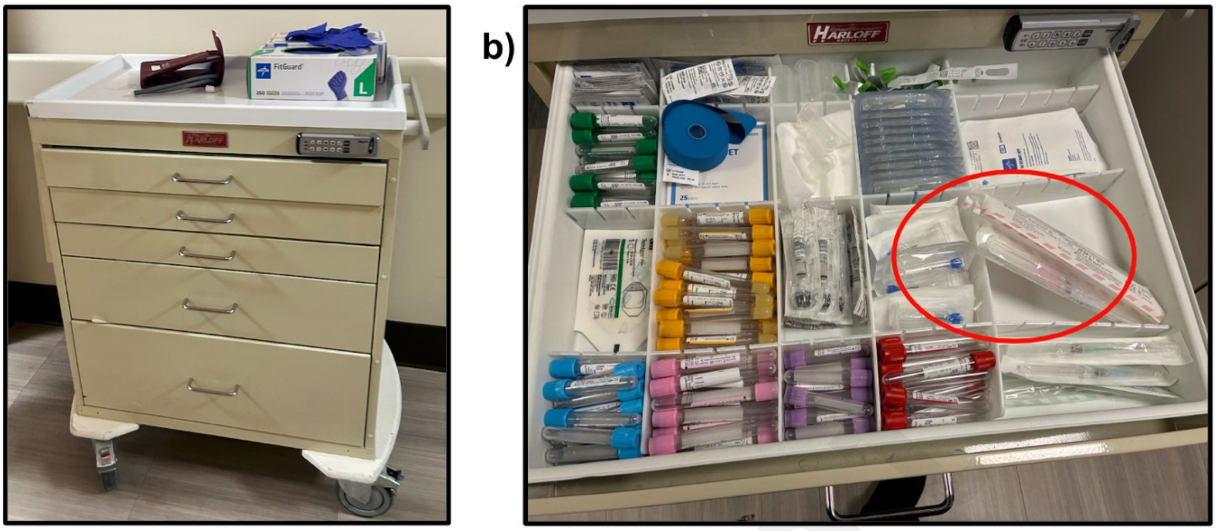


Figure 1: Original Cart System. a) Lockable 5-drawer Harloff ‘‘bedside” cart positioned in the hallway of the emergency department. **b)** Original layout and dividers in drawer 1 (topmost drawer) of the bedside carts. Note that needles (indicated by the red circle) are stored at a diagonal because the allocated space is too short.

2.2 | Clinical Immersion and Key Stakeholder Interviews

The team began by observing users interacting with the beside cart, and interviewing key stakeholders (see Table 1) to understand the key challenges and concerns that they saw with the current carts, and to understand the supplies they needed the most. Interviews were semi-structured[25] with a pre-determined list of questions, but conversations varied according to participant interests. Interviews were conducted with multiple team members present; one person led the conversation while others took detailed notes to ensure no information was missed. After 60 hours of observation, and after the insights from observation and interviewing had reached saturation[26,27], the team used a thematic analysis[28] to identify the key unmet needs (Table 2). These needs were subsequently validated through conversations with nursing staff.

2.3 | Co-design with Key Stakeholders and Initial Solution Selection

Focused solutions to the supply problem were addressed in a series of co-design sprints to determine how to reform the supply distribution system. A multidisciplinary group of stakeholders (including the research team, additional physicians, and nurses) underwent a series of design thinking brainstorming exercises to generate over 40 potential solutions. From there, ideas were screened for viability (whether the solution addressed the core problem), desirability (whether the stakeholders would like and utilize the solution), and feasibility (whether the solution would be possible given other constraints). From the session, the team identified six key domains - accessibility, legality, reliability, ease of restocking, capacity, and feasibility - required for a successful solution based on the unmet needs. Subsequently, screening and scoring matrices were implemented to identify the top solution[29]. Although the original solution selected was to pull out the key items used most often by nurses and put them in their own designated carts, obtaining additional carts would have become a challenge. The team sought to determine whether a similar result could be obtained merely by reallocating the proportions of various items in the existing carts to align with usage and need.

2.4 | Quantitative Analysis of Current Inventory System and Item Usage

An inventory of six different carts throughout the ED was obtained to understand the current supply state. Maximum capacity was calculated as the highest value from each of the carts. During the observation period, the team also collected data on the supplies used to care for 17 different patients with different chief complaints (16 hours of observation). This allowed the team to see supplies being used in real-time and observe nursing micromovements as well as get a sense of overall inventory throughout the department.

From there, the team ran a k-means clustering analysis on the supply usage data to identify if there were any clusters of supplies that were frequently used together. While preliminary data was too limited to generate a large number of solid clusters, the initial results using k-means with two clusters revealed a small cluster of high-use items, and a much longer list of less-frequent items. These high-use items were then compared with reports given by nurses (Table 3).

2.5 | Rapid Prototyping of New Drawer Organization System

Through conversation with nursing staff, the team obtained (i) a list of all of the supplies nurses wanted in the supply carts, (ii) suggestions for changes in quantity for items already present, and (iii) requests for layout changes to improve workflow. The team compared the wish lists to the inventory lists and eliminated unnecessary items, then integrated the qualitative suggestions with their previous quantitative results to create prototypes for drawer dividers to better allocate cart space. This was like the ‘jigsaw’ method described by Shultz et al, where participants were given pieces of paper roughly the size of each supply and told them to fit them into their desired configuration[8]. Here, the team used the actual copies of the supplies; nurses were shown early prototypes made using cardboard and tape, and asked to move around the dividers as needed (Figure 2a). The team also asked nurses to model the movements needed to acquire items so that the new compartments had an ergonomic flow.

Prototypes were designed according to the following principles, all based in human factors engineering: (1) items that were used together should be located in the same drawer and in close proximity; (2) higher-frequency items should be on higher shelves to optimize body posture; (3) compartments should conform to the size and shape of the item; (4) items should fit enough supply for at least one full shift for a nurse; and (5) designs should minimize exterior changes to the cart to minimize relearning.

Once nurses provided feedback on the cardboard prototypes, the team incorporated those changes into new prototypes (Figure 2b-e). Team members created CAD drawings in OnShape (Boston, MA) for each of the drawer bases and inserts based on the final cardboard models, then laser-cut prototypes made from ¼” acrylic using a laser-cutter.

2.6 | Simulation and Evaluation of Design

To ensure that the dividers were an improvement over the original models, the team ran a variety of simulations with the help of nursing staff. The team created four scenarios that would require different combinations of supplies: (i) a patient ready for discharge; (ii) a patient with fever and a recurrent headache; (iii) a patient with chest and abdominal pain; and (iv) a patient with multiple constitutional complaints. The number of scenarios was based on nurse estimates of how many patients they would see in each room throughout the duration of their twelve-hour shift; scenarios were intentionally left vague.

