Human-computer interactions in a cyber-physical system for the surgical suite

Juliette Rambourg

THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par l'Institut National des Sciences Appliquées de Toulouse

Présentée et soutenue par

Juliette RAMBOURG

Le 17 décembre 2018

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Ecole doctorale : **SYSTEMES**

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Unité de recherche :
Laboratoire de Recherche ENAC

Thèse dirigée par **Stéphane CONVERSY** et **Marc GARBEY**

et encadrée par **Hélène GASPARD-BOULINC**

Jury

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Résumé

Une suite chirurgicale est un espace fournissant tous les services chirurgicaux au patient. Elle comprend les salles d'opération, de récupération et de préparation du patient, du chirurgien, de l'anesthésie et des équipements. Une activité clé est la gestion du flux de patients, comme la planification des procédures, l'affectation du personnel, le suivi de l'état des opérations, et surtout la capacité de réagir et d'adapter le flux selon les éventualités. La gestion des suites chirurgicales joue un rôle central pour permettre aux hôpitaux d'offrir l'accès aux soins à des coûts raisonnables.

L'informatisation et l'automatisation sont des évolutions conventionnelles pour soutenir la gestion des ressources et améliorer l'efficacité. Toutefois, un soutien inadapté ne peut améliorer l'activité de gestion et peut même nuire à son action. De précédents travaux estiment que jusqu'à présent, l'informatisation n'a apporté aucune preuve d'amélioration des coûts administratifs ni de coûts globaux dans les hôpitaux, ni d'améliorations de la qualité des soins au patient. Il existe un fossé entre les avantages des technologies de cyber santé postulés et empiriquement démontrés, ainsi que l'absence de lignes directrices sur les meilleures pratiques pour des stratégies de développement et de déploiement efficaces. Le défi consiste donc à fournir un soutien informatique à la gestion hospitalière qui bénéficie au personnel médical. Notre hypothèse est que des fonctionnalités interactives, utilisables, flexibles et adaptée aux spécificités des activités locales peuvent créer un environnement de travail dans lequel le personnel médical est capable de réagir à des événements inattendus et de s'approprier la technologie.

Nos contributions consistent en une analyse de l'activité de l'équipe chirurgicale, basée sur des entretiens, observations, questionnaires, une revue de la littérature et une analogie avec l'aviation civile. Nous avons participé à la construction d'un modèle mathématique du flux chirurgical et à la conception d'une visualisation de ce modèle. Nous avons mené une expérience en combinaison avec des travaux antérieurs sur des capteurs de salle d'opération pour identifier le manque de conscience de situation du personnel. Nous avons identifié les scénarios, exigences et principes de conception nécessaires au développement, à l'intégration et à l'acceptation d'un outil pour soutenir les activités de gestion du flux chirurgical. Nous avons conçu des interactions multi-utilisateurs sur une grande surface et développé un prototype de tableau blanc électronique, OnBoard, qui démontre l'intégration des spécifications et des défis techniques. OnBoard appartient à un système

cyber-physique comprenant des capteurs dans les salles d'opération détectant leur statut. Enfin, nous avons déployé et évalué OnBoard dans une suite chirurgicale.

L'objectif est de proposer un environnement informatisé pour gérer le flux chirurgical. Pour ce faire, nous avons utilisé la conception participative, l'évaluation de la conception et l'amélioration continue du prototype selon des observations et commentaires des utilisateurs. Les observations et entretiens ont montré que les utilisateurs pouvaient s'informer du statut des salles en temps réel au travers de timelines, à l'aide de manipulation directe pour corriger les déficiences des capteurs. Des interactions directes pour changer les horaires, corriger des informations incorrectes et ajouter de nouveaux patients dans le flux ont permis aux utilisateurs de faire face à des contingences. Enfin, les utilisateurs ont été en mesure de s'approprier la technologie avec l'utilisation de couleurs, de l'écriture et le décalage d'objet.

L'expérience de OnBoard suggère que la conception des interactions est primordiale pour offrir un environnement collaboratif efficace au personnel médical.

Abstract

Surgical suites are a group of rooms designed to provide all surgical services to patients. They include surgery, preparation and anesthesia for the patient, sterile preparation of the surgeon, instrument and materials sterilization and storage, instrument cleaning, operating rooms and recovery room. A key activity in a surgical suite is its management e.g. scheduling cases, allocating staff, monitoring the status of operations, and most crucially reacting/adapting according to contingencies. Surgical suite management plays a key role in the endeavor of hospitals: patients' health at sustainable cost. Since half of the revenue of large hospitals comes from operating room procedures, improving capacity through better management of the surgical flow might be beneficial on all levels.

In search of efficiency, computerization and automation of processes are conventional solutions to support resource management. However, unsuitable support might not improve the management activity, and can even be detrimental to it. Previous works estimate that so far computerization has not brought any evidence of improvement in administrative costs neither overall costs or has brought modest improvements in quality of patient outcomes. There is a gap between the postulated and empirically demonstrated benefits of eHealth technologies and the lack of best practice guidelines for effective development and deployment strategies. The challenge is therefore to provide computer support for hospital management which benefits the medical staff. Our hypothesis is that usable and flexible interactivity tuned to local particularities can create a working environment in which the medical staff can cope with unexpected surgery events and become the "owners" of technology.

Our contributions consist first in an analysis of the activity of the surgical team, based on interviews, observations, questionnaires, review of the literature and an analogy with civil aviation. Then, we participated in the construction of a mathematical model of the surgical workflow and the design of a visualization of the mathematical model. We conducted an experimentation in combination with previous work on operating room sensors to identify bottlenecks of workflow inefficiencies and delays. We identified scenarios, requirements and design principles necessary to the development, integration and acceptation of a tool to support surgical workflow activities. We then designed multi-users interactions on a large surface and made a prototype of electronic

whiteboard, OnBoard, for the surgical suite which demonstrates the integration of the specifications and technical challenges. OnBoard belongs to a larger cyber physical system including activity sensors in every operating room of the surgical suite. Finally, we deployed the prototype in a surgical suite and evaluated it.

The objective of OnBoard is to propose a computerized environment for surgical flow management that supports both the hospital management in cost performance and the medical staff in patient care. To do so, we used participatory design, design walkthrough evaluations and continuous improvement from users' observations and feedback in a real setting. Observations and interviews "in the wild" showed that users were able to get up-to-date information from the sensors, especially through timelines, with the help of their direct manipulation to correct sensor deficiencies. Direct interactions to change time, fix incorrect information and add new cases in the flow allowed users to face unexpected events. Finally, users were able to appropriate technology, with the use of colors, handwriting and object shift.

The OnBoard experience suggests that the design of interactions is paramount to provide the medical staff with an efficient collaborative environment.

Mots-Clefs

Interaction Humain-Machine ; gestion de salles de chirurgie ; collecticiels ; systèmes ubiquitaires ; systèmes cyber-physiques

Keywords

Human-Computer Interaction ; management of surgical suites ; computer-supported collaborative work ; ubiquitous computing ; cyber-physical systems

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Publications

Articles in international journals

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Joerger, Guillaume, Juliette Rambourg, Marc Garbey, Stéphane Conversy, and Hélène Gaspard-Boulinc. "Re-engineer operating room data acquisition and transmission for improving surgical suite awareness and management." In *Biomedical & Health Informatics (BHI), 2017 IEEE EMBS International Conference on*, pp. 205-208. IEEE, 2017.

Rambourg, Juliette, Guillaume Joerger, Brian J. Dunkin, and Marc Garbey. "A novel Surgical Suite Management Technology including Automatic Surgery Steps Tracking and a Large Collaborative and Informative Display." In *SAGES 2017, Society of American Gastrointestinal and Endoscopic Surgeons Conference*. 2017.

Posters and Work-In-Progress

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Collaborators

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Nomenclature

ABM: Agent-Based Model

ATC: Air Traffic Control

BR: Board Runner

CPS: Cyber-Physical System

CSCW: Computer Supported Collaborative Work

FDA: Food and Drugs Administration

HCI: Human Computer Interaction

ICU: Intensive Care Unit

MCPS: Medical Cyber-Physical System

NICU: Neuro Intensive Care Unit

ODE: Ordinary Differential Equation

OR: Operating Room

SICU: Surgical Intensive Care Unit

UCD: User-Centric Design

1

INTRODUCTION

"Frequently we see researchers studying other researchers, developers building systems because the technology exists, and managers supporting the development of systems that will appeal to other managers."

Grudin, 1988

The computer of the 21st century as envisioned by Mark Weiser is here. Technologies are "disappearing and are weaving themselves into the fabric of everyday life" [177]. On one hand, miniaturization, energy consumption and cost reduction allow for effectively disseminating sensors and processing capacity in any location of personal and professional life. On the other hand, new fabrication process and material science allow for building large multitouch displays, or "yard-size boards" as Weiser called it. Combining these two trends provides designers with a new means to improve the support of collaborative activities performed by humans, thanks to presumably more accurate data acquisition and richer interactions.

However, one risk of this trend would be to use them together with the renewed interest for Artificial Intelligence to automate some parts of the activity for the sole purpose of getting rid of the humans. This is particularly true for critical environments, where contingencies must be handled with high-levels of safety. Interactions between humans and automation have been studied

in safety-critical fields such as civil aviation [28,54] or power plants [187], and currently is the center of attention with the arrival of self-driving cars [25,149]. Being a critical environment that requires as much safety and quality of care as cost-efficiency, the hospital is an interesting field for exploring where and how humans and automation should be integrated while computerizing its processes. Conversely to civil aviation where stakeholders perform well-defined tasks to manage the air traffic, the diversity of stakeholders, their background and their daily activities make computerization of hospital surgical patient flow even more challenging.

1.1. Hospital surgical suite motivations

The hospitals are cautious with automation and computerization. Indeed, Himmelstein et al. [81] shows that computerization neither brought quality nor costs improvements in around 4000 hospitals between 2003 and 2007.

Improving patient care quality is the main displayed motive of hospitals' computer systems. Nevertheless, underlying reasons of successful stories depend on an efficient management of operations in terms of costs and revenue. In the hospital, Operating Rooms (ORs) are the rooms where surgical procedures are performed. Since half of the revenue of large hospitals comes from OR operations [51,63], improving capacity through better management of the surgical flow might be beneficial at all levels. There is a strong demand for improving surgical results and reduction of high costs of surgical procedures, which directly impact insurance and ultimately patients. This has been translated into a recent movement in the United States to make all health care costs public [188] as they are not affordable for all the population. According to a study [188], there are significant differences in the costs of healthcare for the same services, depending on where it is delivered: for a vaginal delivery, the lowest cost is $10,140 while the highest is $14,578 (27 hospitals listed). The lowest cost for a hip replacement is $22,166 whereas the highest cost is $36,659 (14 hospitals listed). The study shows that higher costs does not imply lower complications/better quality of care. The differences mainly depend on the variations in inpatient facility costs across hospitals, therefore including the patient flow and OR management.

Many studies report about automation *within* the OR, such as surgical robots [34,59,85,111,117,146]. However, few studies report on computerization of the surgical suite as whole. A surgical suite is a group of one or more ORs and complementary facilities within a

hospital, such as a sterile storage area, a laundry room, the recovery room, etc. (see Figure 1, Figure 2, Figure 3). Daily activities consist mainly in ordering "elective patient surgeries" – that are planned surgeries, arrival of the patient in the surgical suite, preparation of the patient for his/her surgery, the procedure itself, and finally the patient recovery in the post-operating areas. This workflow is accompanied by multiple collaborative activities. The surgical staff communicate and coordinate on the patient's condition, his/her needs for the surgery, the equipment needed, and the scheduling and staff management. The different stakeholders deal with unforeseen events such as: an emergency patient who must be emergently integrated in the flow of surgeries, or an on-going operation that lasts 4 hours instead of 2 hours. In this situation, staff must reorganize the schedule of the surgeries and devise a new, safe and optimized schedule.

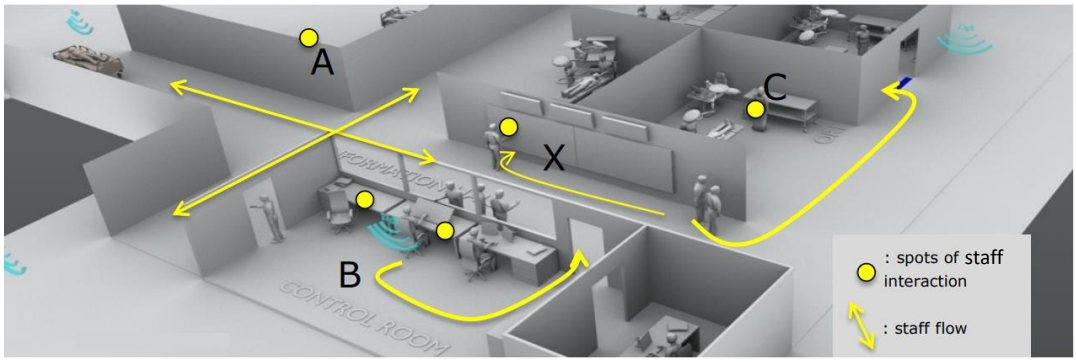


Figure 1. Representation of the DunnOR surgical suite, Houston Methodist Hospital. "A" represents the pre-operating room areas, "B" the nurse station, "C" the ORs and "X" the semi-public area of information (reserved to surgical staff).

Figure 2. Example of nurse station at DunnOR, Houston Methodist hospital. The nurse station has view on the corridor displaying semi-public information, reserved to the surgical staff.

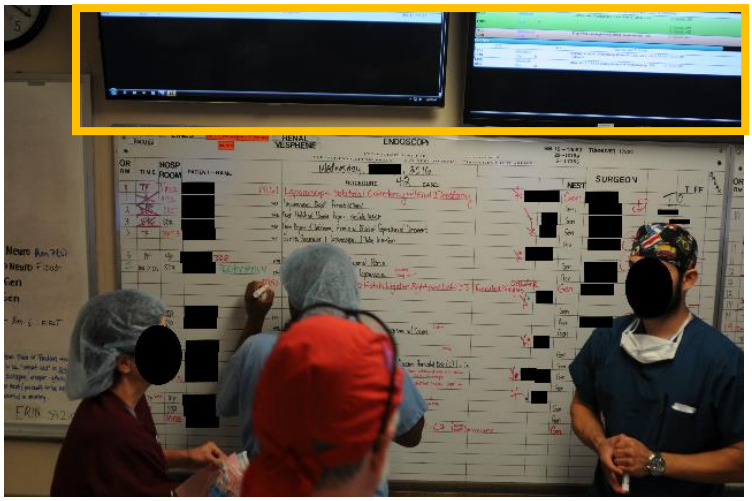


Figure 3. A whiteboard in the semi-public information space at DunnOR, Houston Methodist Hospital. A nurse is writing the schedule of the surgeries. Indicated by the orange rectangle: the non-interactive electronic schedule displays, above the whiteboard.

Large surgical suites must combine high quality of care with an efficient management of operations in complex settings. The diversity of procedures in general surgery and the diversity of staff and patients make staff collaboration a cornerstone of the system. Many surgical suites rely on large whiteboards (see Figure 3) to enable the surgical staff to communicate and coordinate synchronously and asynchronously. The whiteboards display an overview of the status of the surgical suite and a plan for the next surgeries. They are very easy to use and highly flexible. Furthermore, they are reliable as they can never shut down like a computer system. Therefore, these whiteboards have been used for decades and offer a practical and inexpensive means to organize the activity of the surgical suite staff.

However, the whiteboards are usually not up-to-date, take a lot of time to be updated manually and have no archives of interactions. Therefore, their computerization seems interesting in terms of optimization of the surgical flow: better communication, optimization of re-scheduling, and better awareness of the present and past status of the system.

1.2. Context of the thesis

Our study work was carried out at the Houston Methodist Hospital, (www.houstonmethodist.org), counting 8 surgical suites and 1700 beds. The size of the Houston Methodist Hospital and its surgical suites (up to 23 ORs for the biggest suite) makes the overall system complex and is a privileged site to study. The thesis work is part of a larger development project of a cyber-physical system to assist the management of the flow of patients in the surgical suite. The project aims at developing a mathematical model of the surgical flow and the objective is to advise the administrative staff to optimize patient flow in the surgical suite (see chapter 3 "Context: a Cyber-Physical system"). Many sensors can be added to the system to capture information about the operations in the surgical suite. The challenge is to automate data acquisition and transmission to provide accurate information on the status of the surgical suite.

In our thesis, we focus on the interactions between the surgical staff and the cyber-physical system. We aim at improving staff collaboration with new interactive means and improving awareness on the status of the surgical suite from the acquired data. Our work would participate in the improvement of the efficiency of the whole system, as efforts on usability have been showed to lead to a significant return on investments when applied [98].

1.3. Thesis statement and Research Questions (RQs)

Previous work [67,87] included the testing of sensors capturing in real time the status of the ORs. Our work promotes a human-in-the-loop design approach to foster collaboration and awareness of the surgical team, due to the acquired data.

In such context, we particularly focus on the dissemination and manipulation of surgical suite information in the critical environment. How to develop tools allowing a surgical team to better coordinate and follow the optimized schedule, while being able to adapt quickly to unforeseen events? How to deliver tools that will allow the users to perform their activities in the future?

Our hypothesis is that interactions between the surgical staff and the patient flow management tools are key to foster flexibility, collaboration and awareness required by their activity. We study how we can efficiently computerize the surgical staff activity based on our hypothesis.

Our research questions are:

RQ1. How to computerize users' activity without jeopardizing the collaboration nor the flexibility needed for operating rooms management?

RQ2. How to effectively deploy a computerized system in a critical environment and gather information on its usage?

RQ3. Can we generalize our work and promote an effective computerization beyond a particular example?

1.4. Contributions

The contributions of the thesis are as follow:

1. An analysis of the activity of the surgical team, based on interviews, observations, questionnaires, review of the literature and an analogy with civil aviation.
2. The participation in the construction of a mathematical model of the surgical workflow and the design of a visualization of the mathematical model [68,69].
3. An experimentation in combination with the SmartOR [67,86,87] in the surgical suite to identify bottlenecks of workflow inefficiencies and delays [96].
4. The formulation of high-level requirements, scenarios and design principles necessary to the development, integration and acceptance of a tool to support surgical workflow activities.
5. The design of multi-users interactions on a large surface.
6. A prototype of electronic whiteboard for the surgical suite which demonstrates the integration of requirements and technical challenges.
7. The deployment of the prototype in the surgical suite and its evaluation by the surgical staff.
8. A reinterpretation of the work towards ubiquitous computing for the surgical suite.

1.5. Thesis outline

This manuscript is divided in seven parts:

- **Chapter 2** provides a related work on the computerization of collaborative systems, with a focus on hospitals and multitouch surfaces applications.
- **Chapter 3** presents the context of the work among the design of the whole cyber-physical system, including my contribution and the contribution of colleagues.
- **Chapter 4** describes the methods we followed.
- **Chapter 5** reports on the surgical suite staff activity analysis and results.
- **Chapter 6** details the interaction design and implementation of our prototype.
- **Chapter 7** reports on the design evaluations and presents the results obtained through the deployment of our prototype.
- **Chapter 8** depicts a reinterpretation of the work towards ubiquitous computing for the surgical suite.
- **Chapter 9** summarizes the results and concludes the dissertation.

2

RELATED WORK

Technological development drives healthcare innovation and consistently brings improvements to patient outcomes [167]. However, while improving imaging technology brings better information to the doctors, computerizing the hospitals workflow proves to be more challenging. Specific studies in hospitals seem to confirm the need for computerization while highlighting potential pitfalls [18,66,122].

This chapter provides a review of the difficulties of computerizing the hospital workflow, with a focus on surgical staff collaboration aspects. We then review computerization challenges in other fields and explore how large touch surfaces have contributed so far to the support of collaborative activities.

Finally, we position our work and expose the potential contribution that can be made to facilitate computerization in the surgical suite.

2.1. The challenges of the computerization of hospital workflow

Computerization is the act of using a computer to do something that previously performed by people or machines before [189]. There are high expectations when computerizing hospitals, because of the belief that it will improve health care quality, reduce costs, and increase administrative efficiency [81].

In this section, we cover the impact of Electronic Health Records (EHR), and on challenges of user-centered design for computer systems in the hospital and Medical Cyber Physical Systems (MCPS).

2.1.1. Electronic Health Records

Electronic Health Records are an example of digitalized healthcare systems that have been implemented since the 2000s in order to improve healthcare quality, problem solving, documentation and administration [31]. As an example, the Epic Company provides EHR solutions, costing around US$250 million to US$1.1 billion [100]. Epic has an 80% market share (HIMSS analytics Database 2015) in the US and is now taking over day-to-day surgical flow management along with many other aspects of billing and information sharing. One key success of the EHR is its capability to interconnect all the processed data of the hospital systems and serve as the de facto collaborative tool between all the stakeholders; therefore, the EHR is supposed to rigorously track down cost, revenue, and patient care.

However, the implementation of EHRs is considered a potential threat to Private Health Information (PHI) [40] and may not even improve care or safety of the patient [71]. With the rapid adoption of EHRs, two important matters were left aside: first, EHRs should be designed to recognize and flag PHI, in order to be handled differently from non-sensitive information; second, stratified access to PHI based on user profile should be implemented [35].