The team fully stocked both an existing cart and the prototype and asked on-shift nurses to collect the necessary supplies for each of the patient scenarios. Items removed from the cart were not replaced, but instead set aside; nurses were told that if an item was not present in the cart when they needed it, they should go about their normal routine, whatever that was. This often involved searching another cart, or going to the clean supply, substituting a different item or collection of items, or foregoing that item altogether. Nurses were quasi-randomly assigned, in equal numbers, to start the simulation with either the prototype cart or the current standard to grab items from either the old or new carts first so that the time required to figure out what items to select did not bias the overall time. When all four scenarios were conducted with one cart, they would then run the same scenarios with the other cart.

Carts were not restocked between sets of simulations (“shifts”). This was to mimic real-time usage, where stockers often would not be able to resupply carts until multiple shifts had elapsed. After three ‘shifts’ had elapsed without restocking, the carts were fully restocked and the simulations were run again with different nurses.

No identifying information about the nurse was collected, and the team was not assessing their responses for clinical accuracy. Nurses were not compensated for their assistance.

2.7 | Ethical Considerations

The University of Pennsylvania’s Institutional Review Board (IRB) waived the need for ethics approval and participant consent for the collection, analysis, and publication of the anonymized data for this quality improvement initiative. Informed consent was obtained verbally before participation. All data has been anonymized.

3 | Results

3.1 | Clinical Immersion and Key Stakeholder Interviews

The team spoke with a wide range of stakeholders, hoping to engage with people throughout the entire supply workflow. This included nurses, doctors, and physician assistants who used the carts, technicians who stocked the carts, and even the supply manager who oversaw stocking and ensured that the department remained in compliance with hospital policy and external regulations. The full chart of interviewees can be found in Table 1.

Table 1: List of Interviewees for Primary Stakeholder Interviews

Role	Count
Nurse	8
Technician	2
Resident	2
Supply Manager	1
Physician Assistant	1
Attending Physician	1

During the observation period, the team was told that the bedside carts were fully stocked by emergency technicians and were positioned outside patient rooms so that nurses could efficiently provide patient care. In practice, however, carts were constantly understocked, and nurses frequently visited multiple carts searching for supplies. As a result of this, some nurses no longer relied on the carts, and instead went to the central supply closet every time they needed something, or carried a personal bucket of supplies they thought they might need, contrary to hospital policy.

After roughly 60 hours of observations, and thematic analysis of statements obtained during the interviews (see Table 2), it became clear that the current setup did not meet the supply and demand for current nursing staff. For example, each cart could hold only two intravenous (IV) start kits, while nurses reported using at least one per patient. In addition, the cart could only hold up to three one-liter bags of Lactated Ringer’s solution, when a nurse went through an average of five to ten bags per shift across all of their rooms. As a result, these key supplies were constantly in short-supply and frequently depleted.

Table 2: Sample Thematic Analysis of User Statements

Insight	Example Statements
Unreliable or unavailable supply puts patient lives at risk.	*"[When I try to use the carts,] the things I need to save my patient's life aren't there."* *"I'd rather save patient lives than have a clean cart. I can clean the cart later, but I can't bring them back."* *"I can't leave a seizing patient to go look for oxygen masks because my cart didn't have any."*
Stocking is time-consuming and irritating, and there's often no one to do it.	*"The techs are pulled to do other tasks like 1-on-1, and no one has time to restock the carts."* *"If we had safer ratios, I'd be more willing to stock the carts."* *"I just want my carts stocked. The rest, I can work with."* *"Anything to make things a little easier or streamlined, especially with refilling the carts, would be huge."*
Nurses don't trust the carts to have the supplies they need, and often use workarounds.	*"If cart supplies are low I'll get a basin of the most used things and put them on a cart so I know where to find them."* *"I run from cart to cart all day, then say 'F** it, I'm just going to the stockroom.'"* *"I get things from the Clean Supply rather than the carts so I don't waste my time looking."*
There's not a perfect consensus over what should be in the carts.	*"I've been going from drawer to drawer looking for socks for my patient."* *"After the emergency, that's when we can put on socks."*
Cart contents don't match what nurses actually need.	*"A lot of things in the cart are rarely used - they're a waste of space."* *"I really want a space for the ultrasound needles."* *"When there are things in the cart that aren't used, they expire and we have to throw them out."*

Second, while technicians were responsible for restocking these carts, they lacked sufficient time to do so amidst widespread staffing shortages and a host of other, often more-critical responsibilities such as sitting with patients who required continuous monitoring, or helping to transport patients. Nurses could assist with restocking when time permitted, but emergency department shifts were often busy and this was usually impossible. Carts often remained unstocked for several shifts, often for days on end.

In addition, while there was a photographic guide on top of the cart to assist with stocking, there was a lack of consistency of items inside the cart. Over time, nurses had begun to stock the carts with their preferred items and formats. The clean supply room was aptly labeled with items in their respective categories - IV, wound care, comfort, respiratory, fluids, etc. - but this system did not correspond to the organization in drawers.

Finally, the observations and interviews demonstrated the importance of buy-in for any potential solution. Nurses expressed concern that any additional work from a proposed solution would fall upon their already-overloaded shoulders, and stated outright that there were certain proposals that they would simply not implement.

3.2 | Co-Design and Initial Solution Selection

The interdisciplinary team held a design sprint workshop with several nurses to generate over 40 potential solutions. Solutions ranged from developing new technologies and processes to detect when a cart was empty, thus saving nurses from having to check it and flagging that it was ready to be restocked, to hiring a new person with the sole job of restocking carts, to altering the workflows of staff members in other departments to help assist with restocking, to even assigning each nurse their own cart to be responsible for and stock as they wished. However, solutions were limited by resources (the hospital was unable to allocate money to hire a new person or replace the existing carts), and by staffing shortages and workload (the team did not identify anyone in the environment with the extra time and ability to add restocking to their workflow). In addition, policy restrictions meant that each cart needed to be standardized and thus could not be left up to each nurse. Additionally, nurses and doctors rejected any solution that involved making restocking entirely their responsibility. Given these limitations, the most feasible solution involved a reorganization of the cart system, utilizing the existing space but reconfiguring it to increase capacity for high-use items.

3.3 | Study of Cart Inventory and Usage

Before making any attempts to redesign the cart capacity, the team needed to understand both the original layout and typical patterns of item usage. The team thus developed an inventory to track supply usage for nurses across a total of 16 hours to attempt to capture the relative frequency of supply usage, as well as the types of supplies often used in conjunction with each other. From this information, and through consultation with nursing staff, the team was able to isolate three key clusters of highly used supplies: IV, diagnostics, and respiratory supplies. The contents of each of these clusters can be found in Table 3. They also obtained an approximate estimate of the amount of each of these supplies needed per day. IV start kits were the most highly-used item, as they were used with nearly every patient. Along with the kits, nurses also used flushes, hep-locks, and vacutainers.

Table 3: High-Use Items Identified by Clustering Algorithm and Nurse Report

Clustering Algorithm	Nurse Report	Major Spatial Clusters
Most highly-used items: • IV start kit • Luer-lock vacutainer • Hep-lock • 18 gauge IV needle • Flushes • Green test tube • Blue test tube • Orange test tube • Pink test tube • Purple test tube • Red test tube • 4x4 cotton gauze • Lube • 3 ml syringe	Top 5: • IV start kit • Luer-lock vacutainer • Hep-lock • 18 gauge IV needle • 20 gauge IV needle Additional concerns: • Flushes • Green test tube • Blue test tube • Orange test tube • Pink test tube • Purple test tube • Red test tube • Oxygen mask • Nebulizer • Nasal cannula • Aerosol mask • Grey test tube • Red and yellow test tube • Clear test tube • Urine cups	IV and Related (Drawer 1): • IV start kit • Luer-lock vacutainer • Hep-lock • 18 gauge IV needle • 20 gauge IV needle • IV test tubes (green, blue, orange, pink, purple, red) • 4x4 cotton gauze Diagnostics (Drawer 2): • Test tubes (red/yellow, grey, clear) • Urine test Respiratory (Drawer 4): • Oxygen mask • Nebulizer • Nasal cannula • Aerosol mask Bulky Items (Drawer 5): • Urine Cups • Flushes

3.4 | Rapid Prototyping of New Drawer Organization System

After undergoing the rapid prototyping process described in Section 2.5 and shown in Figure 2, the new design provided a marked improvement over the old model. The layouts for the old versus original designs can be seen in Figure 3, and the difference in capacity between the two designs can be seen in Table 4 and Figure 4 (key supplies only; full list in supplemental Table A). Specifically, for the IV kits, the new carts comfortably held nine kits, while previous models held only two or three - a 200% increase for the most highly used supply. Co-occurring supplies, like the flushes (100% increase), vacutainers (125% increase), and hep-locks (75% increase), similarly increased in capacity. Given the total number of carts on the floor, this meant that the number of IV kits stored in the carts jumped from approximately 100 to approximately 300 - enough to make it through multiple shifts without restocking. The new cart design similarly doubled the size of spaces allocated for key respiratory supplies like peak flow meters (200% increase), nebulizers (150% increase), and aerosol masks (150%) increase.

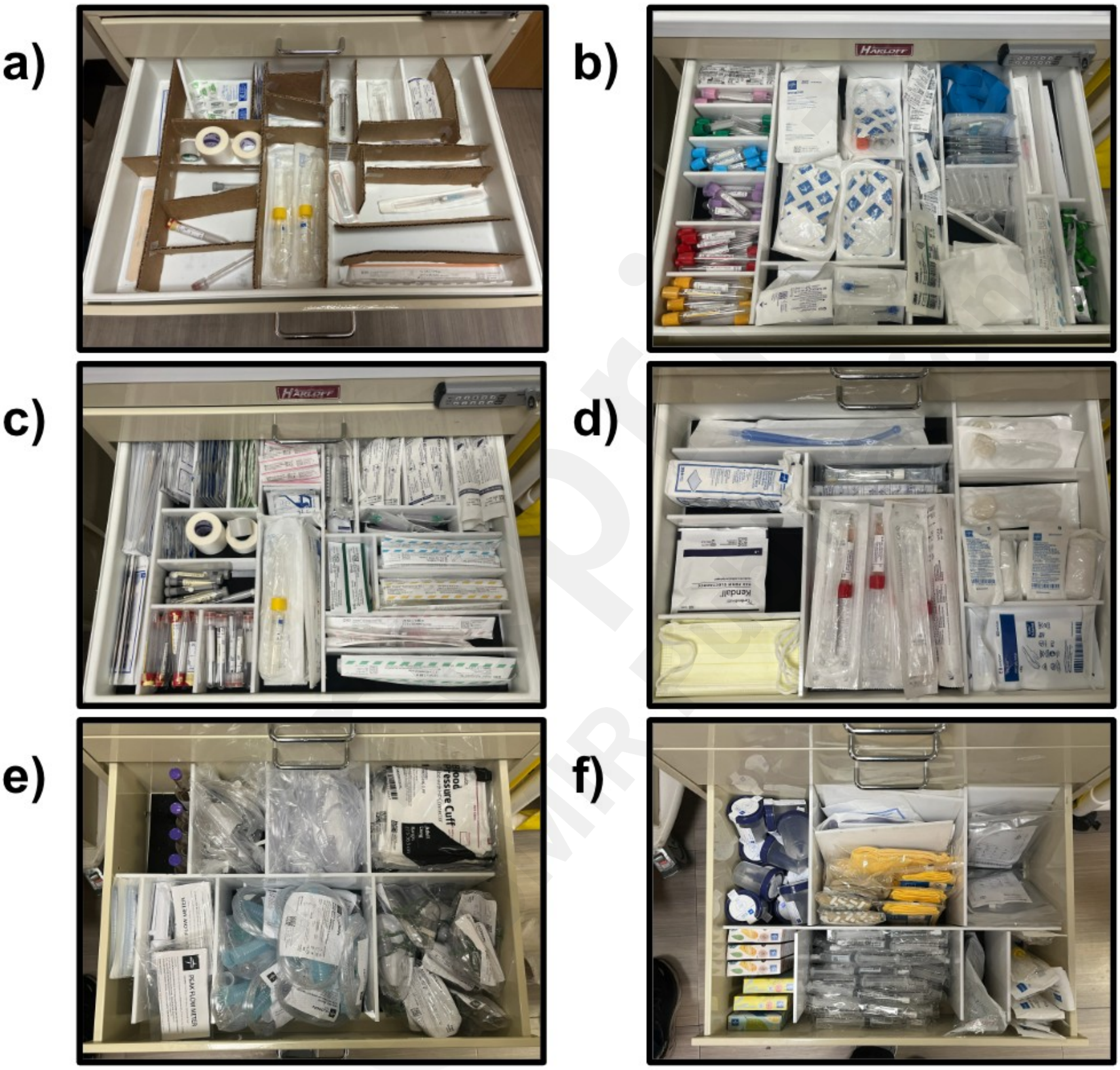


Figure 2: Prototype to Finalized Product. a) Cardboard prototype used in interactive design process with nurses (Drawer 1) **b)** Finalized, fully stocked prototype for Drawer 1 **c)** Drawer 2 **d)** Drawer 3 **e)** Drawer 4 **f)** Drawer 5.

Table 4. Comparison of the number of items in the current nursing carts to the modified amounts in the prototype (key items).