2.1.2. User-centered design

2.1.2.1. *Usability as a key factor to technology acceptance*

Patient data must be entered in the EHR system. This activity is laborious and is a source of frustration [40] for healthcare providers. It is seen as wasted time and a failure with respect to the

usability of the EHR software, leading many institutions to hire "scribes" to specifically enter data into EHRs. A study [84] about the integration of cloud-based systems in healthcare shows that several factors contribute to the resistance of use of this technology. Inertia, i.e. the fact that users tend to be willing to continue using the same technology, seems to be the strongest factor in the resistance to the use of a new technology. The perception that the new system is a threat to the practitioners' role and position play a significant role. In addition, 92% of physicians note that the use of EHRs disturbs communication with patients, which deteriorates the quality of care [155].

For acceptance of a telemedicine system, a study [44] reports that the factors with the highest impact are the perceived usefulness and the personnel attitude toward using the technology. It suggests that user participation can have a positive impact on adoption. In another study [43], ease-of-use has the biggest influence on user acceptance of the new system, comparable with the patient care impact of the system itself. A study [40] shows that acceptance of the technology by providers dwells in whether or not it improves patient care or in the speed of care delivery.

2.1.2.2. *The case for user-centered design methods*

Shaha et al. [156] demonstrate that EHR implementation is based on designers' specifications and hospital administrators' need (the buyers) more than on the clinicians' needs (the actual users). This results in a system that is not flexible enough and does not allow enough communication. The study therefore emphasizes the need to include clinicians in the design process. EHRs were expected to improve some healthcare issues such as accountability, billing and efficiency [80]. However, some studies show that EHRs have not been perfect, as any new technology, and brought inefficiencies and higher workloads [14,39].

Thimbleby et al. [167] made the statement that since no new technologies will be perfect, they need to be developed with the users to make sure they match their needs. They claim that using User Centered Design (UCD) is necessary to deliver the right amount of data to the users and not overload them. One of the largest hospital of the United States [190], the New York-Presbyterian Hospital (based in New York City), comprising 7 campuses and 2,600 beds, performs more than 310,000 emergency department visits annually [191]. Recording data associated with the hospital leads to a large amount of data: a report from EMC and IBC from 2014 [62] states that there were 153 exabytes of healthcare data in the world in 2013, growing at 48% a year, reaching 2,314 exabytes by 2020.

Thimbleby et al. [167] claimed that the use of the technology may solve an isolated problem or increase performance, but it brings changes to staff's routines and therefore, creates new problems when the technology is not designed with end-users. For instance, they mention the problem of physicality. In a traditional setting, a user would complete a form and drop it on the desk of a colleague for him/her to follow-up. This paper represents a task to perform. With a computerized system that would make the first user complete the form electronically. This person does not then drop the paper on the desk of the second user anymore, which increases the risk that the second person will not realize the task he/she has to do. Without considering these non-verbal and more implicit collaboration patterns, communication and safety could be hindered. The authors specifically mention the example of the paper-form patient prescription, given in the hands of the patient after meeting with the healthcare provider. With electronic prescriptions, widely used in the USA and Europe nowadays, patients tend to forget to pick-up their prescriptions at the pharmacy because they do not have a physical paper reminder anymore. The authors suggest considering skeuomorphism (the design concept of making digital items resembling their real-world counterparts) while computerizing to mitigate these problems. Similar concerns about direct collaboration are studied in groupware research [159].

Himmelstein et al. [81] estimate that computerization has not provided any evidence of improvement in administrative costs or overall costs because what is saved is spent on the purchase and maintenance of the computer system (presumably evolution maintenance of the system to adapt to context particularities). They report that so far computerization has not provided any evidence of improvements in quality of patient outcomes.

The failure of computerization is due to the lack of pertinent evaluation of the computer system and should include socio-technical factors to adapt and fit a local activity as best as possible [29]. Evidence of the beneficial impact of such systems is limited to a few academic clinical centers of excellence where the systems were developed in house, undergoing extensive evaluation with continual improvement, supported by a strong sense of local ownership by their clinical users [29]. The contrast between the success of these systems and the relative failure in much of the wider body of evidence is "striking" [29]. Himmelstein et al. [81] mention that the few custom-built systems that have been deployed have improved quality of patient outcomes. However, the extent to which the results of these primary studies on custom-built systems can be generalized beyond their local environment is questionable [29].

2.1.3. Medical Cyber-Physical Systems (MCPS)

Medical Cyber-Physical Systems (MCPS) are an healthcare integration of a network of medical devices [58]. Traditional clinical scenarios can be viewed as closed-loop systems where caregivers are the controllers, medical devices act as sensors and actuators, and patients are the "plants" [105] (see Figure 4). These systems represent the industrialization of healthcare, by bringing new technologies at the bedside, in the OR and beyond.

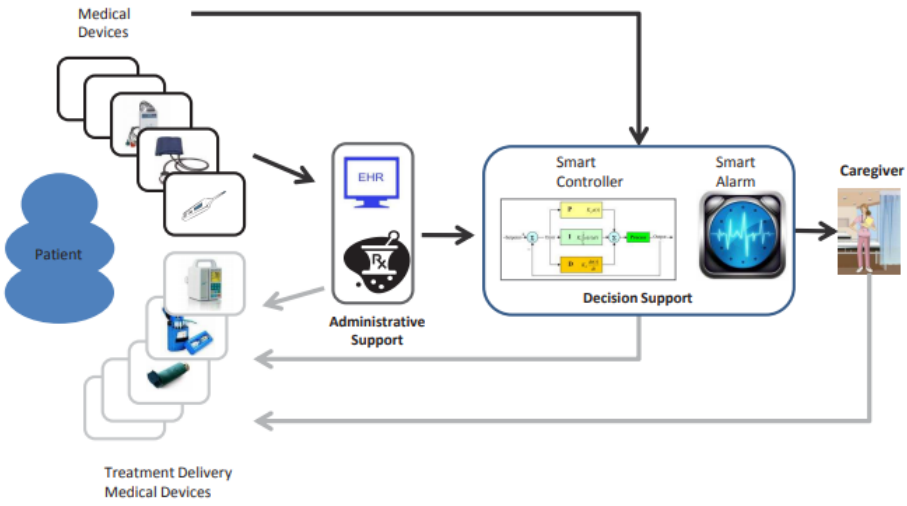


Figure 4. Medical Cyber-Physical Systems: Conceptual Overview. Source: [105]

Few cyber-physical system architectures have been offered for healthcare thus far [74,105]. Some examples of mobile technologies [165], which needed by medical staff [8,122] and in-OR systems [23], or design methods suggestions [103] have been reported, but do not provide a holistic integration of the different parts of the surgical suite (pre-operating room, ORs, post-operating room, Intensive Care Units etc.). In [105], the authors describe research directions and challenges involved in the building of MCPS. They report that the challenges are: High Assurance Software, Interoperability, Context-Awareness, Autonomy, Security and Privacy and Certifiability. In [105], the authors highlight specific Research and Development challenges for MCPS at the system level: primary concerns are security and privacy of information. They warn designers at several levels, including at the user-centered design one: human errors are linked to caregiver stress and poor user interface design has been attributed for these errors. They recommend considering users'

expectations to incorporate a caregiver behavior model in the design of interactive medical devices. They emphasize that the purpose of such projects should not be to design fully autonomous systems that exclude humans.

2.1.4. Summary & research opportunity

Transitioning to new technologies in the medical field is non-trivial and is a complicated endeavor. The literature shows that adopting UCD methods and including physicians in the design of these technologies make a significant difference in effective technology usage and adoption. We believe there is an opportunity in research to emphasize this need and to apply these techniques to a practical example.

2.2. Collaboration with focus on hospitals

We introduce here some insights from previous work on collaborative activities needs within the hospital. The traditional way to manage a surgical suite patient flow is to have the patients' surgical schedule written on a large whiteboard, in a semi-public space for the surgical staff. Semi-public space here means that it concerns the surgical staff only. This whiteboard is updated through the day and serves as a collaboration and information support to monitor the flow (see more details in the analysis done in Chapter 5 "User context analysis"). Many projects attempted to replace them while computerizing the activity of the surgical staff. Fitzpatrick et al. [66] mentions that for 20 years, the commercial offers of electronic whiteboards have been a failure. They claim that the failure comes mainly from the lack of usability and the poor quality of the display and hardware.

2.2.1. Ethnographic studies in the surgical suite

Several ethnographic studies focus on collaboration in the surgical suite [18,19,154,163]. Bardram [18] mentions that the problem of computerization at hospitals is mainly that "*the systems are typically single-user oriented*", whereas teamwork is omnipresent. These studies describe the activity in surgical suites of various hospitals, often around the same kind of surgical whiteboards as in the Houston Methodist Hospital. They provide recommendations for designing collaborative tools for the surgical suite, such as:

- The need to support local mobility within the hospital and to support remote and collocated collaboration [18].
- The need to make systems that can be tailored, to enable evolution of meaning. “For example, the signs used on [surgical] whiteboards may change over time and new signs are needed to support the coordination of new actions” [19].
- Replace the traditional surgical whiteboard with a computerized one [19]. However, the authors support the idea that keeping a real whiteboard is relevant.
- Four design principles for the physical environment of surgical suites, focusing on the surgical whiteboard [154]: connectivity, space adjacency and visibility, access areas and staff-only area. These four principles suggest that the surgical whiteboard is an information hotspot and that it must be considered if one wants to computerize whiteboard’s activities.
- If one wants to replace the traditional surgical whiteboard with a computerized one, surgical whiteboard’s affordances must be preserved: visual persistence, flexibility of the ink primitives, and its situated social and physical context [163]. The authors forecast that users would not easily appropriate the new tools otherwise.

These studies did not include the design of a computerized whiteboard; hence they did not apply their guidelines nor deployed a new artifact in a real-world setting.

2.2.2. Lack of modern co-located collaborative technologies for the hospital

The hospital field is by nature a critical environment, with constant teamwork and adaptation to new contexts. A significant contrast remains however between sophisticated healthcare technologies and the traditional collaborative tools used in healthcare: while increasingly introducing robotics for surgical activities, staff still uses paper-based communication tools such as sticky notes and whiteboards [72]. Possible reasons for the lack of Computer Supported Collaborative Work (CSCW) technologies in the hospital are:

- The lack of deployment possibilities for clinical trials [93] due to the fact hospitals are critical environments.
- The danger of incidents caused by computer systems that change processes and lead to errors [122].
- The lack of evaluation tools [66].

- The technology acceptance gap: many staff of the hospital environments report being worried about computerization and being forced to switch to systems that would be imposed to them [103].

A recommendation [19] would be to start by "*moving from design-for-use to design-for-future-use*". Design-for-future-use can be defined as the adaptation of work practices to foster ownership and appropriation of the technology.

2.2.3. Collaborative affordances

Bardram et al. [22] defines the concept of collaborative affordances as "the relation between an artifact and a set of human actors that affords the opportunity for these actors to perform a collaborative action within a specific social context". They define a set of core collaborative affordances (portability, collocated access, shared overview, and mutual awareness [144]), and highlight that the surgical whiteboards possess some collaborative affordances. They applied it to a prototype of a binder called HyPR, which was designed to "augment and hence extend the paper-based medical records".

Figure 5. HyPR binder prototype. Photo credits: [22].

HyPR augments the paper record by allowing patient tracking and identification and by offering auditory and visual notifications. This hybrid solution was evaluated in a simulation environment and showed that it supports the 4 collaborative affordances described above. The authors showed that HyPR could comprise the benefits of the EHR and the paper-based records. For instance, HyPR allowed EHR information to be portable and offered a better support for rendering actions visible to others.

2.2.4. Communication needs vs. interruptions problem

Interruptions are a problem for the surgical staff: a study [133] reports that significantly more nurses make medical errors when they are interrupted than when they are uninterrupted. Popovici et al. [132] relate the key issues of effective communication among hospital stakeholders, which includes interruption problems and unintuitive user interface – a problem also discussed in civil aviation [82]. A study [99] designed a prototype of a phone application that displays the status of colleagues to nurses. The purpose was to increase mutual awareness of each other's status to help decide whether an interruption is appropriate.

The relationship between information and representation [19,20] is important but rarely served by technology within the hospital. The same information should be portrayed in different ways based on by who/when it is accessed, so that it can be efficiently shared [141]. The compatibility between these representations is necessary for coordination between different places, and computer systems can support it better than paper records [141]. Hence, it would allow more efficient collaboration among people with different purposes and work practices.

Direct communication seems to be the best way of communication in terms of time and understanding. It is however very expensive and effortful [1,122], so other means of communication are often preferred [178]. Direct communication is sometimes physically impossible because of time and space discrepancies or because of the lack of resources.

To compensate the impossibility of direct communication, surgical suite whiteboards are used. They support several "indirect" communication features:

- They are a semi-public source of information, meaning that they are accessible from the staff only.
- They allow "*mutual awareness*" among surgical staff that is important for efficient collaboration [144], i.e. it is important for two distinct users to be aware that they share the same information.
- They support "*trajectory awareness*", Scupelli et al. [153]: the ability to be aware of critical events that are spatially and temporally separated from the staff. We develop here a typical scenario as an example: in the morning, a surgery was rescheduled to the afternoon on the whiteboard. A surgical resident, that was seeing patients in his/her office at the moment of the change, became aware of the change at noon while discussing with

colleagues. The event “rescheduling” was performed spatially away from the surgical resident and the moment he/she became aware of the change was different from the time of the change. In this scenario, the surgical resident could have been informed of the change with explicit means, rather than by chance.

Scupelli et al. [153] points out how the lack of awareness and coordination in the OR escalates to bigger problems. They claim that creating a “collaborative culture” is necessary and can be achieved by giving to the staff the adapted collaborative tools. In this way, Scupelli et al. [154] support that context-aware technology can bridge the gap by bringing automated context information about the surgical suite to the surgical staff.

Moss et al. [122] propose the integration of electronic whiteboards to offer asynchronous communication options and reduce face-to-face, time-consuming, interruptive communication. This could for instance decrease the unnecessary phone call communications and the number of coordination activities disruptions.

2.2.4.1. *Disconnected whiteboards*

Large whiteboards are widespread centralized coordinative artifacts to support surgical team scheduling activities [79,163]. They allow flexibility due to the many ways information can be represented, resulting in great appropriation of information [163,183]. In addition, many studies shows that the whiteboard is the place to meet and exchange directly with colleagues [79,154,179]. They therefore provide several collaborative affordances such as collocated access, shared overview and mutual awareness [22]. The whiteboard of the surgical suite is what Bossen et al. [32] call the “common ground”, and is essential to coordination between teammates. The situation awareness of the staff in the surgical suite relies partly on what is written on the whiteboard. According to Branham et al. [36] whiteboards are familiar, pliant and allow for quick creation and modification.

These whiteboards are however not portable [22] and disconnected from all hospitals computer system. Whiteboards are poor tools for archival and reuse [36]. They could be enhanced by surgical suite context awareness information, and could help digitalize important information needing mobility [19,20,122]. The design choice of Bossen et al. [32] to improve collaboration in the *Care Hotel* was an electronic whiteboard, a large device with public visibility.

2.2.4.2. *The path to computerization without downgrading in flexibility and accuracy*

Some attempts to bring computer support such as electronic whiteboards can be found in the literature [110,138]. Hertzum has been involved for several years in the integration of electronic whiteboards in emergency department to maintain the overview of the state of the department, and reports on the challenge [79,137,139] (see Figure 6).

Figure 6. Electronic whiteboard deployed in a study from Hertzum. Source: [79].

He emphasizes that the notion of overview is key and must be supported through the evolution of the content [78]. Physicians want to build an overview of the surgical suite state [33]: the status of each OR, the forecast on when surgeries will end, the staff allocation etc. Tang et al. [165] propose a mobile system to support surgical suite activity, which is more a mobile desktop than an electronic whiteboard [165] (see Figure 7). Figure 8 shows a variety of proposed electronic whiteboards. Many of them are WIMP-like applications, though according to Weiser "*for both obvious and subtle reasons, the software that animates a large, shared display and its electronic chalk* [should] *not* [be] *the same as that for a workstation."* [177]

Figure 7. COW (Computer on Wheel) system from Tang et al. Source: [165]

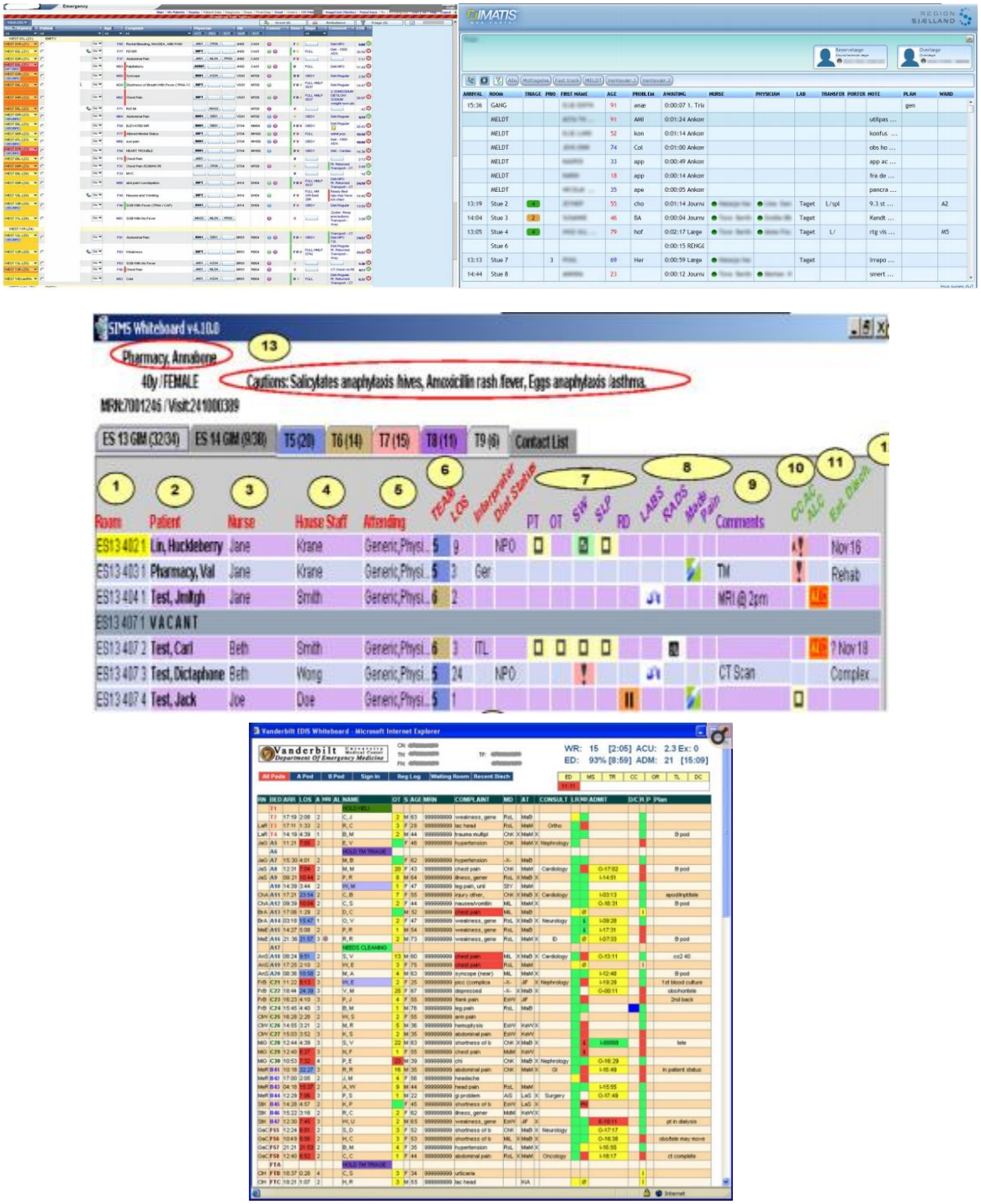


Figure 8. WIMP-based electronic whiteboard applications for surgical suites. From left to right, top to bottom: [65], [137], [181], [13].

The problem stated is that electronic whiteboards deteriorate information accuracy, are inflexible and turn the collaborative tool into an administrative tool [138]. In addition, their appropriation requires the possibility to apply current practices [163] which is often impossible since the proposed electronic whiteboards are not interactive like whiteboards *sensu stricto*.

For an effective computerization of the whiteboard, Tang et al. [163] recommends the new system be a container for task and coordinating information. This would create an environment where information is easily revisable and readily updatable, and which flexibility allows users to build representations of information suitable for many modes of activity.

Hertzum [78] reports on the consequences of introducing an electronic whiteboard in their emergency department. In their specific case, the total time spent editing the electronic whiteboard was significantly higher than the total time spent editing a traditional whiteboard. This reached the point where the total time spent editing over a year represented an additional 1.7 additional full-time clinicians when compared to the previous use of traditional whiteboards. Hence, the usability of these electronic whiteboards plays an important role in their usefulness, and their adoption.

2.2.4.3. *Usability*

The international standard, ISO 9241-11, defines usability as: "*the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*." Effectiveness refers to the ability of the user to actually perform the task and reach their objectives. Efficiency refers to the performance of the user and how easily he/she can perform the task. Satisfaction is a more subjective aspect and refers to how much users enjoy using the system. A number of sets of usability guidelines exist to help design more usable systems in academia [158] or engineering [123]. Some design and evaluation methods also exist to promote better usability [2,97,124,129].

However, reaching a high level of usability is challenging, especially in critical environments like hospitals because the access to users and to the environment is restricted. The hospital activities generate a large amount of data [62] and clinicians need to access it. If more data is welcome, usable data that incorporates satisfactory visualization and interaction features is better.