Item	Difference

IV Hep-lock	+ 76%
IV start kit	+150%
Luer-lock Vacutainer	+125%
4x4 cotton gauze	+75%
Tongue depressors	+100%
Urine specimen collection kit	+67%
Normal saline IV flushes	+100%
Urine collection cup	+20%
Peak flow meter	+200%
Aerosol mask	+150%
Nebulizer	+150%
Cavillon No Sting Barrier Film	+100%
14/16 gauge IV Catheters	+500%
18/20 gauge IV Catheters	Added
Blood collection Tube (Green top)	-47%
Blood collection Tube (Pink top)	-63%
IV disinfecting cap	-34%
Insulin syringe	Removed
50 ml syringe	Removed
Lactated ringer's solution	Removed; added to a locked box on top of the cart

Figure 3: Drawer 1 Original vs. New Layout. Colored boxes highlight key changes that were made. **Blue**: Needles no longer stored at a diagonal with no decrease in capacity **Purple**: Hep-lock capacity increased by 75% **Green**: IV start kit capacity increased by 200% **Orange**: Storing all tubes in one column makes for a more ergonomic workflow; capacity decreased to avoid wastage.

In many cases, this was achieved by removing low-frequency items that were rarely used and could be more effectively stored in the central supply closet. In other cases, it was achieved by ensuring each compartment fit to the size of the tool it was meant to contain, eliminating wasted space and reducing the chances of needles being damaged or bent by attempting to be forced to fit in the cart. The new design also allowed space for the addition of other supplies, like a speculum, that were highly sought after by physicians and nurses and could not fit in the cart previously. The design met with approval from nursing and administrative staff at all stages of the process.

Figure 4: Cart Redesign Corrects Supply Allocation. After redesign, critical items like those used with IVs or for urine collection and testing increased in capacity, while overrepresented test tubes decreased in capacity.

In addition, the finalized model was both sturdier and less prone to breakage than the original model. This took a couple of iterations: the first draft, which used an acrylic solvent, proved unstable and snapped upon construction, so the team reconfigured the designs to use a press-fit layout instead. With this approach, drawers were easy to assemble and very sturdy.

3.5 | Simulation and Evaluation of Proposed Design

Once the prototypes were completed, they were tested for practical usage. After completing the simulation described in Section 2.6 above, the novel carts outperformed their older counterparts. On average, nurses were able to acquire needed supplies from the new cart nearly six seconds faster (21% faster) than they were able to get supplies from the old cart (paired t-test, $df = 23$, $p = .09724$). While this was not significant, this was likely a limitation of low sample size; in addition, this simulation likely overestimated the time required to get samples from the newer cart because nurses were unfamiliar with its organization and needed to spend more time to find where supplies had been moved to.

In addition, the time saved only increased as the carts went longer without stocking. During the first shift, the new cart only saved about 1.5 seconds on average. During the second shift, the new cart saved an average of 4.7 seconds. But by the third shift, the cart saved an average of 11.3 seconds (Figure 5). This time is a direct reflection of an improvement in capacity. While the old cart ran out of IV start kits by the third patient, forcing nurses to search for kits in nearby carts for every subsequent patient, the new cart contained all of the needed supplies for every patient. On average, a trip from a cart to the clean supply room (the preferred solution for nurses who did not trust that supply carts contain the proper equipment) took 1 minute; these trips were entirely eliminated by the use of the new prototype.

Figure 5: Time Savings as a Function of New Cart. a) The new cart saved an average of 5.8 seconds per simulated patient, and the time saved increased as the cart went longer without being restocked. **b)** As the cart went longer without restocking, the percent of time saved while accessing needed supplies increased, from about even when both were fully stocked, to 40 percent after two shifts. Boxplots show distribution of data (n=8 per shift). Sample size was too low to assess statistical significance.

Furthermore, the team noticed that the number of supplies taken from the new cart was much higher than those taken from the old cart. Specifically, there were several items that nurses were not willing to go to another cart for, like speculums or certain test kits, but were happy to grab if they were present. This implied that having carts stocked with these supplies meant that nurses would actually use them, providing better care.

3.6 | Plans and Barriers for Full Implementation

The drawers have not yet been implemented in every cart in the department, due mostly to resource constraints. Full implementation would require a large up-front cost: due to the reorganization of supplies, some supplies were moved to different drawers. Because hospital policy requires that all carts contain the same organization, it is not possible to gradually phase in new carts over an extended period. In addition, because of this reorganization, it is not possible to replace the cart drawers for all carts, one drawer at a time, since incomplete adoption would mean that some items would no longer be included. This is certainly a limitation of the team's design process - had considerations about gradual or modular adoption been considered earlier on in the process, this would not have been an issue. However, the team is working to find the lowest-cost way to implement these new designs.

They are also working to mitigate unintended consequences arising from adjustments to the new cart system. Specifically, to improve the ease of adjustment, they have created a pamphlet showing an updated schematic of the cart with pictures of the contents of each full cart. A written list of the cart's contents and approximate capacity will also be provided to keep at each nursing station for training purposes and reference. They will label carts with the contents of each drawer (i.e., Drawer 1 will be labeled with **IV Supplies**; Drawer 2 will be labelled with **Wound Care**, **Diagnostics**, and **Extra Needles**; Drawer 3 will be labeled with **Miscellaneous Small Supplies**; Drawer 4 will be labeled with **Respiratory Supplies**; and Drawer 5 will be labeled with **Flushes, Urine Cups, Catheters, Tubing**), and the bottom of each section of the drawer will have a photo of the supply that belongs inside it. These improvements will facilitate stocking, assist with the transition, and make it easier to onboard new nurses. In addition, it will decrease the likelihood of drift over time, ensuring that staff use the partitions as directed.

4 | Discussion

This human-centered design process highlighted the importance of co-design for improving workflow and supply management in an emergency department. By observing, interviewing, and directly working with the people who use the system the most, the team was better able to understand the key challenges that influenced the effectiveness and constrained the solution space. The final prototype increased the capacity for key items by up to 200%, enabling cart capacity to last for 36 hours (three shifts) rather than requiring restocking within the first 12-hour shift. In addition, similar to other studies[15,30], the reduction in response time finding supplies did not reach statistical significance, but trended towards a statistical result. This is in spite of the fact that the new design meant people spent more time looking for objects that had been moved, something that would change as people became more familiar with the new system. Notably, the improvement here is likely less because of more logical organization, and more likely to be because the new design reduced the number of trips that needed to be made to other carts or to the clean supply room.

Overall, the findings of improved supply accessibility are in line with reports from other human factors-based redesigns of supply carts in other departments of the hospital[1,2,4,7,12-14]. While the constraints of this setting are not entirely analogous to other settings – here, the challenge was less about disorganization and more about a limited availability of stockers – they nevertheless suggest that cart organization, tailored to the needs of the staff and built with human factors principles in mind, plays a critical role in departmental workflows.