2.2.5. Synthesis & research opportunity

The literature shows that the traditional surgical suite whiteboard – supporting case scheduling activities and overview of the surgical suite state, is not enough by itself anymore: there is a need to go beyond and bring more support to the surgical team (better communication, mobility of information, data support and improved mutual awareness). Thus, so-called electronic whiteboards have already been implemented and tested.

The global failure of electronic whiteboards reported by Fitzpatrick et al. [66] mainly comes from the lack of usability, and the weakness of the quality of the display and hardware. Recent electronic whiteboards might have taken this in account, but to our knowledge there has been no work on introducing a "real" electronic whiteboard i.e., a multi touch display, of the size of a whiteboard, to maximize the support of traditional whiteboard qualities. Indeed, there is two reasons why current whiteboard properties should be preserved:

- Researchers identified and analyzed several of them and the reasons of their efficiency: mutual awareness, trajectory awareness, shared overview, strategic central location and flexibility.
- Although we may not know all the beneficial properties of whiteboards, they constitute a satisfying collaborative tool for the surgical suite. Hence, designers must be careful not to lose these aspects.

A pliant interface is an interface able to be flexible enough to adapt to the users – and not the contrary – even to the users' needs that were not identified by the designers [75]. We believe that this is what we need to explore to support surgical staff workflow and favor a "design for future use" [19] that would incorporate most of the whiteboards properties and bring useful computer support. The technology probe approach [90] could help design more usable electronic whiteboards.

2.3. Computerization and benefits of large interactive surfaces in other environments

Since Weiser's vision of "yard-size" board (see Figure 9), the industry succeeded in democratizing the underlying technology. Large multi-touch & high-resolution surfaces have been explored to support various critical activities as they promise better manipulation and visualization of data. In this section, we explore how other fields of research utilize large surfaces for collaborative activities, from which we derive some requirements.

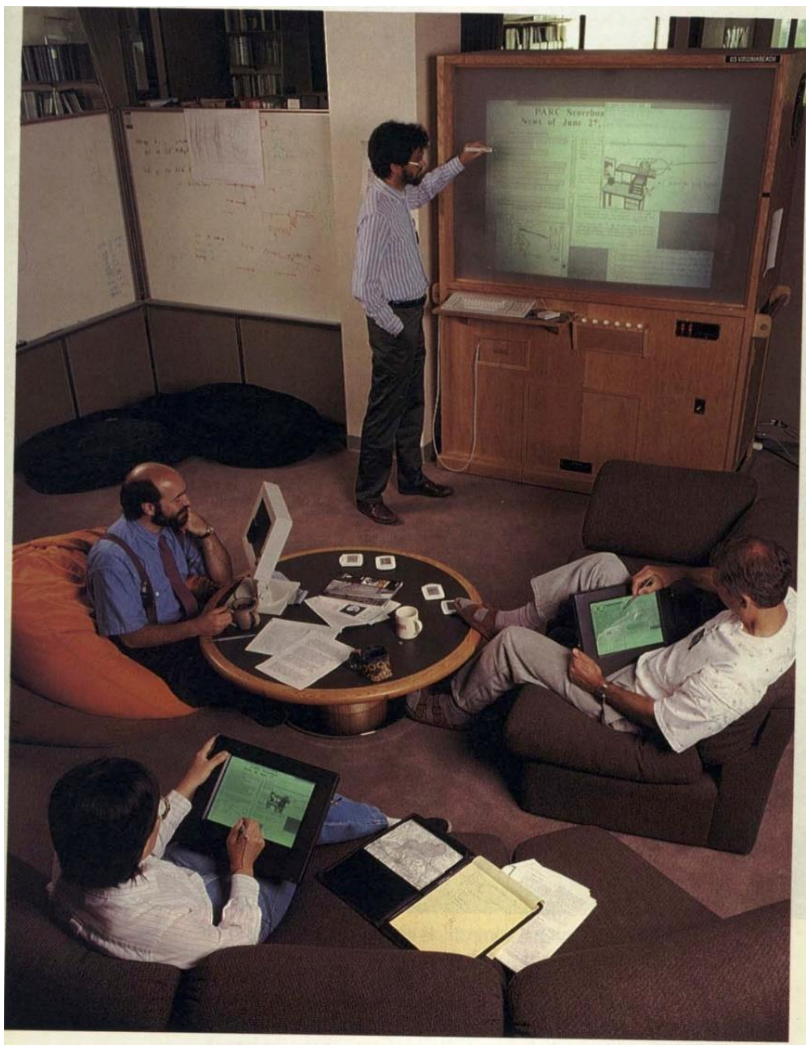


Figure 9. Weiser's ubiquitous "yard-size" board.

2.3.1. Larges surfaces benefits

We present here large touch displays properties and how they impact users' activity.

2.3.1.1. *Definition of large display*

Andrew et al. [9] define a "large display" as being at "human scale", i.e. close to the physical size of a human, with the resolution (ratio number of pixels / size of the display) that matches human visualization capacities. Ultra-High-Resolution Interactive Wall Displays (UHRIWD) are the denomination for extremely large display surfaces.

By being so large, these displays condition the environment of the user. Thus, designers cannot just scale up an existing application to match the size of the display. Simply displaying more data is not enough neither.

2.3.1.2. *Size and resolution impact*

Andrew et al. [9] emphasize that large and high-resolution displays can simply present more data to the users, especially multiscale data. They highlight that displaying a large amount of data can be used efficiently only if people can gain more insights into their datasets. The size and high-resolution allow users to scan a large amount of information at multiple levels of scale [17]. A study [140] shows that larger displays with more pixels can significantly increase the number of discoveries reported during visual exploration. Another study compared [108] a wall-size display and a desktop-type display and showed that the wall gains an increasing advantage as the complexity of the task grows, but that for simple tasks the desktop is faster. Another study [17] shows that increased physical navigation on a large display with high-resolution improved user performance compared to virtual navigation. The study shows that the users prefer being able to physically navigate in the interface rather than perform virtual navigation.

2.3.1.3. *Touch inputs*

With a large surface, users can interact with their whole hands or with combinations of more fingers than on small surfaces like tablets or smartphones. Based on two hands per user, five fingers per hand, many combinations of multi touch interactions can be designed. Such interactions have two challenges: user appropriation and system recognition of the gesture by the system. A study [126] classifies 32 multi-touch gestures and evaluate them according to these two challenges. Among them, 13 are rated above 4 by the participants (1 is difficult to perform, 5 is easy to perform) while offering a 90% recognition rate by the computer system. Another study for tabletop

gestures [113] gets about the same recognition percentage in the testing of 7 hand shapes (see Figure 10).

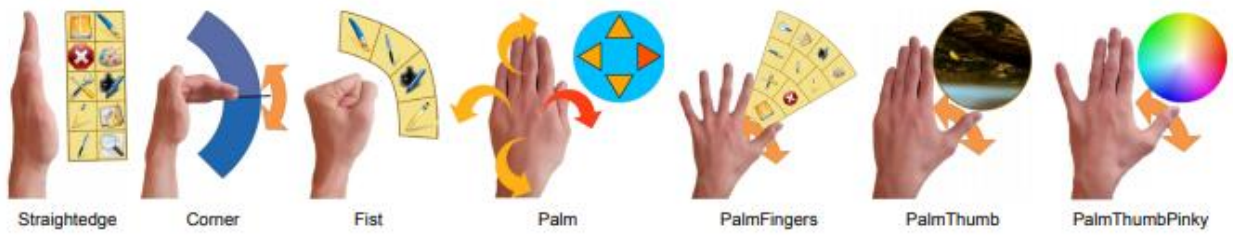


Figure 10. Example of hand gestures on a touch surface. Source: [113].

As mentioned earlier, if more data can be displayed on large screens, the user must be able to explore the dataset and navigate within the data more efficiently. A study on tabletops [148] explore multi-scale navigation interactions and showed that the direct manipulation *slide*, *pinch* and *turn* gestures are now gestures that users appropriate easily.

Types of touch inputs other than hands gestures are possible on touch displays. Touch inputs on a large size display can seem natural due to the size of the display: for instance, on a horizontal surface, one can write with a special pen just like he/she would write on a paperboard or whiteboard support [27,106]. A study [186] does a review on touchscreen stroke gestures (writing/drawing a stroke on the surface). Gestures can follow various design principle such as being analogous to physical effects and must remain simple if they are to be effectively used. Horizontal large surfaces enable the use of tokens, i.e. tangible items laid on the table that guide users' gestures [11,118–120].

2.3.1.4. *Orientation*

Vertical or horizontal interactive displays (in the sense "attached to a wall" or "flat like a table", see Figure 11) has an impact on the way users interact with the surface and each other. Horizontal surfaces favor collaboration [169]. In a study conducted in the domain of touch interactions [127], the horizontal surface was preferred by the participants for being less physically demanding to use than a vertical one.

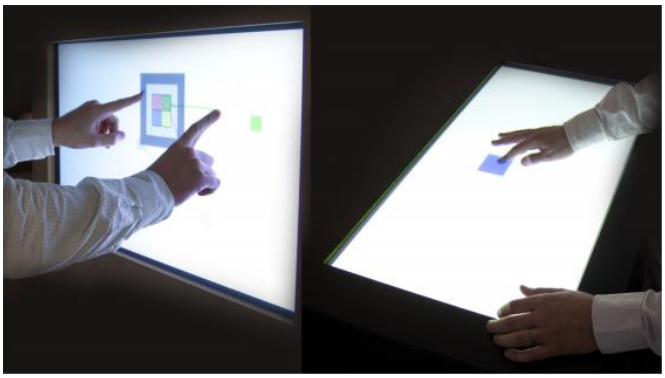


Figure 11. Vertical display (left) vs. Horizontal display (right). Photo credits: [127].

2.3.1.5. *Computer-Supported Collaborative Work (CSCW)*

Harrison & Dourish [61,76] and Akpan et al. [4] claim that a 'place' (social context) is determinant for the ability of an installation to encourage interaction and facilitate engagement with potential users. Harrison et al. highlight that bringing new CSCW tools determines new social organizations within the space, turning it into a new place, giving it a structure of unity, continuity, and meaning [76]. While creating unity and meaning, designers can focus on the concept of common information space [154]. Hence, a large interactive surface is bound to its "place" and will be used accordingly to the collaboration it supports in this place.

Because of high-resolution and their size, large surfaces can be used up close and favor collocated collaboration as proximity and tight collaboration are correlated [92]. For example, wall-sized displays allow multi-user collaboration with a large amount of data [107], promoting face-to-face communication . A study [91] identifies eight types of collaboration styles that can be used to identify how people collaborate on a shared surface such as active discussion, sharing the same view or work on different problems. The authors recommend favoring flexibility of annotations and reorganization of the space to promote collaboration on the shared surface. The study showed that large touch surface favor mutual and situational awareness.

Tang et al. [164] investigated *collaborative coupling* with a tabletop based application, which describes how teammates are involved with each other's actions. This study resulted in implications for tabletop design such as the need for "super lightweight" annotation, offering the possibility to produce visual cues about each other's needs or supporting flexible territoriality [152] to differentiate individual work from collaborative work.

With AwareMedia [21], the authors designed AwareMedia to support three types of awareness in the surgical suite: social (provide cues about the colleagues status), spatial (features of a specific location) and temporal (awareness of past, present, and future activities and events). They chose to deploy two large touch surfaces (42") for the coordination areas.

2.3.1.6. *Application domains*

Many practical applications of large multi touch surfaces in real contexts can be found for non-critical activities such as museum installations [46,73,109,130], education [47,48,64,114] or gaming [128,185]. The exploration of the use of these displays is facilitated by the possibility of installation in the environment. We present hereafter some research projects that tested the benefits of large surfaces for critical environment, which include additional challenges such as access to the context and access to the users.

2.3.2. Air Traffic Control

Systems from civil aviation, and more specifically Air Traffic Control (ATC), are interesting candidates to the use of large multitouch surfaces as their users manage a lot of information in real-time while coordinating among many stakeholders.

2.3.2.1. *Traditional workflow on an ATC position*

In a traditional ATC position workstation (see Figure 12), two air traffic controllers work together as a team to monitor the airspace they oversee. To do so, they use a radar image, computer systems and paper strips (see Figure 13) representing flights on which they can write the orders they send to the pilots The two controllers collaborate constantly, build mutual awareness, analyze and resolve conflicts, or perform inter-sector coordination activities [172]. The controllers face multiple stressful situations daily, sometimes requiring a third controller to help devise solutions in unusual situations such as storm. In case of a traffic overload, a supervisor manage the separation of a specific sector into two smaller sectors, transferring outgoing aircrafts and managing the coordination with other sectors [172]. Collaboration with three controllers raises the amount of verbal communication as the need for synchronization increases [172].

Figure 12. Example of an ATC workstation position and paper strips used in civil aviation to manage the flights.

The controllers manage a set of paper strips to control the flow of flights in their airspace. These strips are printed when an aircraft enters the airspace. It contains a lot of information such as flight ID, destination and origin. Controllers manually write on paper strips (see Figure 13) to take notes of the information sent to pilots. Paper strips are pliant and efficient tools for air traffic controllers activities [112].

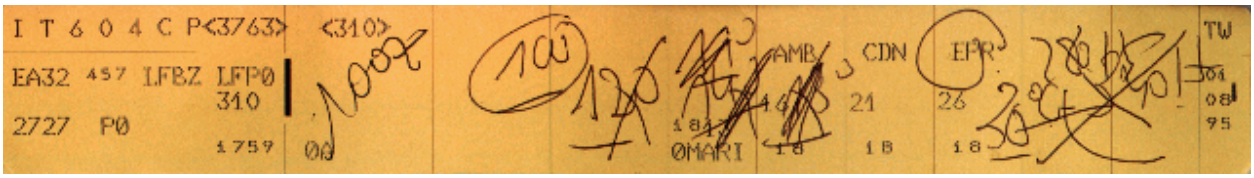


Figure 13. Example of paper strip, representing a flight in Civil Aviation Air Traffic Control. Photo credits: [42].

2.3.2.2. *Computerization of ATC activities*

Air Traffic Control and the surgical suite activity are both critical environments. They share specific requirements related to collaboration. Mutual awareness [144] is key in ATC, as the two controllers working together in their workplace need to act efficiently and congruently. Several studies developed prototypes to support it while preserving and improving the current way of working of the staff to minimize the amount of difference with work habits [50,88,115]. We present hereafter some examples, some of them relying on touchscreens.

Digistrips (see Figure 14) is an interface prototype to support ATC, using a touch screen and digitalized paper strips [115,116]. The authors support that a touch screen is useful in this configuration because it favors direct manipulation [89], mutual awareness (as the screen allows the colleague to see what is done) and sharable content. They state that using animations facilitate users' understanding of the transition of data from one state to another and its understanding by the operator. Most of all, they report that touch screens support manual writing and that Digistrips manual inputs could be displayed with handwriting fonts instead of being converted in computer font: this raises awareness on the fact that a human made the modification.

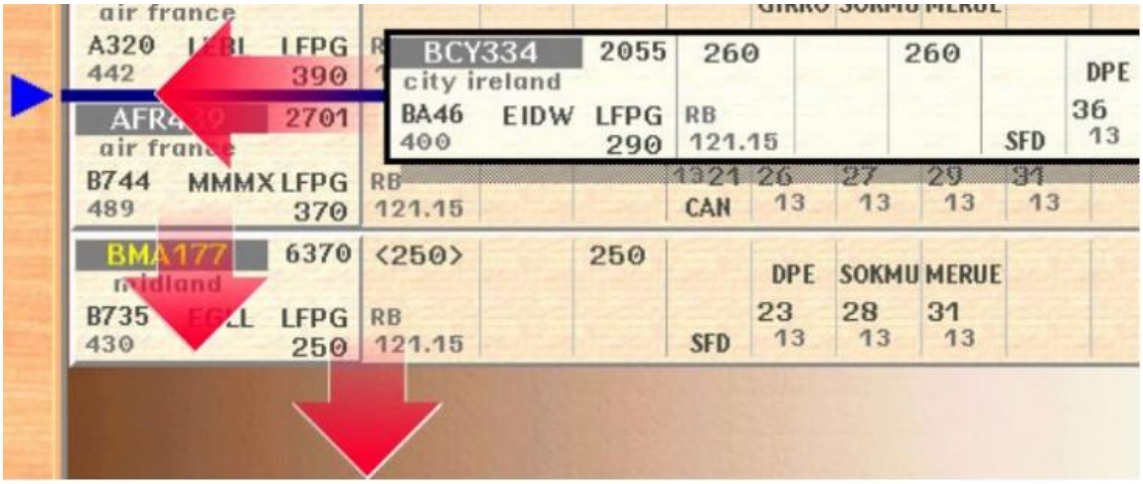


Figure 14. Digital strips visualization and manipulation offered by the Digistrip system.

While Digistrips focus on collaboration between two controllers working on the same position, Sire et al. [160] study the collaboration between air traffic controllers working on distant positions. Indeed, coordination between crossing sectors is needed when aircraft want to deviate from their planned route due to weather conditions or route optimization. Sire [159] proposes the concept of direct collaboration, as a follow-up to direct manipulation, to support coordination through manipulation and exchange of objects. The recommendations aim at preserving social skills of coordination in groupware instead of implementing data control protocols. In particular, they propose media and activity integration, and interaction styles that support prosody and social hints.

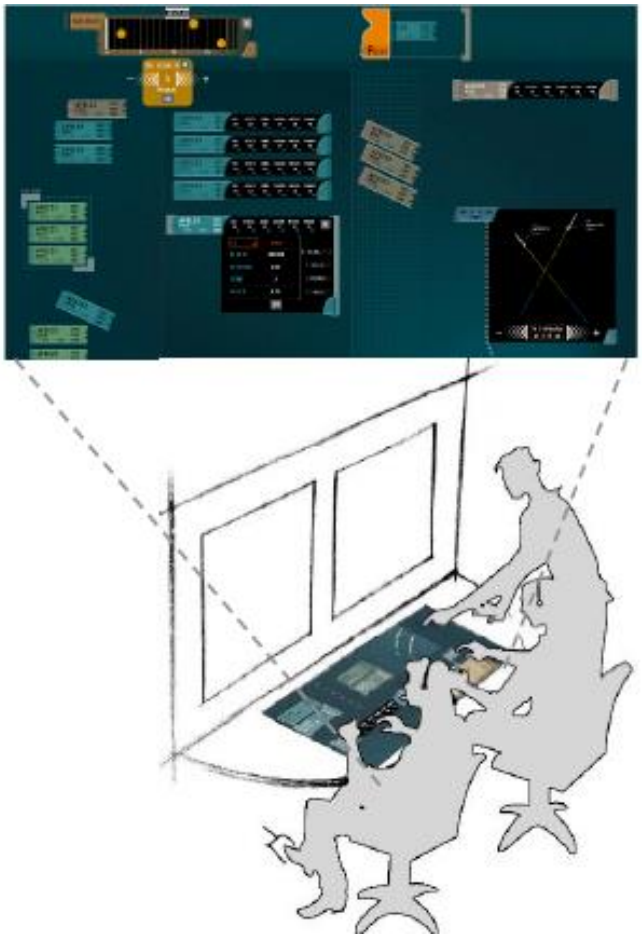


Figure 15. An ATC position using MAMMI system. The whole dashboard is virtual, on a multitouch screen. The strips are reified and used via multitouch and multi-users interactions. Image credit: [174].

The MAMMI (Multi Actors Man Machine Interfaces see Figure 15) multi touch tabletop system [50,172,174,175] reifies strips into a digital equivalent. Strips can be positioned anywhere on the table and rotated in any way. The purpose of free rotation was to enhance collaboration with indirect communication: the user drags a strip toward his/her coworker and rotate it in a way that the strip seems to be needing attention, to suggest to the colleague that he/she has to deal with it and resume an incomplete task. The authors of this tabletop system explored a completely digitalized workstation organization and added other types of digital features to improve communications with the pilots: for instance, supporting the delivery of an order traditionally made on the radio directly in the interface. Finally, the authors fostered partial accomplishment of actions, to foster dynamic task allocation among the controllers.

Strip'TIC [88] on the other hand, chose to keep using physical strips while augmenting them (see Figure 16 and Figure 17) The augmented paper strips can be manipulated and written on by the operators just like the traditional way. They are connected to the underlying computer system. As such they can "receive" information thanks to back and front video projection. They can provide information according to users' input: handwriting on the strips, movements and location of the strips on the stripboard. The physical aspect of the strips allows users to hold them and input information even if far away from the control position, as input is transmitted by the pen over a wireless network.

Figure 16. Strip'TIC: using augmented reality on tangible object to manage flights. On the right: two controllers using the Strip'TIC prototype (digital pens, augmented radar, stripboard, and paper strips). Image credit: http://striptic.fr/ (left) and [88] (right)

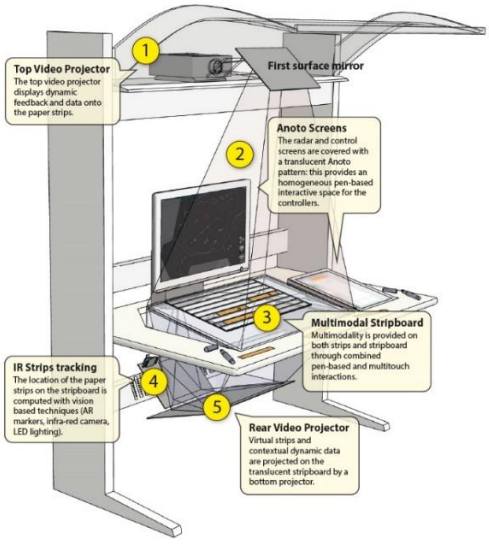


Figure 17. Strip'TIC whole system overview, including projection and retro-projection of augmented information and the radar image. Image credit: http://striptic.fr/

2.3.3. Emergency response

ePlan [45] is a multi-surface environment that includes large and small interactive surfaces for emergency response planning training (see Figure 18). The system gathers information from multiple sources in real-time and displays an overview of the situation on a large surface. The prototype received positive feedbacks for the usability and the learnability of its interactions. The study shows that designers should provide multi-touch interactions that avoid hard-to-remember multi-fingers gestures. The authors emphasize that technology reliability is key to user involvement and trust in the system. For instance, some users can spend a lot of time checking whether they are connected to the system instead of performing their activity.

Figure 18. ePlan multi interfaces system, including at the back a large map visualization and at the front a multitouch table top interface. Photo credits: [45].

TIPExtop [166] introduces a large multitouch display, designed to be used horizontally as a table to support decision-makers activity during emergency response. The authors designed tools to foster communication and explore alternatives around a multitouch map of the area of interest e.g. direct annotation of the map or recorded voice messages.

Figure 19. TIPExtop tabletop multitouch interface. Supporting here three users. Photo credits: [166].

2.3.4. Road traffic overview

Prouzeau et al. [134] explore the benefits of collaboration in front of UHRIWD. They describe a prototype of UHRIWD to overview real time road traffic. The prototype uses a very large screen to foster co-located, synchronous cooperation for two users via several interaction techniques. They design simulations to explore decisions consequences and highlight their different impacts on the current traffic.

The authors showed that UHRIWD are beneficial for collaboration close to the screen, but that operators need individual displays to work on more independent tasks. They therefore combined the UHRIWD with personal devices.

Figure 20. A large multi touch wall display showing the road traffic, allowing the users to interact with the map.

2.3.5. Synthesis & research opportunity

Large multitouch surfaces offer several assets for collaborative work such as size, and diversity of inputs possibilities. Their size would make them able to replace traditional surgical whiteboards (as the latter are usually very large and contain a lot of information). Large surfaces could improve surgical whiteboards in theory by bringing computer support and create a new environment which goes beyond a simple desktop screen.

Some projects involve large multitouch surfaces to support operational activities. To our knowledge, no application with large multitouch screen was designed nor developed for surgical

suite collaboration activities. We believe that there is an opportunity to push further the exploration of the use of large multitouch surface for a critical, real-world activity.

2.4. Opportunity for research

The literature shows a wide variety of studies on the surgical suite collaborative activity, emphasizing the problem of efficiency: up-to-date information, communication, optimization of surgical flow, all of which translates into reducing cost/increasing revenues. Other studies claim that computers could bring better support, but we remain aware of the risks: jeopardizing collaborative perks of existing methods, non-updated displayed information, more administrative work on the side of the physicians and lack of usability. For such environments, the computerization of activities is complex and UCD methods that include end-users during design are necessary. Finally, few studies included a clinical installation and experiment in real settings.

We think that a large multi touch display can combine the advantages of whiteboards with that of connected digital devices. Our aim is to build and deploy a system that fosters teamwork and flexibility, as needed for surgical flow management, using a large multi touch surface. We believe that following UCD methods will lead us to the design, development and clinical tests of a practical example of what can be done for the surgical suite staff.

The remaining questions are: what design techniques can we use? What interactions can we allow on this support? How to link the interface to the rest of the cyber-physical system and the hospital system? What methods can we use to design a prototype that is deployable in the clinic for testing?

3

CONTEXT: A CYBER-PHYSICAL SYSTEM

The present thesis is part of a larger project that consists in equipping surgical suites with a Cyber-Physical System (CPS) [67,86,87,94,95]. The CPS aims at providing information on the state of the suite. This chapter provides elements of context and describes the contributions I made to this larger project. It serves as an introduction to OnBoard, the interface prototype of the CPS to support surgical suite workflow.

The CPS is comprised of two pieces that were part of a separate work [67–69,86,87,95]:

- The SmartOR element, for which my contribution consists in the evaluation of awareness problems in the surgical suite.
- The mathematical model of the surgical flow, for which my contribution consists in the participation in the calibration of the model, the design and development of a visual simulation of the surgical flow using the model output and its utilization to support awareness, a key factor in the surgical suite efficiency.

We will detail the contributions of these two elements and show how they are first steps toward the full integration of humans in the cyber-physical system. The design of the integration of the human element in the cyber-physical system (the interfaces system) is detailed along Chapters 4,

5 and 6. This repartition is overall representative of my contribution on each elements of the cyber-physical system.

3.1. Rationale and preliminary introduction to the cyber-physical system architecture

3.1.1. Rationale

Large surgical suites (>6 ORs) present many advantages that enable them to be more productive. They have more resources: staff and equipment, ORs and perioperative rooms. Hence, more surgeries can be performed during the day. More resources allow for more flexibility in terms of daily adjustments of scheduling than smaller ones, as the resources are shared and can be redistributed according to the need.

However, large surgical suites are by nature more complex as to their management. Staff context awareness is key to make the right decisions that lead to better control of the surgical suite, reduced frustration of the staff and better patient health outcomes. The surgical staff constantly need to be updated on the state of ORs to anticipate what they must do. The acquisition of real-time information about the surgical suite state (i.e. each OR state, patient state etc.) is often done by "looking" inside the operating room to "guess" the status of the surgery, or even by asking directly the staff that are performing the procedure.

More and more hospitals get equipped with electronic hospital systems that contain the schedule and sometimes tentative prediction of times – like Epic Software. Such systems require the staff to manually input timestamps. For instance, a nurse inputs in the computer that the patient has just entered the OR at 8:06am. However, the information on time can be inaccurate because the staff has other priorities than memorizing and entering times in the computer (like taking care of the patient). Thus, the awareness of the whole surgical suite staff is compromised.

The need of measurement that emerged a couple of years ago in several industries (oil and gas, aerospace…) is happening more recently in the medical field. Management of such complex hospitals that tend to be larger and larger needs to follow the principle of continuous improvement

[55]. For a process to be stable, its workflow outcomes need to stay in a certain range and try to avoid as much as possible outliers.

Consequently, continuous real-time rescheduling is done by the staff based on their expertise and one-to-one communication with other staff members [162]. Common sources of discrepancies for OR management include [170]:

- Turnover time between surgeries above the hospitals management policy [15].
- Delays in the start time of the first case of the day [57].
- Surgeries that run longer than anticipated and lead to cancellation of other cases [12].

Hence, there are three concerns about the surgical suite flow optimization (Surgical Suite Concerns – SSC):

SSC1. How to acquire surgical suite data and measurements relevant to surgical suite steps.

SSC2. How to use data to raise staff awareness.

SSC3. How to use data to define a predictive model of surgery times and help the staff make better decisions.

We detail in the next sections the construction of the CPS which aims at answering these concerns.

3.1.2. Preliminary introduction to the architecture

The CPS is comprised of three elements that aims at answering the three concerns:

- SmartOR sensors [67,86,87,94,96]: automatic and non-invasive sensors and signal processing software modules installed in every OR of the surgical suite that acquire the OR state in real-time (patient in/out of the OR, patient intubation/extubation, laparoscopic procedure start/end). *SSC1*
- OnBoard [94,96,135,136]: an interactive interface system to support staff awareness and collaboration. This part is my principal contribution to the development of a cyber-physical system to improve surgical suite efficiency, patient outcomes and safety. *SSC2*
- A mathematical model of the surgical suite patient flow [68,69]: an agent-based representation of the surgical suite organization and surgical staff. The output of the model helps to understand the accumulation of delays within the surgical suite. *SSC3*

Figure 21 shows the architecture between the ORs, equipped with SmartOR sensors, the hospital network and the interface system, OnBoard.

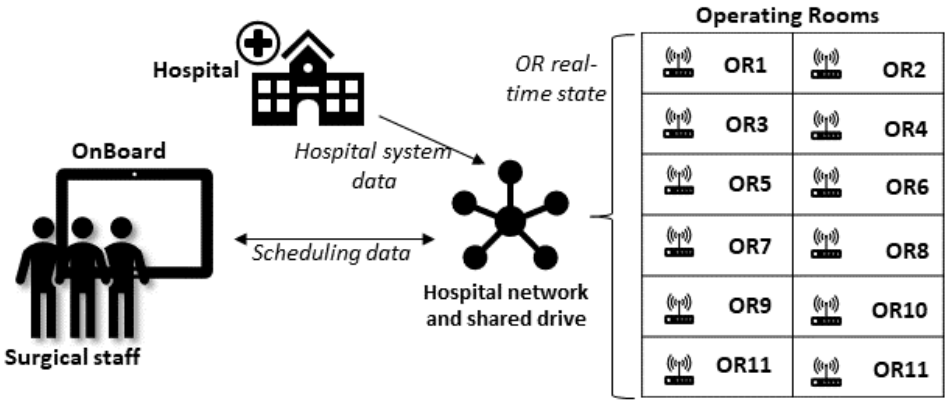


Figure 21. Architecture of the CPS.

3.2. SmartOR

I present here the work done prior to my thesis on the technical acquisition of the surgical suite state. I present our evaluation of awareness delays in the surgical suite.

3.2.1. Previous work insights (no contribution from the present thesis)

Surgical staff enters timestamps of events in the hospital system, such as: “Patient entered the OR at 8:06am”, “first incision at 8:15am”, etc. These timestamps always have the risk of presenting errors as the nurses for instance have other priorities than entering information in the computer – such as taking care of their patients. Previous work on the CPS for the surgical suite [67,86,87] describe an array of sensors and signal processing software that were installed in the surgical suite and that automatically tracked surgical cases to identify and quantify inefficiency bottlenecks (see Figure 23 and Figure 24).

Theses sensors communicate with a server where all the data are saved and processed to get only the key events. To avoid false positive detection, redundancy of different sensors has been used. The resulting system is a real-time timeline of the surgery events that can be used every day by the OR manager and the staff of the OR to make better operational decisions.

Figure 22. A colleague installing a SmartOR door sensor for detecting opening and closing.

Figure 23. Operating Room equipped with 2 SmartOR sensors. The left one is a camera detecting the motion of the ventilator, giving the event "Intubation" and the event "Extubation". The right one is a magnetometer detecting a mass of metal entering the OR by the front door. Coupled with signal processing, this sensor can detect if this mass of metal is the patient's bed, giving the event "Patient entry" and the event "Patient exit".

Step of procedure	Event target	Sensor type
Instrument/back table setup	Instrument racks placed on table	Pressure sensing strip
Patient brought into OR	Stretcher crossing door threshold	Pressure sensing strip
Patient transferred to OR table	Patient weight transferred from stretcher to table	Pressure sensing strip
Induction of anesthesia	Ventilation initiation	Small motion detection camera
Operation	First incision	Scalpel pick up detection
Reversal of anesthesia/extubate	Ventilator cessation	Small motion detection camera (same one as induction of anesthesia)
Patient transferred to stretcher	Patient weight transferred from table to stretcher	Pressure sensing strip (same one as prior)
Patient taken to recovery room	Stretcher crossing door threshold	Pressure sensing strip (same one as prior)
Occupancy of the OR	Movement in the OR	Infrared detector

Figure 24. Sensors targeting key events at each step of the procedure. Source: [67].

Other sensors such as Zigbee modules and RFID systems were added later in these studies to track patients and staff. These studies resulted in the acquisition of accurate and real-time measurements of OR times, such as average turnover times and first case start delays.

Tracking the surgical staff raises the problem of privacy and remains controversial. It had a negative impact on the staff that considers it is an invasion of their privacy. Patient's tracking seems to be acceptable as patients expect to receive care in a safe way. In addition, conversely to the surgical staff, they do not fear such tracking to be used for professional evaluation purposes.

This work [87] raised the need to deliver the data in real-time to the surgical staff in the best way to help making operational decisions and long-term strategy decisions. The authors proposed a first draft of potential interface systems (see Figure 25). However, they did not build any interface, nor did they conduct research on how it should be designed.

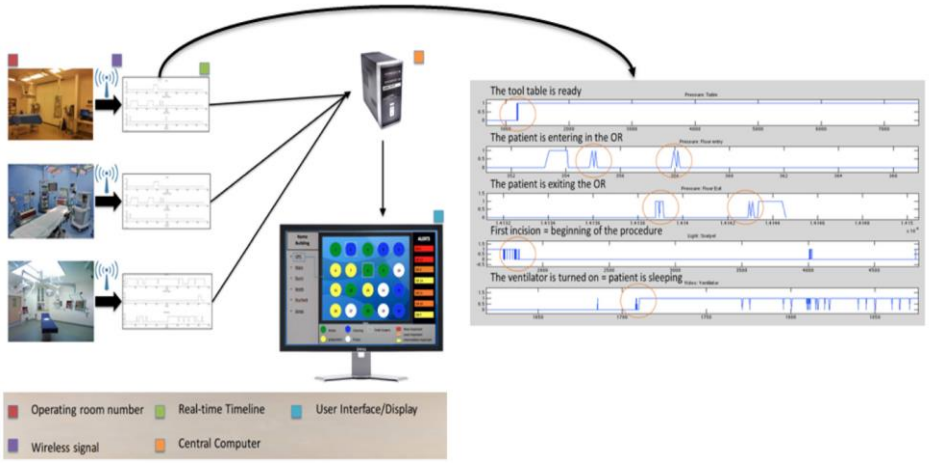


Figure 25. Real-time visualization of OR state (right) integrated with the SmartOR network system (left), Source: [87].

3.2.2. Evaluation of awareness problems in the surgical suite (contribution of the thesis)

As already explained in the related work, whiteboards in the surgical suite are centralized collaborative instruments to inform the surgical staff of the state of the surgical suite (OR state, staff allocations, equipment required for which surgeries etc.). The usage we observed will be more accurately described in chapter 4 “User context analysis”.

We performed an experiment to evaluate how up-to-date the information on the whiteboards was, compared to the actual state of the surgical suite [94]:

- Two sensors of the SmartOR system were installed and were recording the timestamps of patient entry and exit from the OR.
- An observer was manually writing timestamps on a paperboard of patient entries/exits from the ORs when this information would be written on the whiteboard.
- We finally compared the times and evaluated the awareness delays.

The complexity of the surgical suite, in terms of critical environment and activities, made the development and deployment of the SmartOR sensors challenging. Between regulatory approvals and staff approval, it was unclear whether these sensors could be installed in ORs. After requesting approvals, the cyber-physical system project was cleared by the Food and Drugs Administration (FDA) and by our institution Institutional Review Board (IRB) representative as a Non-Human

Research Project. We were therefore authorized to install sensors in the ORs and deploy staff interfaces in the surgical suite with the approval of the surgical suite manager.

During a period of 8 days, we quantified for 42 cases the time differences between the real entry and exit times in 5 ORs (patient entering and exiting the OR detected by the SmartOR sensors) and the respective times displayed on the whiteboard. From the whiteboard's analysis, two important steps of a surgery can be detected: patient entry and patient exit of the OR means beginning and end of a case. These steps are important because they indicate that the surgery started, i.e. the surgical staff is aware that this OR just started a new procedure, and because they indicate that the surgery is finished, i.e. the surgical staff can anticipate the next case to come in this OR. Our purpose was to understand better the interaction between the whiteboard of a large surgical suite and what is in fact happening in the OR. By doing so, we wanted to analyze whether the time differences were significant enough to create a disruption in the awareness of the surgical suite.

3.2.2.1. *Entry time records*

We first compared the "entry time" information. When a patient enters an OR, the board runner or a nurse crosses the start time information of a case with a red star (see Figure 26). We took note of the time at which the surgical staff would write this star and compared it later with the SmartOR sensors records. We detail in the chapter 5 "User context analysis" the surgical staff use of the surgical whiteboard more in detail.

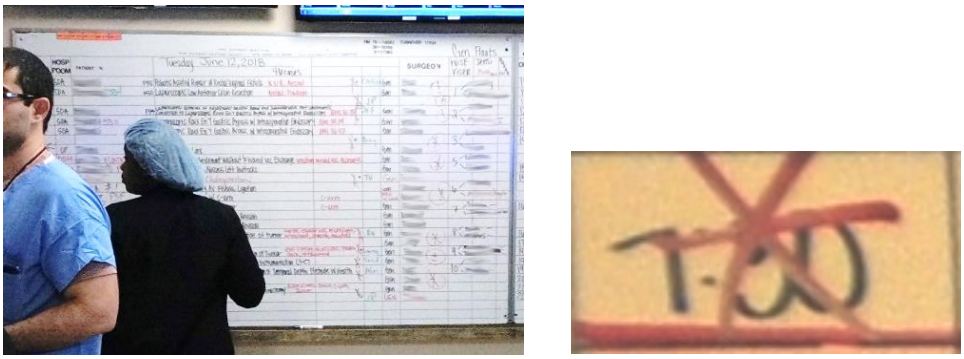


Figure 26. Left: a surgical suite whiteboard to schedule cases. Right: start time of the surgery crossed on the whiteboard.

Table 1. Time difference between the actual patient's entry in the OR and the report of this event on the whiteboard.

Patient entry in the OR	Average time difference	Standard deviation
	15min	22min

We compared (see Table 1) the time the case is "crossed" (see Figure 26) on the whiteboard to the time the patient enters the room. Table 1 shows that on average there was a 15 min start time difference per surgical case, which is significant at the scale of the surgical suite: in a typical day with 2 cases in 3 ORs, the time lost would be 2x3x15=90 min. In this surgical suite, surgical case last anywhere from 1h to 10h. Potentially, one surgical case could have been added in one of these ORs. When we presented our results to one of the board runners in our home institution, he was not surprised about these differences, but he realized that it was preventing him from making real-time rescheduling and reaching higher efficiency.

3.2.2.2. *Exit time records*

We then compared the "exit time" information. When a patient leaves an OR, the board runner or a nurse erases the whole surgical case from the whiteboard. We took note of the time at which the surgical staff would erase the surgical case and compared it later with the SmartOR sensors records.

Table 2. Time difference between the actual patient's exit of the OR and the report of this event on the whiteboard.

Patient exits the OR	Average time difference	Standard deviation
	13min	29min

As we did for the entry time, we compared (see Table 2) the time at which the case is erased from the whiteboard to the time when the patient actually exits the room. Here again, even if it is shorter, a time difference exists between the two events and can bring unnecessary waiting time in the continuity of the OR workflow, especially in the turnover time. The large standard deviation is linked to the variability of workload of the board runners and nurses.

3.2.3. Conclusion

We found an average difference of 13 to 15 min between an event that happened in the OR and this exact same event being reflected on the whiteboard, with important standard deviations.

Two sensors constitute the SmartOR system that we used for this experiment. One is installed on the door and capture patient entry and exit of the OR using signal processing: the magnetometer that detect a large amount of metal passing (patients' beds). The other sensor is installed on the ventilator and capture intubation of the patient and extubation with an infrared camera that detects the motion of the ventilator via image analysis.

The SmartOR system can capture automatically real-time OR status with more precision than what is today input on the whiteboard. By bringing a user interface delivering real-time information on the surgical suite state with SmartOR data acquisition systems, we would offer to the staff a cyber-physical system that will potentially enable a more omniscient surgical team. Not only every elapsed time is analyzed and stored for later analysis, but we can transmit this information to all the employees who need it.

If one could record every action that was performed on the whiteboard, it could also become a sensor and archive inputs information.

3.3. A mathematical model of the surgical flow

We detail here the rationale behind the development of a mathematical model of the surgical flow and an example of its exploitation.

3.3.1. Rationales for a mathematical model of the surgical flow

Surgical flow is a highly complex process occurring at multiple scales across the hospital system. Some of the critical surgical maneuvers that affect patient outcomes should be set in context of the overall management and organization of surgical staff and performance. A single event in the OR can negatively affect other steps and the combination of otherwise benign events can cascade and result in adverse outcomes for the patient. Figure 27 shows the different scales that can be impacted by adverse events. Figure 27 must be read from the center to the edge of the circle for the impacts on space scale and following the unit circle for the impacts on time scale.

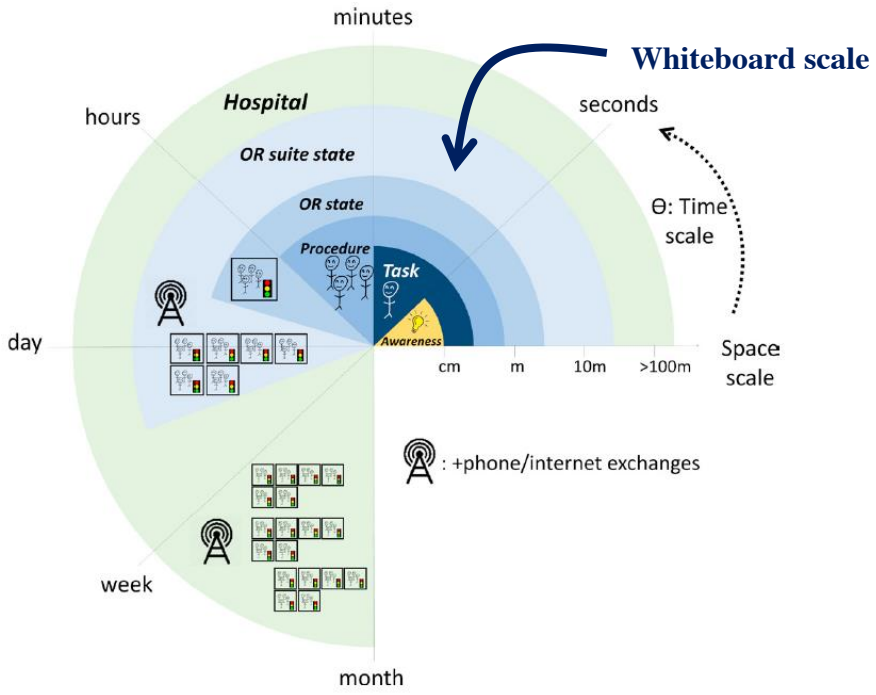


Figure 27. Symbolic representation of the multiscale distribution of surgical flow ranging from the smallest scale, OR awareness, to the hospital system level involving hundreds of staff.