Even when the carts were fully stocked, nurses noted that the items that were present were there in the wrong quantities. Low-frequency items were present in large quantities, while there were hardly any of the most commonly-used supplies. In fact, the supply manager told us that she had gone through the carts and had to toss hundreds of dollars' worth of unused supplies that had expired, an enormous waste of money and space for a department that had little to spare of either. This finding of overstocked items leading to wastage has been found in other sites as well[3,31], and suggests that periodic evaluation to ensure that carts can contain appropriate quantities of each supply is necessary. Our discovery of clusters of items frequently used together also matches the findings found by Hansoti et al[32].

In addition, the success of the quality improvement demonstrated the importance of human-centered design, particularly the frequent consultation with stakeholders during the ideation and prototyping process, ensured that the team's proposed solution was both effective and acceptable. Stakeholders were glad to be able to address a problem that mattered a great deal to them, and helped to ensure that the new designs addressed their particular concerns about the old model. Co-design is widely used in applied health research and is critical for ensuring that solutions focus on outcomes that are most important to end-users[23].

Tailoring the cart's contents to user workflow, and specifically minimizing the number of drawers that needed to be opened, improved user experiences. Although the cart's organization changed slightly, and users were less familiar with it, they still found it easier to use and preferred it over the standard cart. This is similar to the results found by Agarwal et al, where nurses preferred to use a cart that only required them to open one drawer per patient rather than a cart where everything was organized by tool but required multiple accesses[13].

In addition, nurses discussed how glad they were to be able to participate in the process. While this has been a persistent problem, engaging nurses in the redesign process gave them a voice, helping them feel like change was possible. This matches with previous research which found that nurse involvement in the co-design process improves nurse satisfaction[14].

The prototype created by this team is an example of how human-centered design can create substantial improvement in a nursing workspace. The team was able to identify the key items nurses needed most, and provide sufficient quantities of those items to last an entire day without restocking, substantially improving workflow. Organization was designed according to nurses' priorities, focusing on ergonomics and efficiency using the same principles found in other studies[14,15]. While the solution could not solve the root causes of the issue – low funding and staffing shortages – it still made a meaningful, actionable contribution within the preexisting constraints by reducing the frequency of needed restocking. Once fully implemented, it is expected to save nurses a substantial amount of time per shift looking for items, reducing frustration and increasing the amount of time available for providing better patient care. In addition, the durability of the acrylic, the work done to document and improve ease of replicability of the system, and the buy-in from stakeholders all help to cement its durability and reduce the drift in restocking practices.

While the final design of the drawers in this project is specific to the specific hospital, the co-design process used demonstrates how stakeholder contribution and co-design can enable teams to make a meaningful impact in a low-resourced setting, working around structural barriers to improve nurse workflow and patient care.

4.1 | Limitations

This project, while useful, was unable to address the root cause of the problem of supply shortages: the lack of a dedicated person who could simply restock all of the carts on a reliable basis. Despite this challenge, the implemented solution managed to ameliorate these effects by decreasing the time needed to restock and increasing the time the cart could go without stocking.

The project also suffered from challenges regarding implementation – specifically, that because some items were moved to different drawers, and institutional policy required that all carts be organized the same way, implementation would need to occur all at once rather than being phased in gradually, requiring a larger up-front cost.

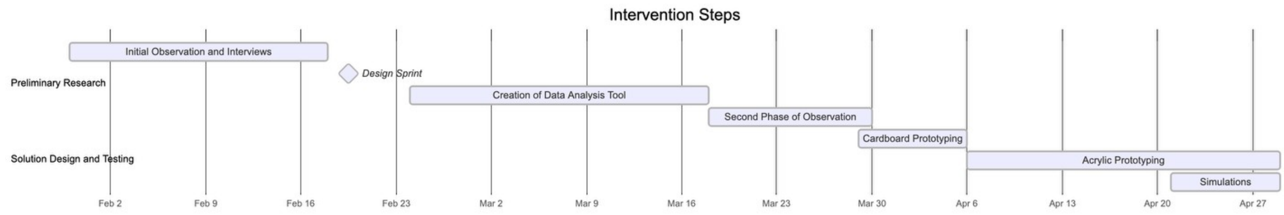
In addition, the data collection for the simulations was limited due to team availability and the availability of nursing staff to assist during their own busy shifts. The simulations also relied on convenience sampling, working with whatever staff was available at the time. Staff received the same prompts for both carts in the simulation; it is possible that thinking through the supplies beforehand made them faster at accessing the supplies the second time. We attempted to mitigate this response by randomizing which cart the team used first. Variable levels of experience with both the old and revised carts may also have led to bias with how quickly nurses found supplies in each cart[15]. Despite the lack of significance in time saved, the team was able to validate the utility of the intervention through the increase in capacity for key supplies, and through positive qualitative feedback from nursing staff indicating that based on their past experiences the cart would make a substantial improvement.

Lastly, the designs for the cart interiors created during this project were tailor-made for this specific department and the cart system already in place, and would not necessarily generalize to other emergency departments. However, the processes used to design and validate the solution would still be applicable, and the designs could be tweaked to fit the unique contexts of other departments.

5 | Conclusion

The co-design process used in this study demonstrates the importance of stakeholder engagement and contribution to quality improvement, and the utility of the double diamond approach in a healthcare setting. Stakeholder input was crucial for navigating around institutional barriers and ensuring that any proposed solutions would be accepted and implemented, rather than ignored. Indeed, the buy-in generated from participatory design ensured that the changes made would be sustainable. While the team's designs were specific to the ED's context, the process and insights can be applied to any other type of workplace improvement process. Specifically, we recommend engaging with stakeholders at every step of the way, particularly during the rapid prototyping phase. However, we suggest that future teams consider the ease of implementation, especially gradual implementation for budgetary reasons, while evaluating their designs.

Supplemental Figure 1



Supplemental Figure 1: Timeline of steps for cart intervention project.

Supplemental Table A: Comparison of the number of items in the current nursing carts to the modified amounts in the prototype (complete inventory).