Current optimization techniques to schedule surgery [24,56] have limited capability because of the uncertainty with regard to procedural time, lack of detailed information on the state of the system and a large number of last minute emergency cases added to the schedule.

Standard techniques commonly employed, such as check lists and team work protocols [121], cannot maintain satisfactory performance in such a stressful and uncertain environment. We propose that staff and patients would greatly benefit from a usable cyber-physical infrastructure [105] that constantly monitors events and uses a sophisticated model of surgical flow to anticipate difficulties and efficiently assists rescheduling efforts of the OR team.

Arising from the conceptual work described above on the CPS, a mathematical model of the surgical flow in a large OR suite emerged. Each OR process can be represented by an algorithm that has a complex graph structure for its execution and requires a minimum number of stakeholders to achieve the task corresponding to each node. Normalization of large-volume surgery times, such as cholecystectomy (600,000 cases per year in the United States) or bariatric surgery (200,000 cases per year) by major surgical associations such as the Society of American

Gastrointestinal and Endoscopic Surgeons (SAGES) provides a solid base to develop a predictive model of surgical times.

3.3.2. Exploiting the model

The analytical method results in a staff-specific, agent-based model that retains the key features observed in daily clinical practice and is based on a comprehensive multi-scale view of activities in the OR suite. The goal of the mathematical model is to add some predictive simulation capability of the surgical flow to help optimize OR management decisions. For example, once the timelines of hundreds of open surgeries are available, a good statistical predictor of the time spent at any given step of the process can be developed.

The proposed model explicitly takes the OR staff and their communicational and technical skill levels into account. Parameter identification in the agent-based model improved as the database of SmartOR measures grew and became patient and surgeon specific, by relating it to the hospital system. The preliminary analysis was able to differentiate between standard and longer cases as a function of patient risk class in anesthesia (e.g., bariatric surgeries) but not yet at a satisfactory level of precision. The patient condition prior to surgery plays a key role in those predictions and needs to be much further refined in the analysis. Therefore, to provide reliable guidance, the CPS must be able to recover extensive information from the hospital system.

Table 3. Ranking the influence of the parameters on key factors of OR efficiency (q*), such as turnover.

	PARAMETERS ↓			
	Ideal time to clean OR (q8)	#Anesthesiologists per OR (q9)	#Janitorial Teams per OR (q10)	Readiness of janitorial team (q11)
Anesthesia		1		
Waking Up		3		
Turnover	2	4	3	1
↑ SURGERY MACROSTEPS				

We discuss how the model accounts for the awareness factor in the study reported in [96]; a more detailed description is available in Appendix 1. The model ranks the influence of parameters, such as the ideal length of time to clean the OR or the number of anesthesiologists/number of ORs, according to their impact (see scale on Figure 28) on the macro steps of the procedures (turnover time, anesthesia time, etc.) – see Table 3.

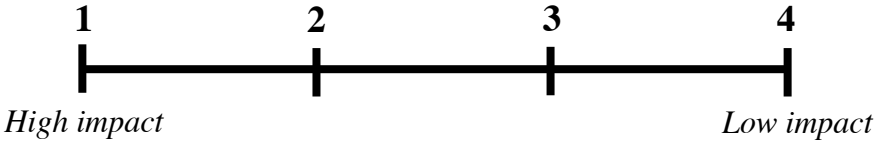


Figure 28. Quantification of impact score of parameters in the model.

Parameter q11, awareness and communication delay until the OR cleaning staff (cleaning OR after surgery) arrives in the OR, has a very high impact score (1) on the turnover time performance. Therefore, the model suggests that we must increase our efforts on improving surgical suite awareness to improve turnover times. The model could suggest what would be the most relevant information the staff need to see during the operations.

3.3.3. Data visualization of the workflow based on the model output

I designed a visualization of the output of the mathematical model of the surgical workflow and patient flow. The purpose of the visualization was twofold: help mathematical researchers design and assess the underlying model, explore the resulting data, and assess potential improvements; help the surgical suite executive staff understand the workflow of the surgical suite, discover and discuss opportunities for improvement, and make informed decisions.

The visualization in an animation showing the map of the surgical suite and the movement of staff, patients and the changes of OR states. The visualized data are a set of time-stamped events related to staff and patients in the surgical suite. An excerpt of a spreadsheet containing such data is visible in Figure 29. For instance, a column represents an OR and its different status through the day (12 hours), sampled every minute. These data are the output of a run of the model. To produce these

data, the user must input to the model several parameters such as number of ORs, number of patients, their time of arrival, number of surgeons, awareness levels, patient's time of arrival strategies, individual performance, number of cleaning crew or number of endoscopes (in the case of Figure 30, the simulation is about the surgical flow of a flexible endoscopy surgical suite).

	A	B	C	D	E	F	G	H	I	J
1	**OR1**	**OR2**	**OR3**	**OR4**	**OR5**	**OR6**	**OR7**	**OR8**	**OR9**	**OR10**
2	1	1	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	1	1	1	0
4	1	1	1	1	1	1	1	1	1	0
5	1	1	1	1	1	1	1	1	1	0
6	1	1	1	1	1	1	1	1	1	0
7	1	1	1	1	1	1	1	1	1	0
8	1	1	1	1	1	1	1	1	1	0
9	1	1	1	1	1	1	1	1	1	0
10	1	1	1	1	1	1	1	1	1	0
11	1	1	1	1	1	1	1	1	1	0
12	1	1	1	1	1	1	1	1	1	0
13	1	1	1	1	1	1	1	1	1	0
14	1	1	1	1	1	1	1	1	1	0
15	1	1	1	1	1	1	1	1	1	0
16	1	1	1	1	1	1	1	1	1	0
17	1	1	1	1	1	1	1	1	1	0
18	2	2	2	2	2	2	2	2	1	0
19	2	2	2	2	2	2	2	2	1	0
20	2	2	2	2	2	2	2	2	1	0
21	2	2	2	2	2	2	3	2	1	0
22	2	2	2	2	2	2	3	2	1	0
23	2	2	2	2	2	2	3	2	1	0
24	3	3	4	3	4	3	3	3	1	0

Figure 29. Example of data output from the model of the surgical flow. Here, each column represents the evolution of the OR state according to time (1 row = 1 min). 0 represent an idle time (OR not used), 1 represents procedure started, 2 represents intubation started etc.

The resulting animation is a 4min video (see a picture in Figure 30) that updates, through 12 hours, the OR state, staff, equipment' and patients' locations. It shows the evolution of 4 key performance indicators for surgical suite optimization (top-left in Figure 30): the global patient waiting time, the turnover time (time between the moment the patient leaves the OR and the next patient enters the same OR), and the volume of surgeries and in this specific case the endoscope delivery delay. At the end of the animation, the simulation displays the total volume of surgeries and the revenue of the surgical suite for this day.

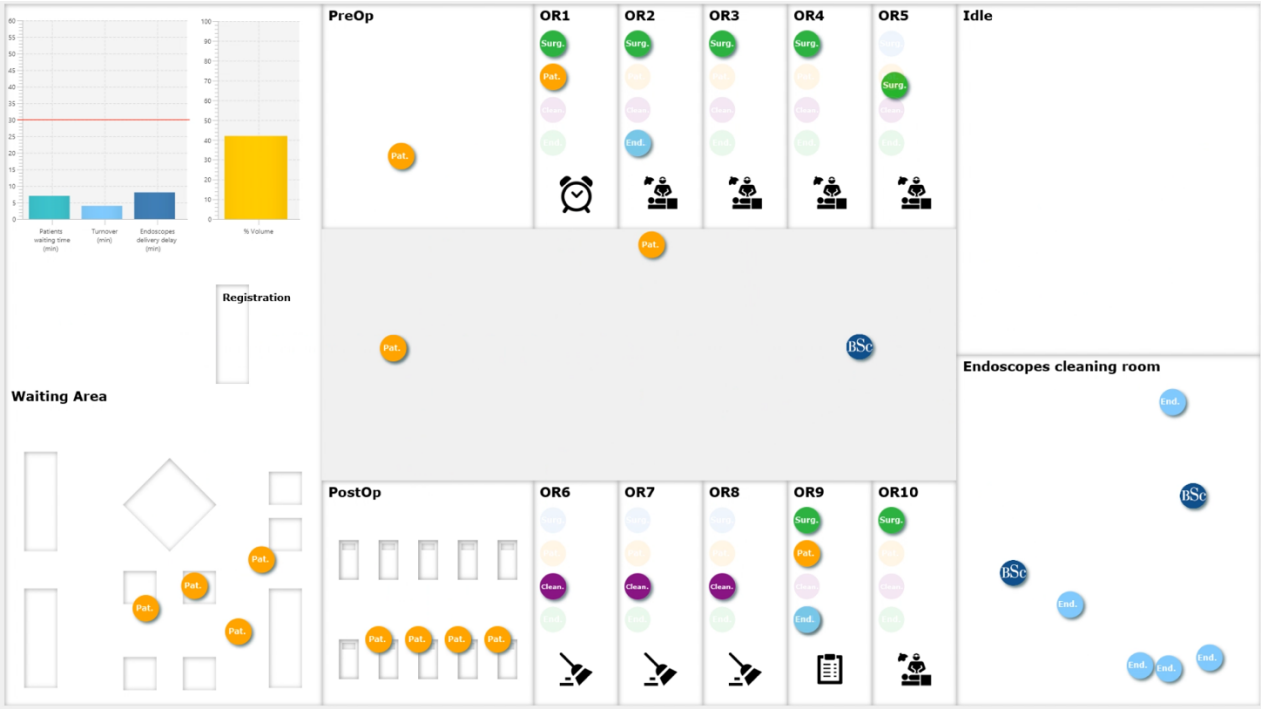


Figure 30. Extract of the video representing the output of the mathematical model of the surgical flow for a flexible endoscopy surgical suite of 10 ORs.

The visualization succeeded in helping the designer of the model to partly assess its correctness. The simulation visually exhibits inaccuracies, for instance when a surgery has started but not patient is in the room, or when a procedure starts in the same OR though it has not been cleaned yet.

It succeeded in helping designers and executive staff discover the relationships between all elements that take part in the models. By tuning parameters' values, they could identify which work best in specific situations. For example, we have tested 3 scenarios on surgical flow efficiency in the context of Gastro-Intestinal surgery (GI). GI is characterized by short procedures (colonoscopy or EGD). We have tested three situations in our simulation:

1. A baseline with standard scheduling and OR awareness delays observed in clinical conditions.
2. An optimum overbooking to compensate for cancelation.
3. An optimum OR awareness.

We observe a growth of 30% in productivity of the surgical suite going form scenario 1 to scenario 3 and one can visualize the flow to appreciate this improvement and share that observation with management levels.

The visualization helped the researchers involved in the project to communicate to the executive staff on the value of their research at improving the surgical suite management in terms of productivity and increased revenue. Notably, it highlights the complexity of the surgical workflow and helped the executive staff understand that to improve it, a system approach is necessary i.e. an optimized schedule is the result of complex interactions between all the surgical suite subparts.

3.4. Conclusion

This chapter presented the CPS and the contributions made to the study of the CPS:

- An evaluation of awareness problems in the surgical suite, which showed important differences between times of events in the OR and the times reported on the whiteboard.
- An exploitation of the model, showing that the awareness of the surgical team has the highest impact on turnover times.
- A visualization of the surgical flow simulation to help researchers and executive staff discover and decide on potential optimizations

In the rest of the dissertation, we focus on the design of a user interfaces to bring the data from the sensors to the staff and foster collaboration and awareness among the surgical team.

4

METHODS

Previous results and the review of literature shows that a user interface system is needed for the CPS, with focus on usability and collaboration. Hence, we chose User-Centered Design (UCD) methods [192] to design the user interface of the CPS. This chapter presents the different methods we used to conduct this work regarding user context analysis, design and evaluation. The results of the application of the methods are presented in subsequent chapters.

We performed an initial analysis of the surgical suite and of the surgical staff workflow. We had the opportunity to access the surgical suites of the hospital for observations and interviews. We performed participatory design sessions, usability inspections and design walkthroughs for the evaluations. We borrowed principles from the technology probes approach. Finally, we performed an analogy between ATC and surgical suite activities.

4.1. Technology probe

We initially considered conducting the project with a technology probe approach [90]. Technology probes are simple, flexible, adaptable technologies with three interdisciplinary goals:

1. Collect information about the activity in the surgical suite;

2. Inspire the staff and the design team for prototyping;
3. Engineer and Test prototypes.

Since we were designing an electronic whiteboard to replace a traditional one, we figured that we could design and implement a very simple version with few features only to foster adaptation and appropriation. We planned to directly install technology probes in the surgical suite and observe their use. Technology probes have already been used in healthcare, notably to design a medical checklist [102]. However, the surgical suite is a critical environment. The difficulty we met to get authorization to install technology probes in the surgical suite prevented us from conducting the PhD work with this method. Hence, we utilized more classical UCD methods.

Nevertheless, we borrowed 3 principles from this approach to guide the design:

TP1. Flexibility, Open-ended and co-adaptive: Technology probes must be open-ended with respect to use, and users should be encouraged to reinterpret them and use them in unexpected ways.

TP2. Real-world: Technology probes must work in a real-world setting. Therefore, the main technological problems must be solved for the technology probes to serve their purpose.

TP3. Instrumented: Technology probes collect data about users and help them (and us) generate ideas for new technology. Logging allows researchers to create visualizations of the use of the probes, which can be discussed by both users and designers.

Following the design principles of technology probes favored the possibility of deployment. We could in *fine* collect information on the usage of the prototype, which inspires the staff when ideating during design iterations.

4.2. User context analysis methods

We performed the analysis of the workflow in six of the eight surgical suites of the Houston Methodist Hospital, with a System Usability Scale questionnaire, interviews, contextual inquiries and observations.

We followed a UCD approach with a total of 27 surgical staff. Table 4 shows the staff involved in the UCD methods. More detailed description of the users' roles will be presented in chapter 5 "User context analysis".

Table 4. Summary of user-centric design procedure with surgical staff and researchers. (N) next to BRx means that the board runner is also a nurse.

Surgical suite	Board runners (BR)	Nurses (N)	Surgeons (S)	Anesthesiologists (A)	Managers (M)
DunnOR	**BR1** (N)	**N1**	S1	A1	M1
	BR2 (N)		S2	A2	
	BR3		S3		
FondrenOR	BR6	N2	S4	A3	
	BR7 (N)	N3	S5	A4	
		N4		A5	
OPC19	**BR4** (N)				
	BR5 (N)				
Other Suites		N5	**S6**		
			S7		
			S8		
			S9		

Legend of Table 4:

Interview	Contextual inquiries	Evolutions with technology probes	**Participatory design**	Design walkthrough

We used System Usability Scale (SUS) questionnaires [2] answered by 22 surgical staff of FondrenOR about the use of whiteboards in the surgical suite. We conducted 13 interviews and 12 contextual inquiries within the surgical suites DunnOR, FondrenOR, OPC and "Other Suites" (see Table 4), with 20 surgical staff [26]. The purpose of these interviews was to identify the tasks performed by the surgical staff, their collaboration activities, the general workflow and layout of

a surgical suite, and its issues. During interviews, we oriented the questions towards the use of the whiteboard, and how it supports their activities (see the whiteboard in Figure 31). We oriented questions toward critical situations such as cancelation of cases, emergency management or resources management issues. The answers were recorded with handwriting on paper documents, associated to each user profile.

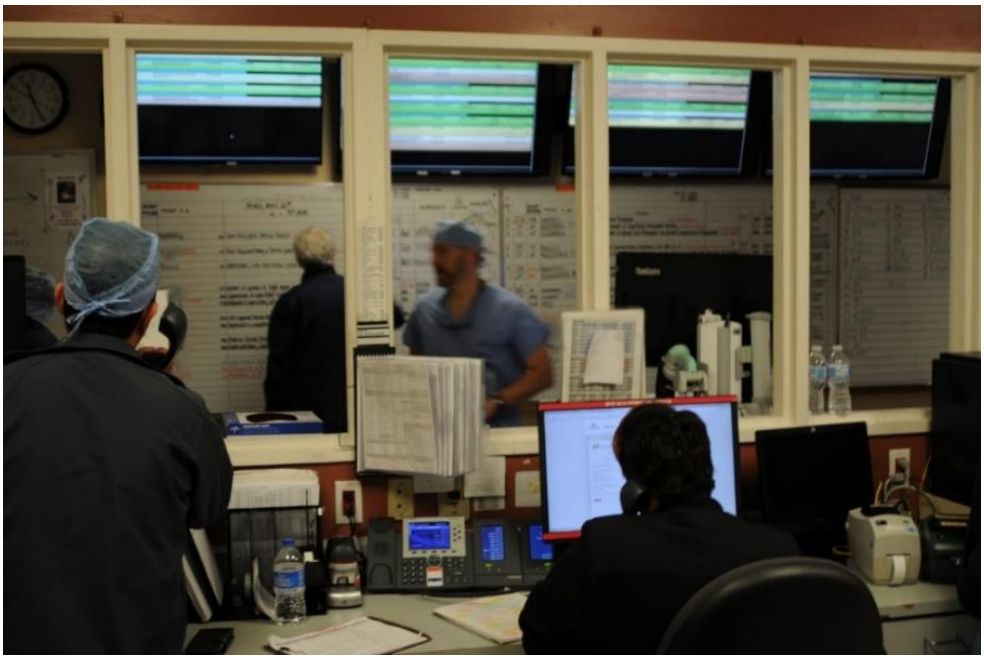


Figure 31. Picture taken from the surgical suite control room, where there are computers to access scheduling and patient information. This room opens windows on the information corridor, containing semi-public information (available only to the surgical staff), including two large whiteboards displaying schedule and notes, and screens at the top displaying hospital system information.

We performed observations using cameras to capture the actual usage of the whiteboard. We set up a camera that could capture a whole whiteboard (see Figure 32). With the camera, we captured 1000 pictures per day, taken with 1min delay between each photo or 30s. We recorded pictures during 3 consecutive weeks. On the pictures, we could see the symbols that are written/put on the whiteboard, the modifications/evolutions (updates, adds, writing/erasing) made on the whiteboard along the day, and the user-whiteboard and the user-user interactions (see bottom pictures in Figure 32).

Finally, we identified 19 work scenarios [41] of surgical suite activity which were validated by the surgical staff BR1 (see Table 4) as the main activities of the surgical suite staff. Scenarios are stories based on interactions between people and tools that describe a sequence of actions and events that lead to an outcome. From these scenarios, we established 6 high-level requirements to be fulfilled by the new system.

Figure 32. Installation of the camera (circled in yellow on the top picture) to take pictures of the whiteboard (facing the camera). The top picture shows the control room (on the other side of the windows) and computer systems to access patient medical records in front of the surgical whiteboard. The bottom pictures show an example of the pictures taken by this camera.

4.3. Participatory Design

We designed and iterated on technological solutions to support surgical staff activity by performing participatory design sessions [151] with 9 surgical staff from DunnOR, OPC surgical suite and others surgical suites (see Table 4). We performed brainstorming sessions and generated ideas about suitable tools for a digital surgical flow management system. Two sessions consisted in a brainstorming in a meeting space on how to represent and arrange elements on an electronic whiteboard to be able to perform the same tasks as on the whiteboard and enhancing them with the support of a computer. 3 questions were asked during these sessions and the participants had to propose ideas to answer them. The 3 questions were:

- What overall layout to support the case scheduling activity?
- How to represent information that is very important for a case?
- How to display the current status/advancement of a case?

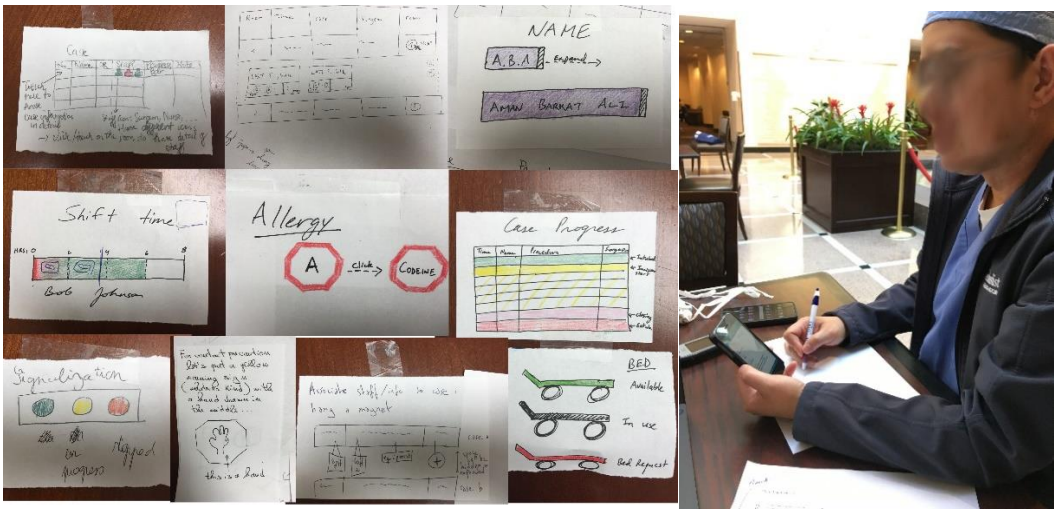


Figure 33. Some idea results after a participatory design session with the surgical staff.

These sessions allowed us to start prototyping. Discussions led to more specific design questions:

- How to carry information away from the board?
- How to modify a surgical case?
- How to modify the OR number?
- How to modify the start time?

- How to insert an emergency case?
- How could we practically build the system so that we could test it in the surgical suite?

We show some example of ideas that were designed in Figure 33. The answers and ideas were collected on paper notes or drawings during the sessions. They were then analyzed for their contents and similarities between different answers to see how and if they should be implemented during the design of interactions on the prototype.

4.4. Design Evaluation – Design Walkthrough sessions

We performed design walkthrough [97,124,129] sessions on 3 different versions (see Figure 34) of the prototype with a total of 12 surgical staff (see Table 4), with 13 separate sessions (see Table 14).

Figure 34. From left to right: version 1, 2 and 3 of the prototype.

The first part consisted in 5 sessions, with a total of 6 surgical staff walking through 9 tasks. The second part consisted in 1 session, with a total of 2 surgical staff, walking through 10 tasks. The third part consisted in 5 sessions, with a total of 5 surgical staff, walking through 8 tasks. The last part consisted in 2 sessions, with a total of 4 surgical staff, walking through 5 tasks. All the tasks were built upon the work scenarios extracted from the user activity analysis (see Table 7).

Data were collected via observations during the walkthrough sessions. For each of the scenarios, we recorded on paper sheets: the success or failure of the performance of the task (effectiveness), the way the user performed the task (efficiency), the user's satisfaction by asking to answer "How difficult was the task?" on a scale from 1 to 5 (satisfaction), and free comments from users and questions asked during and after the task and the time to perform the task.

Other participatory design sessions were performed at the end of the design walkthrough sessions. These sessions allowed us to know what to adjust and to re-iterate the design of our prototypes. The implemented ideas that had satisfying performances and positive feedback after the design walkthrough were kept for later deployment.

4.5. Usability inspections

We performed usability inspection [124] to prepare the system for deployment and followed usability guidelines [124,125]. With a team of usability experts (Human-Computer Interaction researchers), we reviewed all the interactions of the prototype with focus on error prevention and error recovery. The objective was to assess that no critical action could be triggered unexpectedly or with insufficient feedback.

We verified the quality of implementation or implemented the missing interactions of 4 error prevention features and 6 error recovery features.

4.6. Analogy with Air Traffic Control activity

As shown in the related work, Air Traffic Control (ATC) shares with the surgical suite many similarities. Air Traffic Control consists in managing the flow of flights in each airspace or on the ground. To do so, air traffic controllers use specific systems such as the radar, paper strips (see chapter 2) or radio communications to organize the flights, anticipate and avoid collisions and optimize the flow. Like in the surgical suite, ATC systems run in a critical environment and high levels of stress and workloads, and should support complex flow management and risks management [77,168]. We thus decided to analyze previous studies or systems related to ATC to apply their results when pertinent.

4.7. Methods conclusion

We started with the use of technology probes in mind to explore the needs of the surgical suite. The context however prevented us from performing a real technology probe approach. Hence, we followed more classical UCD methods all along the analysis, design and evaluation, in order to efficiently build features that fit the users' needs. We kept some of the technology probes design principles while designing interactions to help us with the deployment.

We performed interviews and contextual inquiries with 20 surgical staff to understand the staff activity within the surgical suite (see Table 4). This work allowed us to define more precisely the surgical suite workflow, the different roles of the users involved in this work and more specifically the use of whiteboards in the surgical suite, with the identification of 19 scenarios (see Table 7), 24 features and 6 requirements.

We closely worked with 16 surgical staff to perform participatory design and design walkthrough sessions. This work allowed us to re-iterate on 3 main versions of the designs and develop useful and adapted features with the staff. A timeline of the design process is available Figure 35.

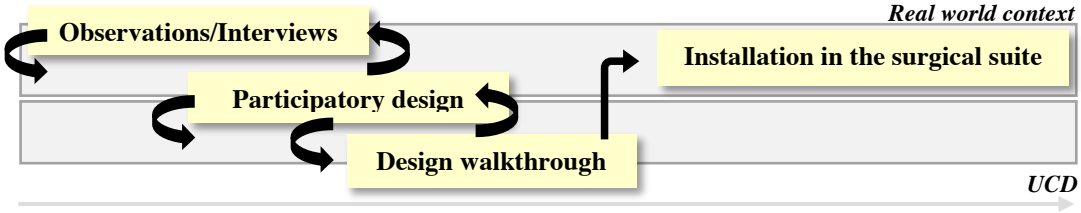


Figure 35. Timeline of methodologies used for the design of OnBoard.

We developed an analogy between the surgical suite workflow and ATC.

We presume that such methods maximize the chance of success of deployment in the surgical suite, which would allow us to analyze the real use.

5

USER CONTEXT ANALYSIS

In this chapter, we detail the results of the user context analysis. We first describe the surgical suite context, then the results of interviews and observations. Then, we present the identified needs and scenarios of the surgical staff workflow which helped us determine high-level requirements. We end this chapter with the analogy with air traffic control and the introduction of design principles.

5.1. Surgical suite general description

Surgical suites are areas that are dedicated to the care of surgical patients. They are overloaded with information, short deadlines (emergencies) and missing spatial organization (which patient for which OR at what time? Where is this laparoscopic tool or imaging device?).

Each surgical suite has its own culture and rules, including social ones. The surgical suite staff is comprised of nurses, surgeons, anesthesiologists, board runners, technicians, cleaning crews, transporters etc. They all work as a team to deliver the best care to the patient and need continuous access to the surgical suite information to perform their work. A key activity in a surgical suite is its management e.g. scheduling cases, allocating staff (surgeons, anesthesiologists, nurses), scheduling activities among an operation, monitoring the status of operations, and more importantly, reacting/adapting according to contingencies.

Inside current ORs, several independent computer systems may coexist. The surgical suite is comprised of numerous equipment: equipment to carry information (paper notes, medical records etc.), equipment to communicate (whiteboards, phones, and emails), computer equipment to access the hospital system and patient information.

Figure 36 shows a 3D visualization of a surgical suite. The central organizational and collaborative tool consists of two large whiteboards (see Figure 31) placed in the surgical suite. On Figure 36, "X" represents where the large whiteboards are. "A" represents the Post-Operating Rooms (*PostOp*). There are other rooms where the patient scheduled for surgery may reside before or after the surgery: Holding Room - *Holding*, Pre-Operating room – *PreOp* and *PostOp*. "B" represents the Coordinative Area. It is physically separated in 2 parts: the *Information Hall* with the whiteboards and the *Control Room* where necessary information about cases is dispatched. Information within the *Control Room* is available for individual consultation. Information that is displayed in the *Information Hall* is meant to be semi-public i.e. the whole staff of the surgical suite. "C" represents the operating rooms, where the surgeries take place. DunnOR, where most of the observations were made, contains about 23 operating rooms and requires a complex organization in terms of management of the resources – human and equipment.

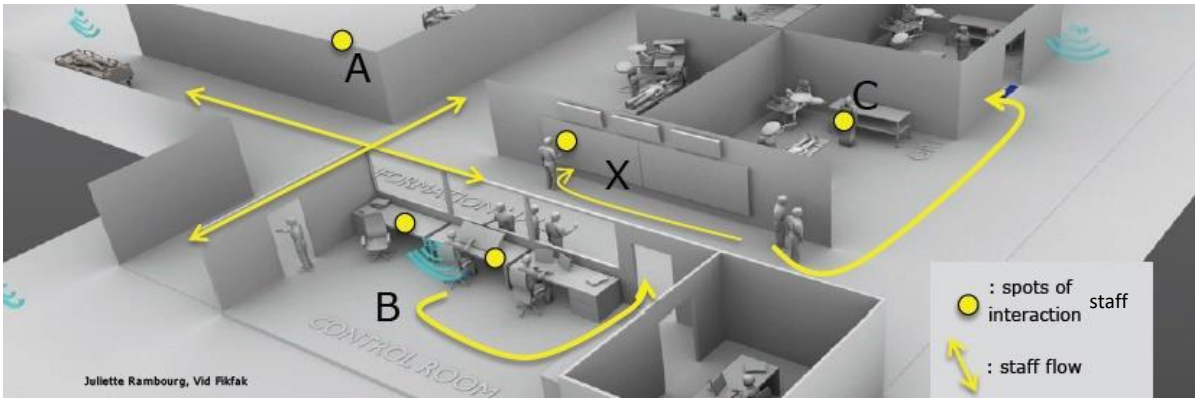


Figure 36. Surgical suite visualization.

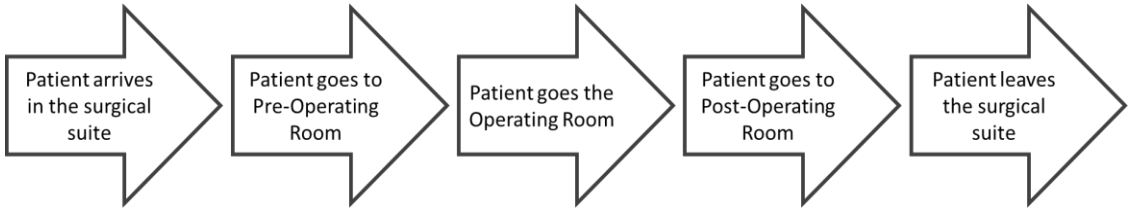


Figure 37. Theoretical and simplified journey of a patient in the surgical suite.

5.1.1. Surgical suite stakeholders

We describe here the different types of personnel working in the surgical suite, based on our interviews and observations results: surgeon, anesthesiologist, nurse and board runners.

The surgeons are responsible for the surgery outcomes and are at the center of the procedure. They schedule their cases with the hospital. The day of the surgery, they go in the pre-operating room to identify their patient, they then perform the surgery, after which they sum up the patient's state and outcomes with the family and/or the patient (the same day if possible).

The anesthesiologist's job is to determine the best anesthesia plan for the patient before surgery. They are responsible for putting the patient asleep during the procedure and for monitoring the patient's anesthesia all along the surgery. At the end of the procedure, they oversee waking the patient up. The anesthesiologists have assistants that are assigned to ORs on the whiteboard by a chief anesthesiologist.

The nurses work as a team with the surgeon and the anesthesiologist before, during and after the surgical procedure to perform care delivery. They are assigned to ORs for the day by the board runner. Their assignments can be changed according to the needs of the surgical suite.

The transporters are responsible for moving patients (i.e. patients being in the hospital before the surgery and staying after the surgery) from their rooms to the surgical suite and from the surgical suite to their room.

The board runners manage the whiteboard, the schedule and resources assignments. They are in charge, the night before, of editing the whiteboard for the next day, writing all the cases, their scheduling and associated notes. They edit the whiteboard by printing on a sheet of paper the schedule that is initially input in the hospital system by the scheduling department. They oversee the nurses' assignments and adapt the scheduling according to the needs of the surgical suite (staff, patient and resources). Board runners are the central persons to make requests to for a change in the schedule and special requests such as equipment or staff assignments. They have the best overview of the surgical suite status. The Board runners' job is intensive as they must analyze all scheduling information along the day. They are the only ones authorized to make changes of scheduling on the whiteboard. Still, other staff such as nurses or anesthesiologists can add notes about cases (case started, staff took their lunch break, etc.).

The OR manager oversee the day-to-day operations and the long-term strategy of the surgical suite.

The surgical patient enters the surgical suite by going to the pre-operating room first if the patient is an outpatient. If the patient is an inpatient, he/she is brought on his/her bed by transportation staff to the pre-operating room. There, the patient is identified by his/her surgeon and anesthesiologist and receives the first cares by the nurses. Then, the patient is brought to the operating room on his/her bed by the nurses. The patient then receives his/her care in the operating room. At the end of the procedure, after waking up, the patient is brought to the post-operating room by the nurses, where he/she finishes to fully wake-up, see relatives and is then brought to his/her room by transporters if he/she will stay overnight.

No patient was interviewed about their journey in the surgical suite, as we focused on the care givers only.

5.2. Interviews results

In this section, we classify the results of interviews and questionnaires with the surgical staff. We conducted 13 interviews and 12 contextual inquiries within the surgical suites DunnOR, FondrenOR, OPC and "Other Suites" (see Table 4), with 20 surgical staff [26].

5.2.1. A controlled chaos

The staff calls the surgical suite a "controlled chaos". It is an accurate description as patients are taking care of with a significant quality of care, 24/7, including difficult emergency cases, in a complex environment with many independent systems and many stakeholders. Some systems are based on paper, other on whiteboards, other on the hospital system, and not everybody use them the same way. For each interview, the staff especially refers to the use of the whiteboard, as it is their central tool. They like its flexibility and the fact that the information it displays is more updated than the hospital official digital system. However, the whiteboard is not perfectly updated, and users report that its visualization offered could be better with computer screens.

In Table 5, we summarize the shared and unshared bottlenecks indicated by the surgical staff:

Table 5. Summary of bottlenecks (B1-5) indicated by the different surgical staff.

	Anesthesiologist	Nurse	Surgeon	Board runner	Manager
B1	The viscous mobility of information.				
B2	The non-flexibility nor readability of certain tools such as electronic displays on top of the whiteboards.				
B3				No accurate data for long-term strategy	
B4	The lack of up-to-date information to take operational decisions.				
B5				Writing the whole schedule every day on the whiteboard is time consuming.	

We list hereafter examples illustrating the bottlenecks summarized in Table 5:

- *B1*. Important update information that is written on the whiteboard is only present on the whiteboard. Hence, if one wants such information, he/she has to go to the whiteboard, or call someone to read it for him/her. The information can be then written on paper and then carried away, but with no updates on the sheet of paper.
- *B2*. The staff reported not using the electronic displays as much as the whiteboard, because the whiteboards contains more up-to-date information and is editable in the "semi-public" space i.e. the corridor of the surgical suite.
- *B3*. The managers have the data that was manually input in the system (for instance, "surgery started at 9:06AM"). However, the nurse that inputs the data can be busy and not entering the exact times in the system.

- *B4*. For real-time management of ORs, information has to be updated in the system and on the whiteboard, which is often delayed as the personnel is busy..
- *B5*. Every evening, for the next day, the board runner fills the whiteboard with all the next day surgical cases.

We finally identify a gap between the needs of the surgical staff and their managers: the surgical staff is more interested in tools to improve the daily commutation and real-time updated surgical suite state information, whereas the interviews with the management level reveals that they are interested in tools to track their staff performance and cases data to make reports and work on the long-term strategy of the surgical suite.

We report hereafter on questionnaires' results about the main collaborative tool of the surgical staff. Our purpose was to evaluate how much satisfaction the surgical whiteboard brings to the staff.

5.2.2. System Usability Scale questionnaire about the whiteboard usage

We asked 22 staff of FondrenOR to fill a System Usability Scale questionnaire [97] comprising 1 board runner, 16 nurses, 3 surgical techs, 1 anesthesia staff and 1 that preferred to remain completely anonymous. After processing, the answers can be seen in the graph on Figure 38, Figure 39 and Figure 40. On Figure 38, each line corresponds to the answers of one person. The questionnaire revealed very heterogeneous opinions about the usability of the whiteboard, even among the different experience categories, with an average rating of 79/100. All the answers to the negative questions have been inverted for homogeneity.

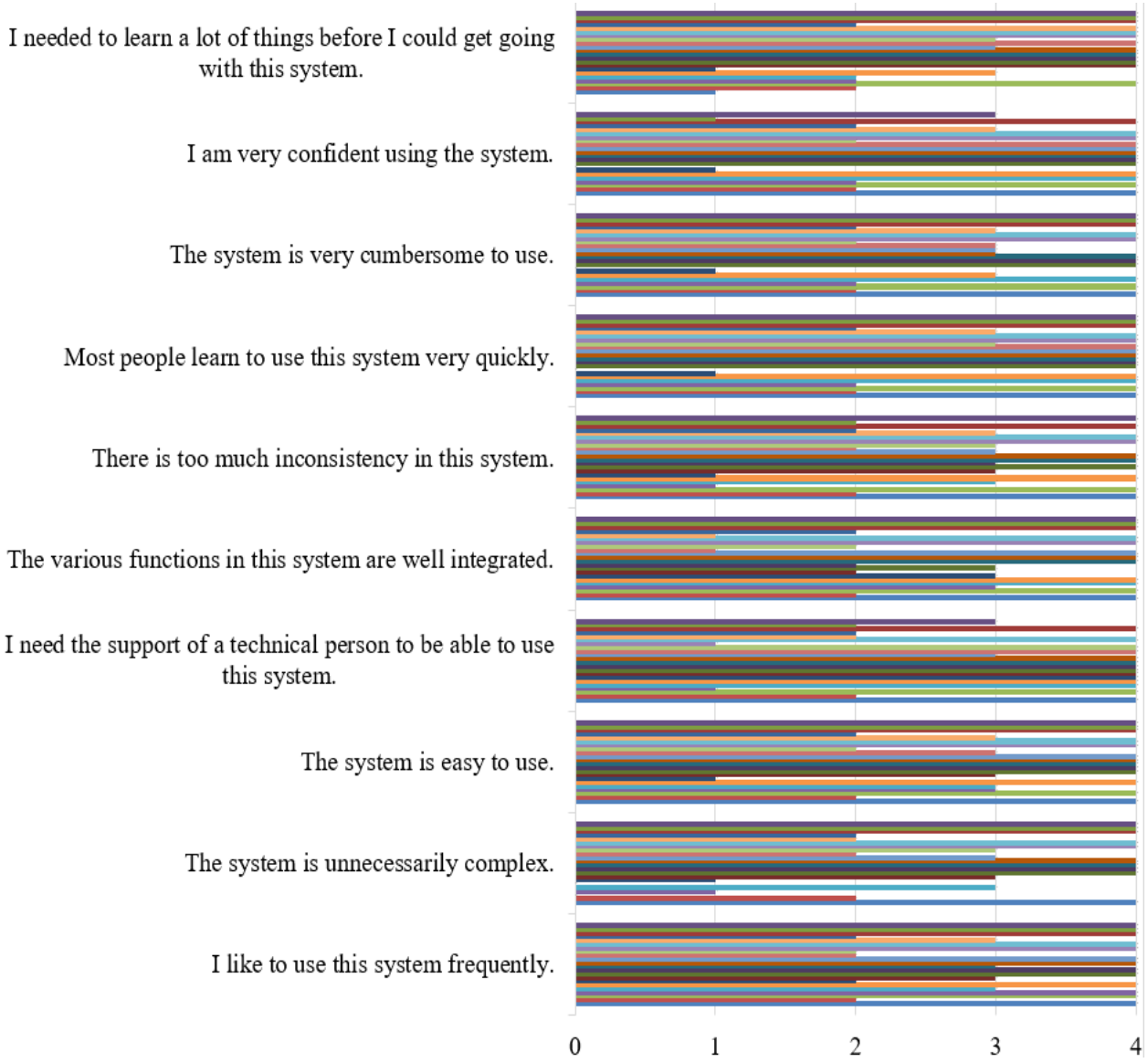


Figure 38. Questionnaires results about the whiteboard use feedback (SUS questionnaire), n=22.