	Item	Request	Current	Prototype	Difference
Drawer 1	Alcohol prep pad		55	35	-20
	Blood collection tube (Green top)	Less	30	16	-14
	Tegaderm		45	32	-13
	Blue test tube	Less	25	12	-13
	IV Hep-lock	More	17	30	13
	Tourniquet		2	2	0
	Blood collection tube (Orange top)	Less	40	16	-24
	Blood collection tube (Pink top)	Less	24	9	-15
	Clear empty tube	Less	24	18	-6
	4x4 cotton gauze		20	35	15
	VBG Aspirator	Less	12	6	-6
	blood collection tube (Purple top)	Less	20	13	-7
	IV disinfecting cap	Less	50	33	-17
	Push Button Blood Collection Set	Less	20	6	-14
	Luer-lock Vacutainer	More	8	18	10
	Blood collection tube (Red top)	Less	30	11	-19
	IV start kit	More	4	10	6
	20-gauge needles		9	10	1
	18-gauge needles		8	8	0
	16-gauge needles		1	0	-1
Drawer 2	Tape		14	5	-9
	Tongue depressors		20	40	20

	Cotton tip swabs		39	40	1
	Urine specimen collection kit	More	6	10	4
	Germicidal Disposable Wipe		25	16	-9
	Cavillon No Sting Barrier Film		8	16	8
	Sterile Lubricating Jelly		21	20	-1
	Neosporin	Remove	20	0	-20
	Bandage - big		5	30	25
	Bandage- small		19	30	11
	Clear top tube		35	21	-14
	1 ml syringe		10	8	-2
	Insulin syringe		20	0	-20
	Yellow and red speckled tube	Less	30	21	-9
	Grey top urine culture tube	Less	30	18	-12
	14/16 gauge IV Catheters		2	12	10
	18/20 gauge IV Catheters		0	12	12
	22 gauge IV Catheters		15	10	-5
	24 gauge IV Catheters		7	10	3
	3 ml syringe		14	28	14
	5 ml syringe		14	24	10
	10 ml syringe		8	5	-3
	21-gauge tip		11	6	-5
	22-gauge tip		11	6	-5
	23-gauge tip		4	6	2
	24-gauge tip		2	6	4
	25-gauge tip		2	8	6
	18-gauge tip		30	30	0
Drawer 3	Conforming stretch gauze		15	10	-5
	2x2 gauze		100	200	100
	Biohazard lab specimen bags		54	60	6
	Telemetry electrodes		10	6	-4
	Face masks		6	20	14
	E-Swab Kit		10	10	0
	Covid Swab test		15	18	3
	50 ml syringe	Remove	3	0	-3
	30 ml syringe	Remove	7	0	-7
	Yankauer		3	4	1
	ChloraPrep applicator		3	3	0
	Abdominal pad	Remove	8	0	-8
	Pulse Oximeter		8	8	0
Drawer 4	Anaerobic blood culture bottle (Purple Cap/Maroon Ring)		6	6	0
	Aerobic blood culture bottle (Grey Cap/Blue Ring)		6	6	0
	Gauze sponge		13	20	7
	Drain sponge	Remove	16	0	-16
	7-inch tubing	Remove	4	0	-4

	Nasal cannula		10	10	0
	Peak flow meter	More	2	6	4
	Aerosol mask	More	4	10	6
	Nebulizer	More	4	10	6
	Non-rebreathing mask	Same	5	4	-1
	BP Cuffs	More	8	10	2
Drawer 5	Purewick Female External Catheter		5	2	-3
	Urine collection cup	More	15	18	3
	Suction tubing		15	5	-10
	Male Purewick Catheter		11	2	-9
	Normal saline IV flushes	More	30	60	30
	Tissue box	More	1	10	9
	Secondary tubing		10	8	-2
	Primary tubing		5	6	1
	Gravity tubing		9	5	-4
	Socks	More	3	10	7
	Sterile vaginal speculum	Add	0	1	1
	Suction tubing		15	8	-7
	Lactated Ringer's solution		3	0	-3*

*****- LR is now placed on top of the cart

Acknowledgements:
The content is solely the responsibility of the authors and does not necessarily represent the official views of any funding agency. This work could not have been done without the incredible staff at the emergency department, whose insight and perspective was crucial. We greatly appreciate their time and willingness to speak with us. In addition, we are grateful to Helen Zhang for her perspectives on design.

Financial Disclosure / Conflict of Interest: None

Funding: KH is supported generally by the National Institute of Health (5T32NS091006-10). This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. No external organization had any role in the data for the present study.

Ethics Approval and Informed Consent: The University of Pennsylvania's Institutional Review Board (IRB) waived the need for ethics approval and participant consent for the collection, analysis, and publication of the anonymized data for this quality improvement initiative. Informed consent was obtained verbally before participation. All data has been anonymized.

Data Availability: Full anonymized data may be made available upon request.

Other Information: This study was conducted in the Emergency Department of the Hospital of the

University of Pennsylvania’s campus at Cedar Avenue (HUP-Cedar).

Author Contributions:
KH: Conceptualization, data curation, formal analysis, investigation, methodology, writing – original draft, review, & editing.
SD: Conceptualization, data curation, investigation, methodology, resources, writing – review & editing.
TH: Conceptualization, data curation, investigation, methodology, writing – original draft, review, & editing.
AM: Conceptualization, data curation, investigation, methodology, resources, writing – original draft, review, & editing.
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ON: Project administration, supervision, writing – review & editing.
NR: Conceptualization, project administration, supervision, writing – review & editing.

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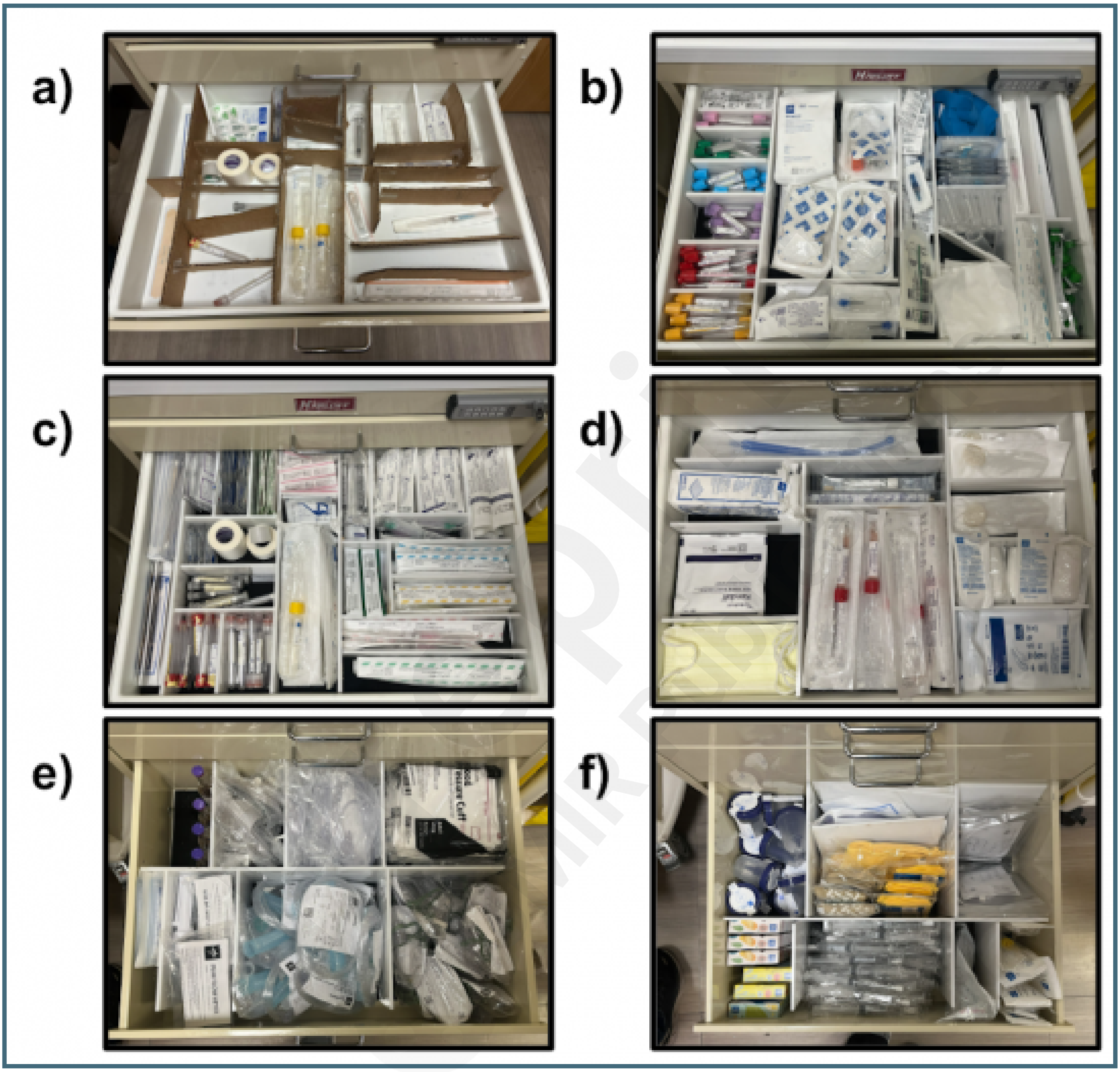
Supplementary Files