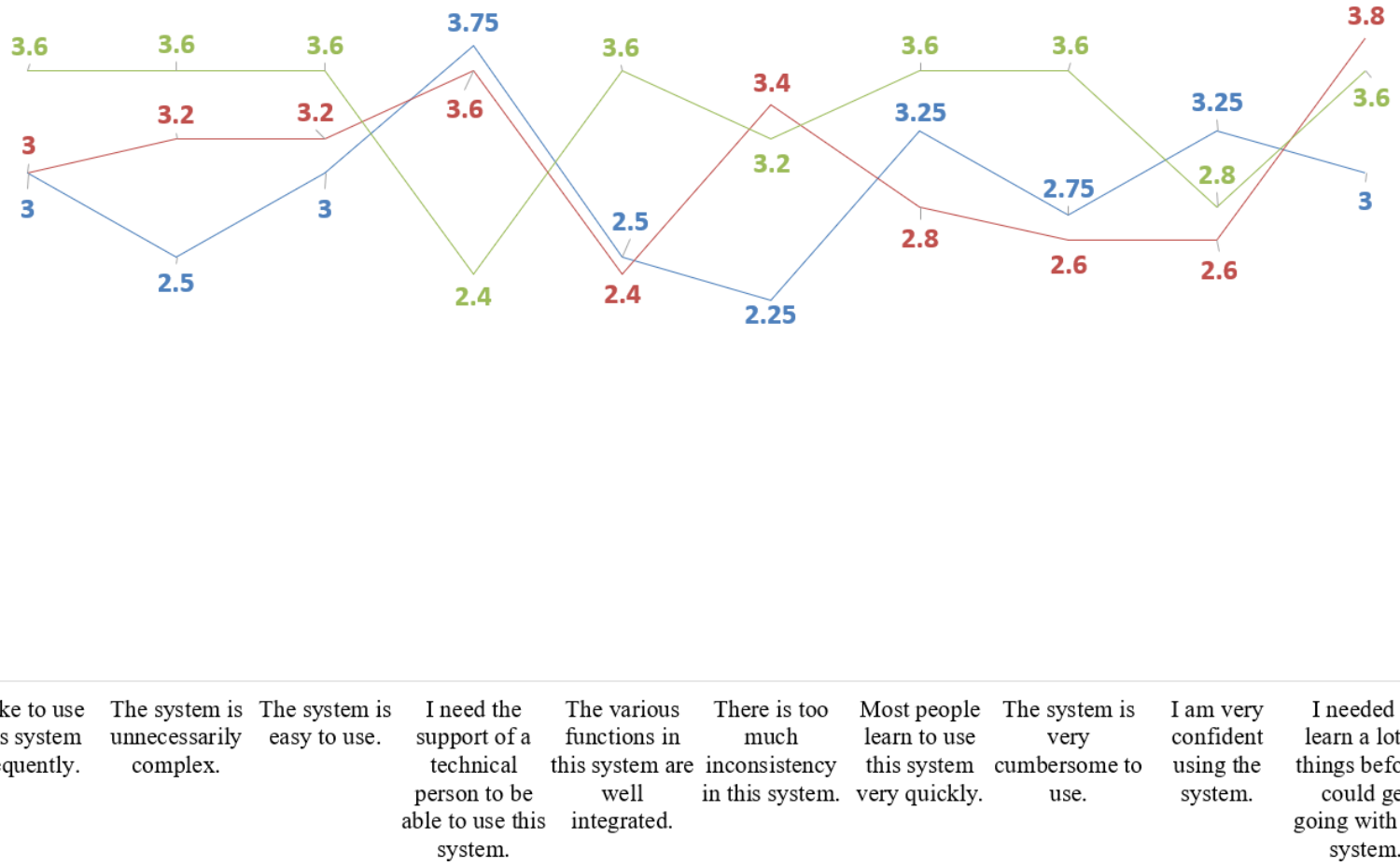


Figure 39. Questionnaires results about the whiteboard use feedback (SUS questionnaire) – Average of answers by experience categories, n=22. Green: >5years in the surgical suite, Red: between 1 and 5 years, Blue: <1 year.

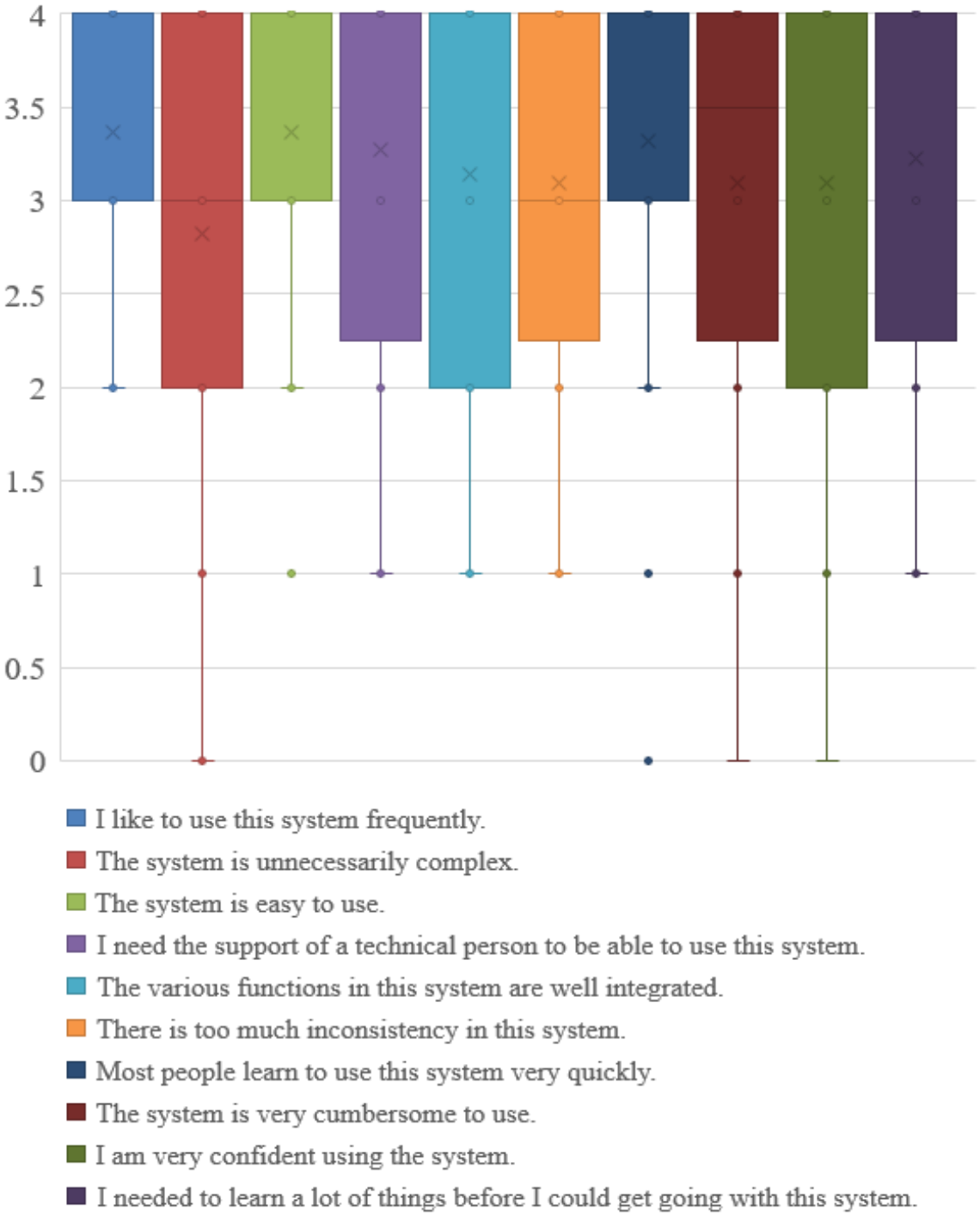


Figure 40. Questionnaires results about the whiteboard use feedback (SUS questionnaire) – Box and whiskers chart per question, n=22.

Figure 38 shows that the answers to the questionnaire are mitigated but tends to be on the higher side. Which explains the repartition in Figure 40 with large boxes and several outsiders. The average of answers by experience levels indicates that high experienced staff (in green in Figure 39) are more satisfied (average score=3.4) by the whiteboard than the medium experienced staff (average score = 3.1) (in red in Figure 39), which are more satisfied by the whiteboard than the least experienced staff (average score = 2.9) (in blue in Figure 39). This suggests that the learning curve for the whiteboard use and rules might not be immediate, or that younger staff is disappointed maybe with using a "ancient" technology. The average scores are between 3 and 3.5 except the answers to the question 2 "the system is unnecessarily complex" which is 2.8.

These usability questionnaires about the whiteboard use to the surgical staff suggest that on average the whiteboard satisfies the surgical staff. It is effective as the staff is able to fully perform their work with it. The efficiency is more complex to assess here. These whiteboards are updated manually and only when time is available as shown in the experiment about the difference between the updates on the whiteboard and the real state of the OR, that we presented in chapter 3.

5.3. Observations summary

We performed observations in six of the eight surgical suites of the Houston Methodist Hospital.

5.3.1. Content of the whiteboard

As the whiteboard is central in the surgical suite staff activities, we made a detailed observation of its use and its users.

5.3.1.1. *Cases information*

The whiteboard is initially manually filled by board runners in the evening for the next day at around 7.00pm. To do so, they print a spreadsheet-like document from the hospital system (see Figure 43), they go to the board, and they transcribe the data from the document to handwritings on the board.

The whiteboard starts to be used by the staff early in the morning (at around 6.00am). It is used during the night for emergency cases.

The cases are updated throughout the day (see Figure 41): new scheduling, shifts, patient location, equipment, case status, etc. The surgical suite needs two whiteboards because the number of cases can go up to 50 cases for one day. All necessary information about the organization of a case is contained in a line of the whiteboard (see Figure 42), which makes it the main source of information. The cases schedule for the next day is edited late in the evening on the whiteboard.

Figure 41. Surgical staff working in the surgical suite whiteboard.

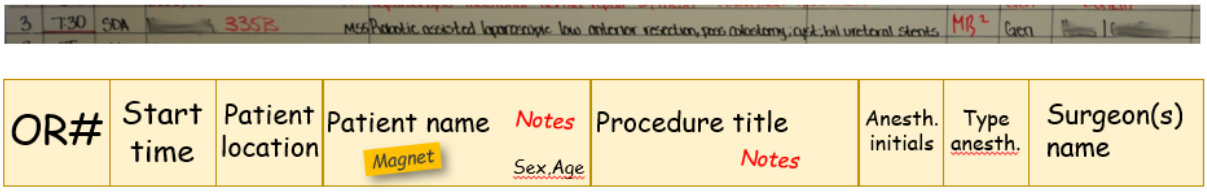
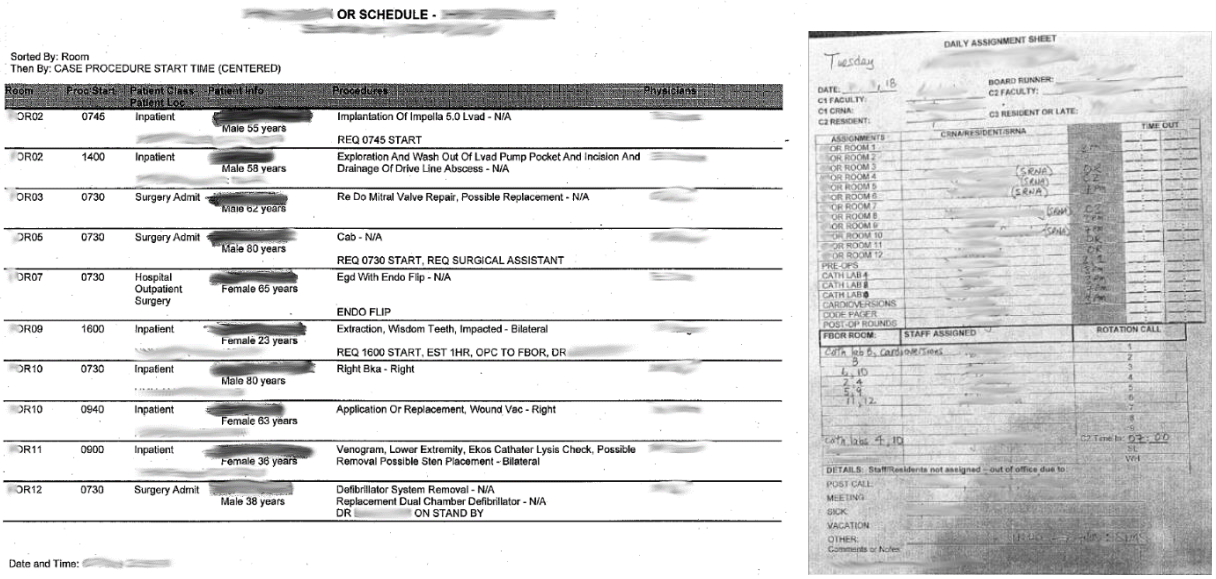


Figure 42. Description of a line of the whiteboard, representing a patient and his/her procedure. Each line is updated through the day according to changes of status of the procedure or change in the schedule. Magnets can be added, as well as notes and symbols.

The OR number column is the OR where the procedure will take place. It is chosen initially but can change along the day. The start time column represents the time at which the procedure is

scheduled to start. It can be re-estimated and updated through the day and can be left unchanged though the case has been delayed. The location column informs about the patient current location within the hospital: it can be a bedroom, a pre-operating area or an outpatient center. The patient column comprises his/her name, age and gender. It can contain extra notes (in red in Figure 42) and magnets (in orange in Figure 42). The procedure column reads the full title of the procedure the patient will receive. There are often additional notes such as equipment requirements. Sometimes, the procedure is abbreviated. The anesthesiologist column is the anesthesia staff assignments and organization of their schedule. The surgeon column shows which surgeon(s) is(are) performing the procedure. Finally, the staff column is the nurses' assignments to patients and ORs. The only information that does not change is the patient information (name, age, gender). The surgeon or the procedure rarely changes except for emergency cases or difficult diagnostics.



OR SCHEDULE -

Sorted By: Room
Then By: CASE PROCEDURE START TIME (CENTERED)

Room	Proc Start	Patient Class / Patient Loc	Patient Info	Procedures	Physicians
OR02	0745	Inpatient	Male 55 years	Implantation Of Impella 5.0 Lvad - N/A REQ 0745 START	
OR02	1400	Inpatient	Male 58 years	Exploration And Wash Out Of Lvad Pump Pocket And Incision And Drainage Of Drive Line Abscess - N/A	
OR03	0730	Surgery Admit	Male 62 years	Re Do Mitral Valve Repair, Possible Replacement - N/A	
OR05	0730	Surgery Admit	Male 80 years	Cab - N/A REQ 0730 START, REQ SURGICAL ASSISTANT	
OR07	0730	Hospital Outpatient Surgery	Female 65 years	Egd With Endo Flip - N/A ENDO FLIP	
OR09	1600	Inpatient	Female 23 years	Extraction, Wisdom Teeth, Impacted - Bilateral REQ 1600 START, EST 1HR, OPC TO FBOR, DR	
OR10	0730	Inpatient	Male 80 years	Right Bka - Right	
OR10	0940	Inpatient	Female 63 years	Application Or Replacement, Wound Vac - Right	
OR11	0900	Inpatient	Female 36 years	Venogram, Lower Extremity, Ekos Cathater Lysis Check, Possible Removal Possible Sten Placement - Bilateral	
OR12	0730	Surgery Admit	Male 38 years	Defibrillator System Removal - N/A Replacement Dual Chamber Defibrillator - N/A DR ON STAND BY	

Date and Time:

DAILY ASSIGNMENT SHEET

Tuesday

DATE: , 18
C1 FACULTY:
C1 CRNA:
C2 RESIDENT:
BOARD RUNNER:
C2 FACULTY:
C3 RESIDENT OR LATE:

CRNA/RESIDENT/SRNA | TIME OUT

ASSIGNMENTS
OR ROOM 1
OR ROOM 2
OR ROOM 3
OR ROOM 4
OR ROOM 5
OR ROOM 6
OR ROOM 7
OR ROOM 8
OR ROOM 9
OR ROOM 10
OR ROOM 11
OR ROOM 12
PRE-OPS
CATH LAB 4
CATH LAB 8
CATH LAB 6
CARDIOVERSIONS
CODE PAGER
POST-OP ROUNDS

FBOR ROOM: | STAFF ASSIGNED | ROTATION CALL

1
2
3
4
5
6
7
8
9
10
11
VH

DETAILS: Staff/Residents not assigned - out of office due to:
POST CALL:
MEETING:
SICK:
VACATION:
OTHER:
Comments or Notes:

Figure 43. Prints of the surgical schedule from the hospital system to manually edit the whiteboard the evening before the next day of surgeries.

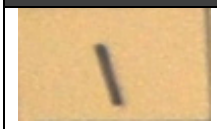
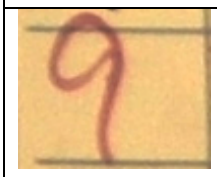
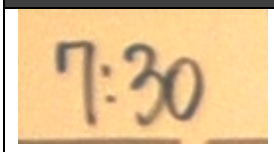
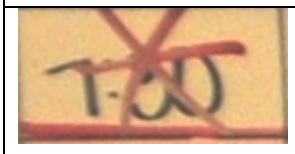
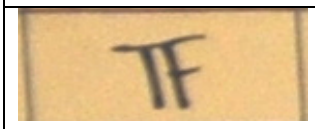
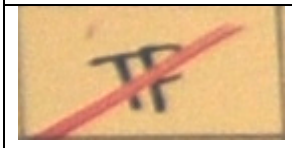
"Epic" is a hospital computer system that centralizes its data. The screens at the top of the whiteboards in Figure 41 display the schedules as entered in Epic: surgical cases associated with an OR number, a time, a surgeon(s) and an anesthesiologist(s). It is used in combination with the whiteboard.

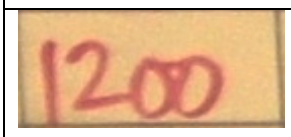
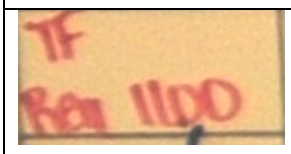
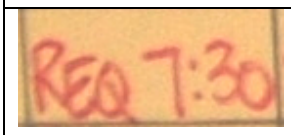
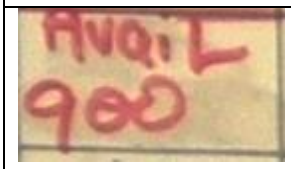
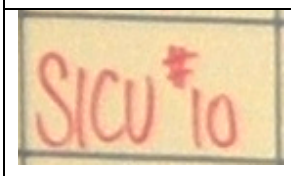
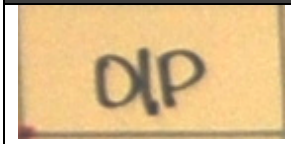
5.3.1.2. *Symbols, magnets and notes*

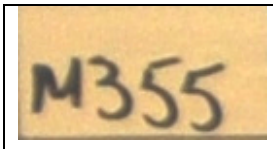
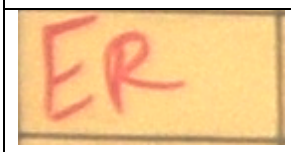
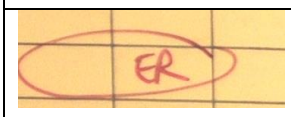
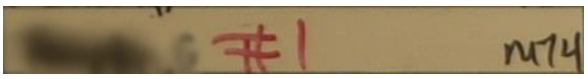
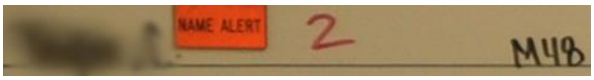
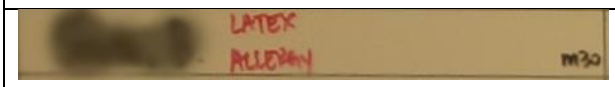
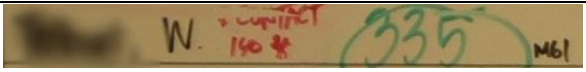
We observed the symbols, magnets and notes used on the whiteboard. Users rely on them to define a dictionary and communicate information asynchronously. Indeed, the symbols/notes can be understood only by people who were "told" what they mean. This creates a sort of fortuitous security barrier as this information is not understandable by anyone.

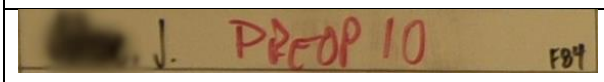
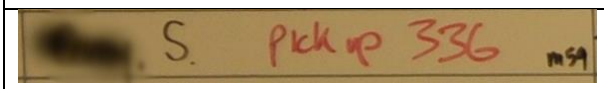
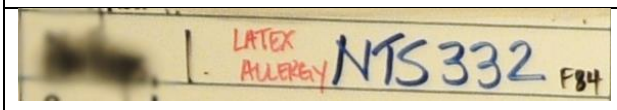
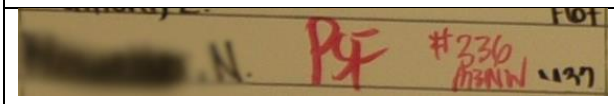
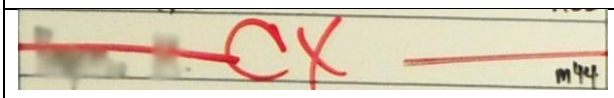
We detail the full dictionary we were able to observe along the past three years in Table 6.

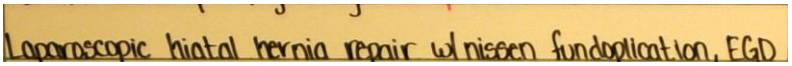
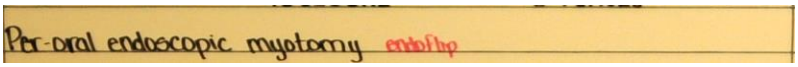
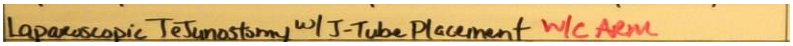
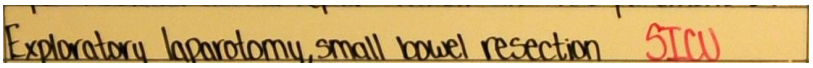
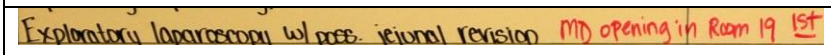
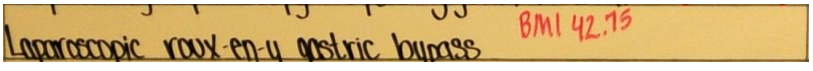
Table 6. Symbols, magnets and notes used on the whiteboard. From the left to the right of a line of the whiteboard.