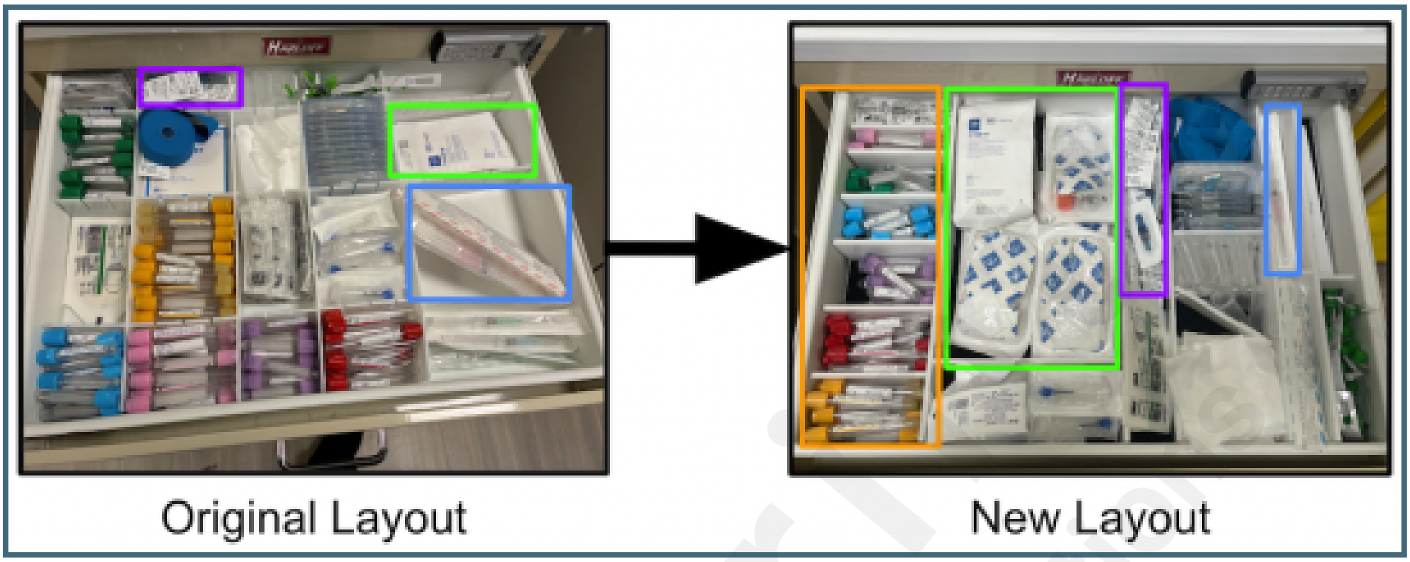
Figures

Original Cart System. a) Lockable 5-drawer Harloff ‘‘bedside” cart positioned in the hallway of the emergency department. b) Original layout and dividers in drawer 1 (topmost drawer) of the bedside carts. Note that needles (indicated by the red circle) are stored at a diagonal because the allocated space is too short.

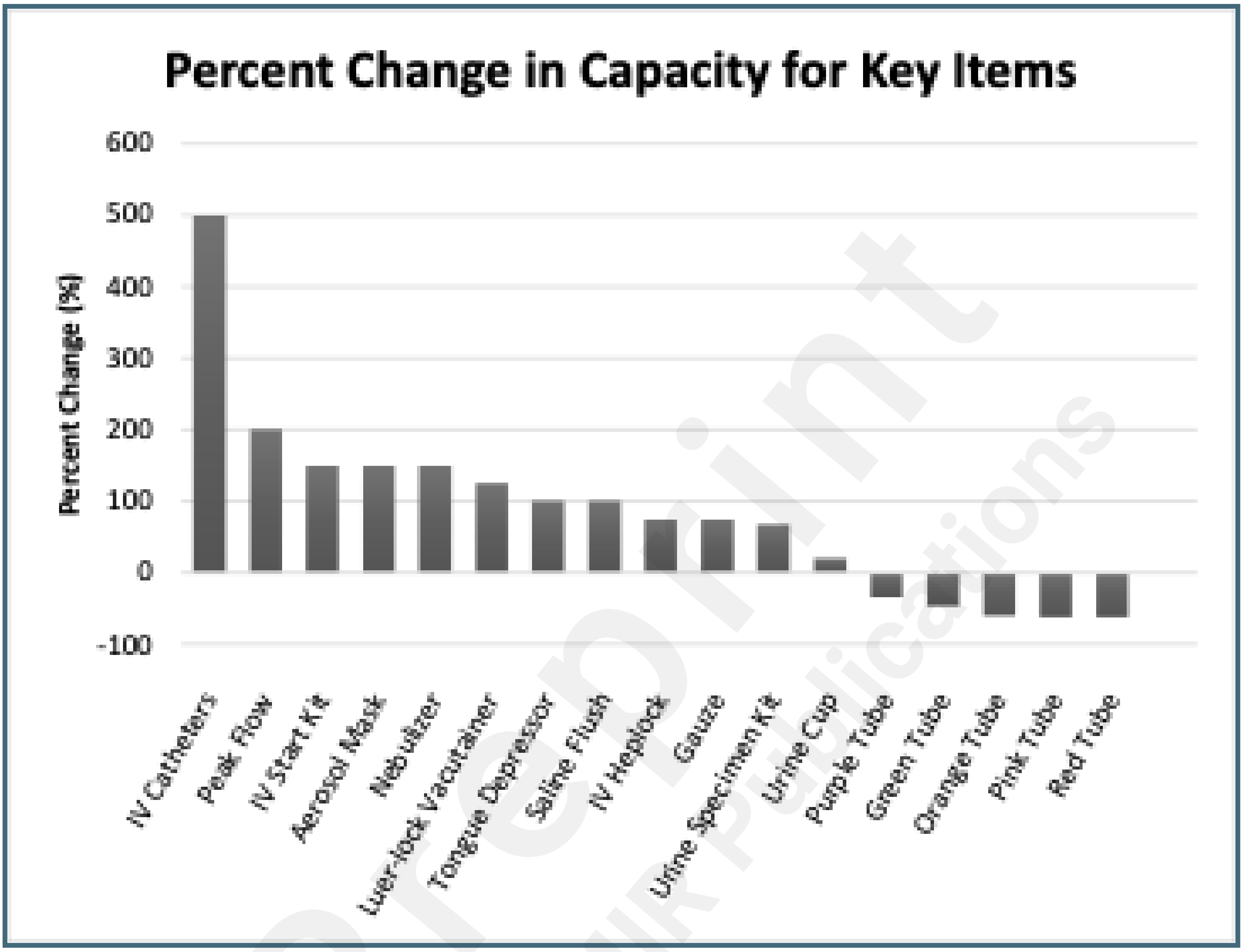
Prototype to Finalized Product. a) Cardboard prototype used in interactive design process with nurses (Drawer 1) b) Finalized, fully stocked prototype for Drawer 1 c) Drawer 2 d) Drawer 3 e) Drawer 4 f) Drawer 5.



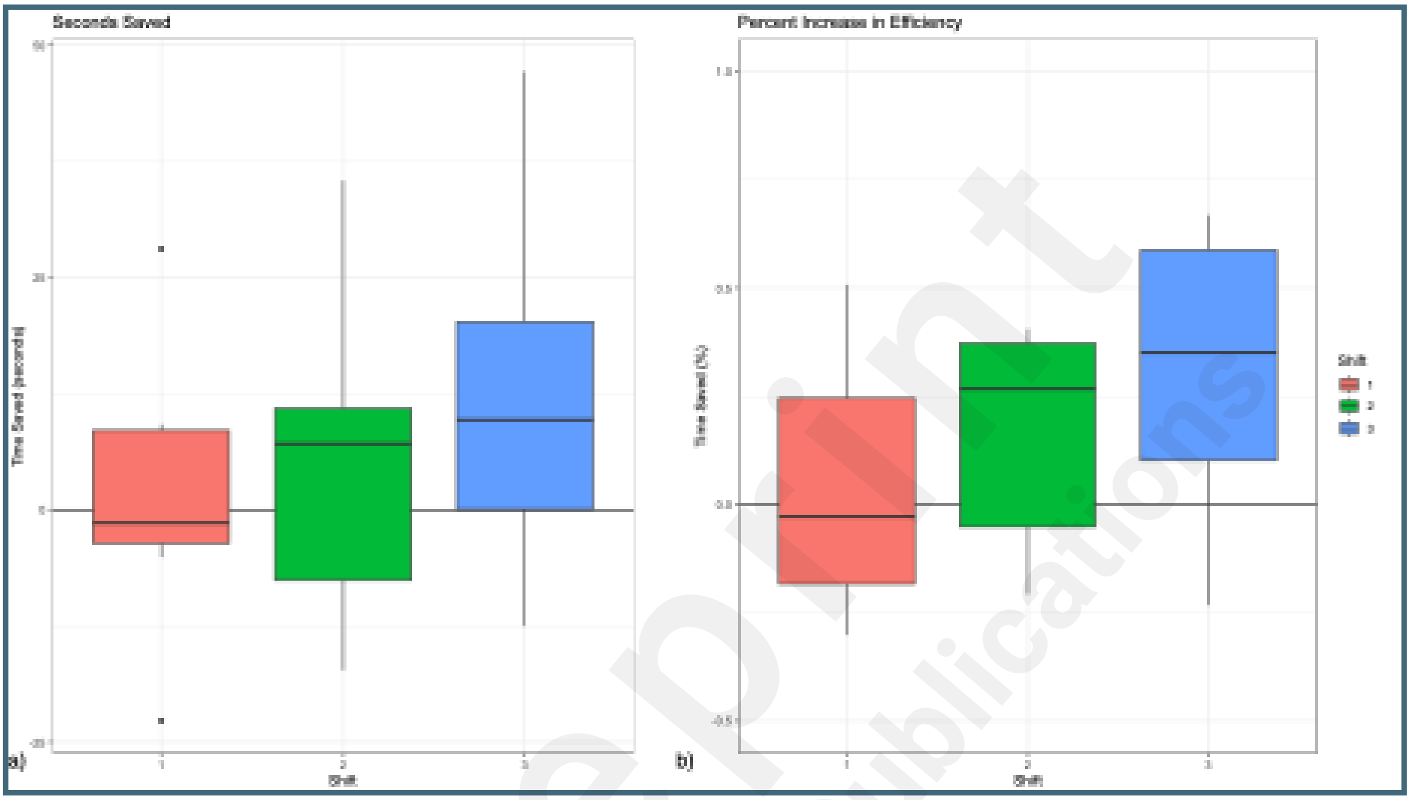
Drawer 1 Original vs. New Layout. Colored boxes highlight key changes that were made. Blue: Needles no longer stored at a diagonal with no decrease in capacity Purple: Hep-lock capacity increased by 75% Green: IV start kit capacity increased by 200% Orange: Storing all tubes in one column makes for a more ergonomic workflow; capacity decreased to avoid wastage.



Cart Redesign Corrects Supply Allocation. After redesign, critical items like those used with IVs or for urine collection and testing increased in capacity, while overrepresented test tubes decreased in capacity.



Time Savings as a Function of New Cart. a) The new cart saved an average of 5.8 seconds per simulated patient, and the time saved increased as the cart went longer without being restocked. b) As the cart went longer without restocking, the percent of time saved while accessing needed supplies increased, from about even when both were fully stocked, to 40 percent after two shifts. Boxplots show distribution of data (n=8 per shift). Sample size was too low to assess statistical significance.



Multimedia Appendixes

Supplementary Figure 1: Timeline of steps for cart intervention project.
URL: http://asset.jmir.pub/assets/eecaf487ac00f99a4448e9d55cc55de4.png

CONSORT (or other) checklists

SQUIRE Checklist.
URL: http://asset.jmir.pub/assets/1ecd50397b9cb5d5b1d49a74d54c023b.pdf