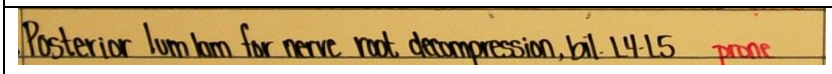
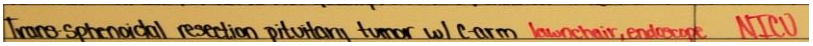
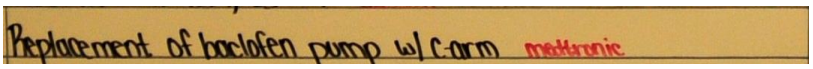
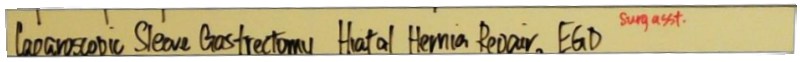
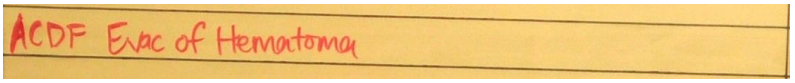
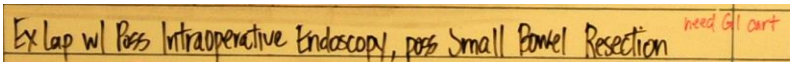
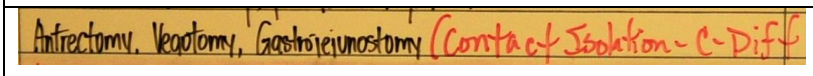
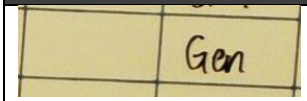
OR number of the surgery column	
	Number of the OR where the surgery is scheduled. First edition is in black.
	Number of the OR where the surgery is scheduled. When it is re-scheduled, or added, the staff uses the color red.
Start Time of the surgery column	
	Time scheduled for the case. Patient is not in the OR.
	Patient is in the OR.
	TF: To follow. This case will follow the one immediately before, with no start time expected.
	Patient has arrived in the pre-operating room.

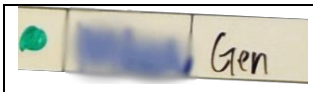
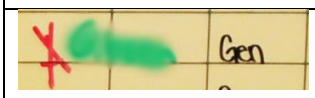
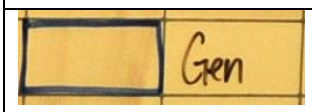
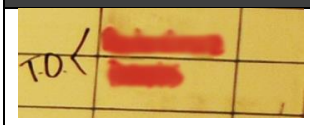
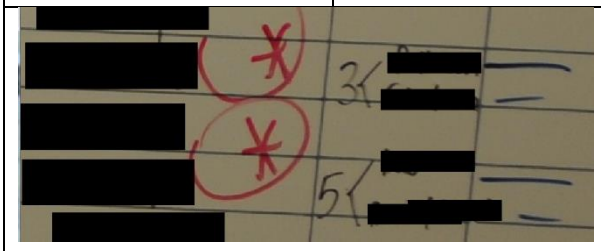
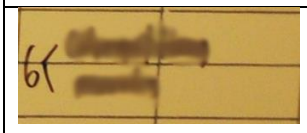
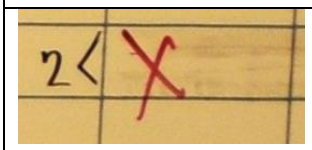
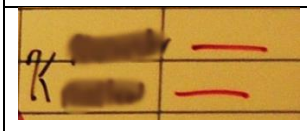
	Patient is in the OR – just a different marker available.
	TF: To follow. This case will follow the one immediately before, with no start time expected. It is in red because the case was a non-elective case.
	Time requested for an unplanned case that has just been added.
	TF. Req: request of time.
	TF Self: Surgeon is requesting for this case to follow his/her scheduled cases in the same room. + Patient has arrived in the Pre-Operative / Holding room.
	Add-on time of request.
	When surgeon is available to perform add-on surgery.
	Surgical Intensive Care Unit, bed number 10 .
Patient current location column	
	Outpatient. Patient that is coming from home and going back home after surgery.

	Main building. 3rd floor. Room 55.
	Fondren cardiac cathlab unit bed 14.
	Same Day Admit. Patient will be admitted to the hospital after the completion of the surgery and will become a inpatient.
	Emergency Room.
	Emergency Room too. The circle was drawn to draw the attention.
Patient Name column (Last name. Initial of the first name. + notes + Gender and Age)	
	"Patient Sent For". A transport staff was sent to pick up the patient in the hospital.
	Order of cases if surgeon chooses different order than what is on the schedule. This case was re-scheduled to be the first case in this OR.
	"Name alert" on a patient. It is meant to draw the attention to the staff that two patients have a similar name.
	Patient is allergic to latex.
	Patient is in room 335. Sometimes if a green pen is at the board the staff will use it as the

	blue. It is the explanation we got when asked to the staff.
	Is in pre-operating bed 10.
	Patient to be picked up in room 336.
	Need To Send a transporter to pick the patient in room 332.
	Patient has been sent for + room number 336.
	Case canceled.

Procedure title column	
	Normal situation: first edition of a procedure.
	Endflip: device needed for the surgery.
	c-arm: fluoroscopy (x-ray machine) needed for the surgery.
	Surgical Intensive Care Unit – patient is and will be in SICU after surgery
	Complicated note.
	Draw attention on the fact the patient is obese (a high BMI – Body Mass Index,

	requires special equipment in the OR)
	Prone. Surgical position.
	Position, equipment, Neuro Intensive Care Unit
	Medtronic is a company. It means a representative is going to assist the surgery, supervise if the equipment is well used.
	Device needed for the surgery.
	Surgeon will need a surgical assistant.
	Anterior cervical discectomy and fusion. Abbreviation.
	Special needs for the surgery.
	Indicates that OR staff is not needed. Staff from a different location will perform the procedure.
	Special needs.
Anesthesiologist(s) columns (green/blue: name or initials of the anesthesiologist)	
	Normal situation: general anesthesia.

	Anesthesiologist has had breakfast.
	Need this person for after 3.00pm.
	Means that the anesthetist board runner is missing an anesthetist for a case. “room is not covered”.
	Anesthesiologist has had lunch.
Surgeon(s) columns	
	Name of the surgeon
Staff columns	
	Time off: staff that is on time off.
	This staff is needed after 3.00pm. (group 3 – group 5).
	Normal situation: number of the OR and assigned staff to this OR.
	No staff assigned yet. Task to do.
	Staff is currently in break.

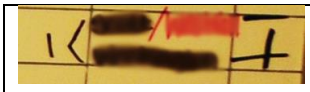
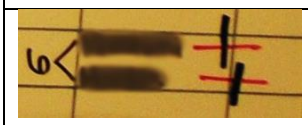
	Staff has come back from his/her break if "+".
	Staff has come back from his/her break.

Table 6 shows that a variety of combination between colors, symbols, writings and magnets are used to represent information on the whiteboard.

Color is associated to the level of attention the writer wants the reader to receive. Black is used for everything that was planned the night before. Hence, this color does not raise a special attention, the reader knows that this is what was planned. On the contrary, red is always used for information requiring attention: missing resources, updates about the staff or the case, special needs for the surgical case or modification of a surgical case schedule (case canceled, OR number changed, start time changed). Blue and Green are the color of the anesthesia staff for their schedule. They however use red for information about their staff breaks.

Name alert magnets are used for a repetitive type of information that is very important: the risk to mistake a patient with another.

Finally, free writings are used for all the scheduling management and notes. As it is very flexible, the staff uses it when they need to write down an information that has no magnet prepared in advance for it such as a latex allergy or the staff took their first break.

Interestingly, along the three years of observations of the surgical suite, we sometimes noticed new symbols or notes never seen before. When I asked the surgical staff about it, they would tell me either "this is a very rare situation we rarely write this" or that they just "needed to find a new way to inform other staff about it, and that [they] made up this [new symbols or note]". Writings here allow such flexibility. For instance, a new workflow was implemented in the hospital, some patients were now coming from a different area of the hospital: the board runners would indicate it with a new abbreviation.

5.3.2. Commonalities and differences between observed surgical suites

We observed that many whiteboards are in used throughout the Houston Methodist Hospital. Along the study, all of them became accompanied with an electronic display of the schedule, modifiable only from a remote desktop. Some surgical suites contain only the electronic displays now and no whiteboard for cases anymore (the smaller surgical suites containing less than 6 ORs – see Figure 44, pictures E, G and H). There is however always a whiteboard for organization of the staff at least (F, I…).

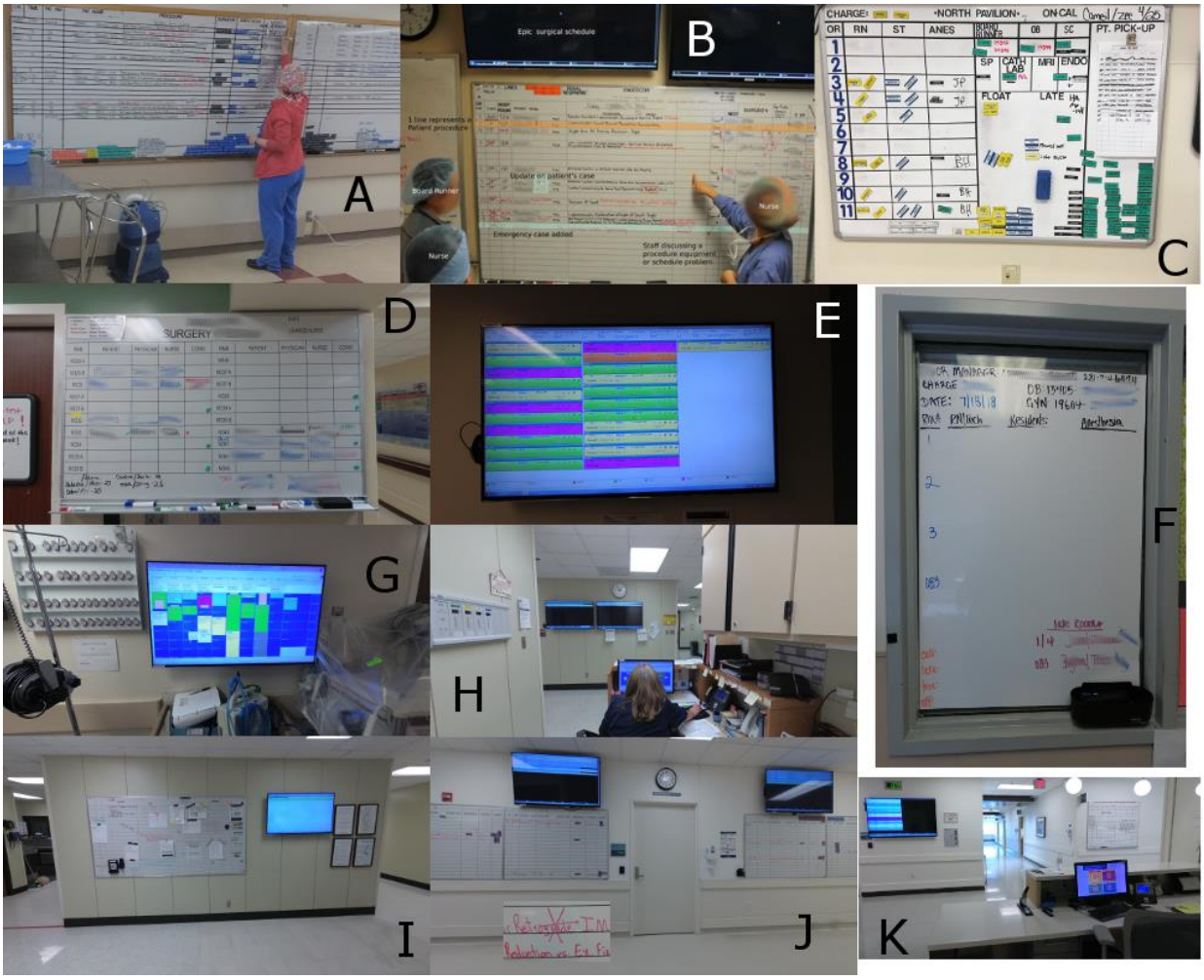


Figure 44. Several whiteboards and electronic schedules displays in used at our hospital.

Figure 45. Whiteboards and transparent boards in the surgical suite of a hospital in Boston.

We observed whiteboards in use for surgical patients flow management in another hospital in Boston (see Figure 45), which has the same fundamental functionalities, with some interesting differences: some boards are two-sided and transparent. One side is for the board runners only, the other is public to the rest of the surgical staff. The transparency allows users to see information of the reverse side through the information on the side they are looking at. They use maps on which they show the status of operating rooms, together with different magnets.

5.3.3. Summary interviews and observations

The surgical suite staff is comprised of a very heterogeneous stakeholders, with different backgrounds and needs. The whiteboard is their central collaborative tool and is welcomed because of its ease of use. The whiteboard allows many collaborative and informative activities such as synchronous and asynchronous communication, overview of information, note taking, updates in the surgical flow.

On another level of analysis, the whiteboard has a social translucence which makes it the meeting point of all staff, planned or unplanned, and allow communications that would not exist without it.

In the next section, we present the representative scenarios of the surgical staff and refer to them as we built the requirements and design principles.

5.4. Usage scenarios

From interviews and observations, we identified 19 relevant scenarios in the surgical suite activity (see Table 7), based on the whiteboard. More details on the scenarios and associated images can be found in Appendix 2.

These scenarios can be separated in 2 categories:

- Central location activities: Sc1, Sc2, Sc4, Sc5, Sc6, Sc9, Sc10 Sc11, Sc13, Sc14, Sc17. These scenarios comprise all the interactions between the surgical staff and the surgical whiteboard, in the semi-public place. They are single-user tasks. They consist in an update of the whiteboard or getting information from it. They comprise asynchronous coordination activities.
- Direct interactions between people to solve a problem: Sc3, Sc7, Sc8, Sc12, Sc15, Sc16, Sc18, Sc19. These scenarios comprise interactions between people, with the support of the whiteboard or a phone. They are multi-users tasks. They consist in a negotiation for a change or a communication to get information about the whiteboard content. They comprise synchronous collaboration activities.

To these scenarios, we add separately in the next section 7 scenarios that do not necessarily involve the use of the whiteboard. These 7 scenarios are focused on staff communication with their phones. They constitute more detailed descriptions of Sc15, Sc16 and Sc8.

Table 7. Scenarios of use of the whiteboard in the surgical suite (wb = whiteboard).

ID	Description	Relevant interactions	Potential issues
Sc1	The Nurse arrives at the beginning of his/her shift at Dunn OR.	Go check the wb, find his/her name and the work/team associated.	Must physically go to the wb. Wb often packed of information and hard to read.
Sc2	The Surgeon arrives at the beginning of his/her shift at Dunn OR.	Go check the wb, verify the schedule is right.	Must physically go to the wb.

Sc3	The Surgeon wants to squeeze an additional case in the schedule of the day (called “add-on”, or “emergency” even if it most of the time is not an emergency).	Surgeon and board runner meet in front of the whiteboard to discuss the additional case.	Sometimes no space on the wb to write the additional case.
Sc4	The patient has arrived in pre-operating room.	Board runner or nurse will update the wb (cross start time in red).	Delay in the update.
Sc5	The case started.	Board runner or nurse will update the wb (re-cross start time in red to make a star).	Delay in the update.
Sc6	The current day is over, edition of the new whiteboard for the next day – “elective cases”.	Board runner erase the rest of the wb. He/she prints the new schedule and write it on the wb.	Takes a long time to fill the wb. Human error possible.
Sc7	The case is delayed but will start as soon as the surgeon is ready for his/her next case.	Board runner writes “TF” on the wb instead of an accurate start time.	Not accurate.
Sc8	Talk about a case with a colleague.	The 2 stakeholders meet at the wb and exchange information using the corresponding line on the wb. OR by phone. OR meet in the corridor.	Be physically present in front of the wb gives better exchanges about the case as there a support with the information.
Sc9	Create a “name alert” for two cases.	Nurse or board runner picks up the “name alert” magnets (red) that are on the wb and put them next to the corresponding names.	Magnets can be removed. They can fall.
Sc10	Nurses break.	Nurse or board runner write a line or a star (if second break)	Must go to the wb.

		next to their name in the staff column	
Sc11	Display that the patient is in Neuro Intensive Care Unit (NICU) or SICU.	Board runner write “SICU” or “NICU” in the procedure column of the patient on the wb.	
Sc12	Not enough room on the board to manage all the cases (not often)	Board runner makes room on another side wb and write the case.	Not organized with the other cases.
Sc13	A case is canceled	Board runner or nurse draws a red line on the case on the wb and write “CX” or “CANCELED”.	If the case is not canceled anymore, it is hard to erase the line without erasing the rest + has to rewrite.
Sc14	The nurse goes see the patient in pre-operating room.	Nurse take a pen, look at the wb, look at the patient medical record and fill the pink sheet.	Carry additional paperwork around.
Sc15	Surgeon or Nurse or Anesthesiologist or else needs to have information that is on the whiteboards while being far away from it.	They call the board runner to ask about the wb information.	Additional phone calls. Generate interruptions.
Sc16	Board Runner or another staff making an input on the board needs involved people to be aware of changes that have been made on cases that they work on.	Board runner calls each staff involved with the important change.	Additional phone calls. Generate interruptions.
Sc17	A case is finished.	Board runner or nurse erase the case on the wb.	If the patient comes back in the surgical suite, they have to re-write all the case on the wb.

Sc18	Assignments of nurses per ORs	Board runner write on the wb the OR number and the associated nurses.	Static and needs to be erased and rewritten every time
Sc19	Assignments of anesthesia staff per ORs	Anesthesiologist chief writes on the wb the anesthesia staff assignments in the anesthesia column.	Static and needs to be erased and rewritten every time

5.4.1. Scenarios with a smartphone app connected to the surgical schedule

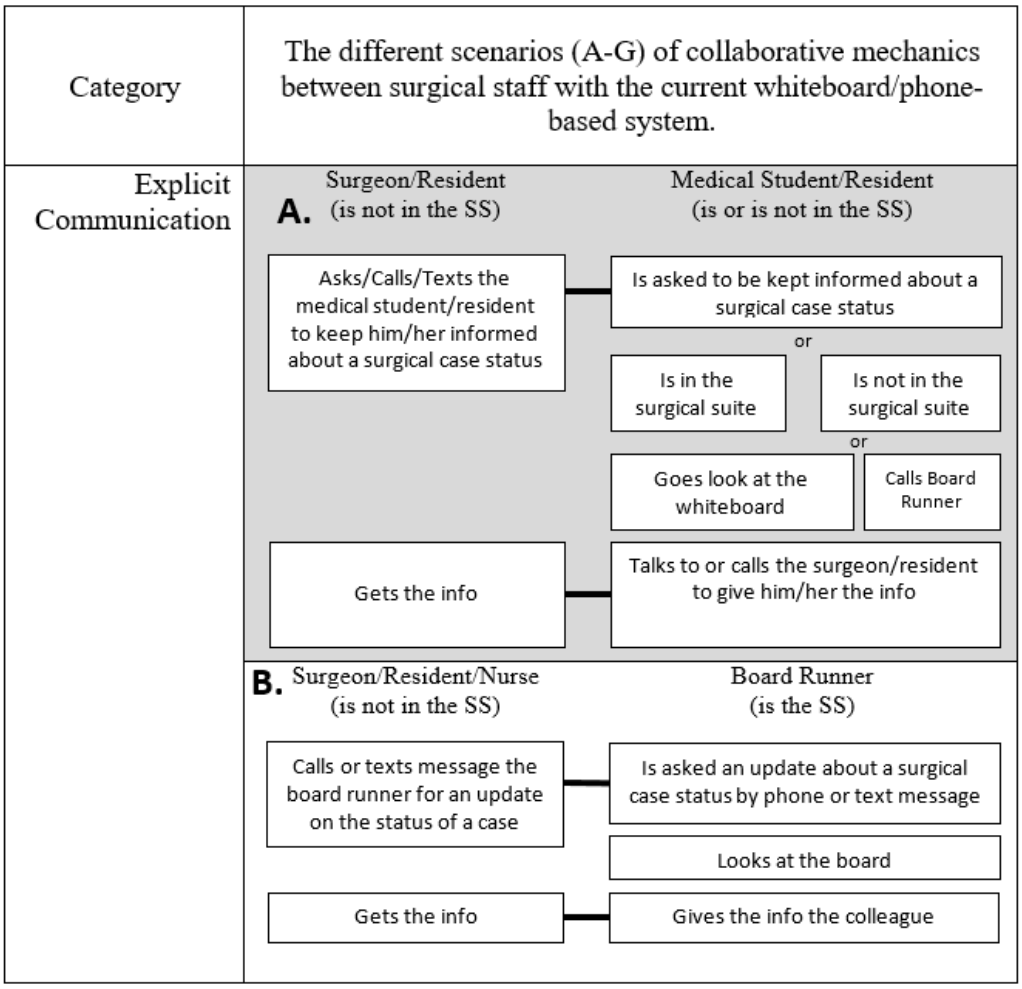
From the user analysis, we spotted a main disadvantage of the surgical suite whiteboard. The surgical staff reported (see B1. in Table 5) that if someone is not physically present in the surgical suite, he/she cannot be aware of whiteboard modifications he is involved in (change of the start time, location of the patient etc.) except if another person in the OR sends information to him/her via text messages/phone calls or if he/she comes to see the whiteboard. These two solutions are for the moment the most used ones by the surgeons and other staff but they are not convenient: it requires a synchronous communication involving interruptions issues [82].

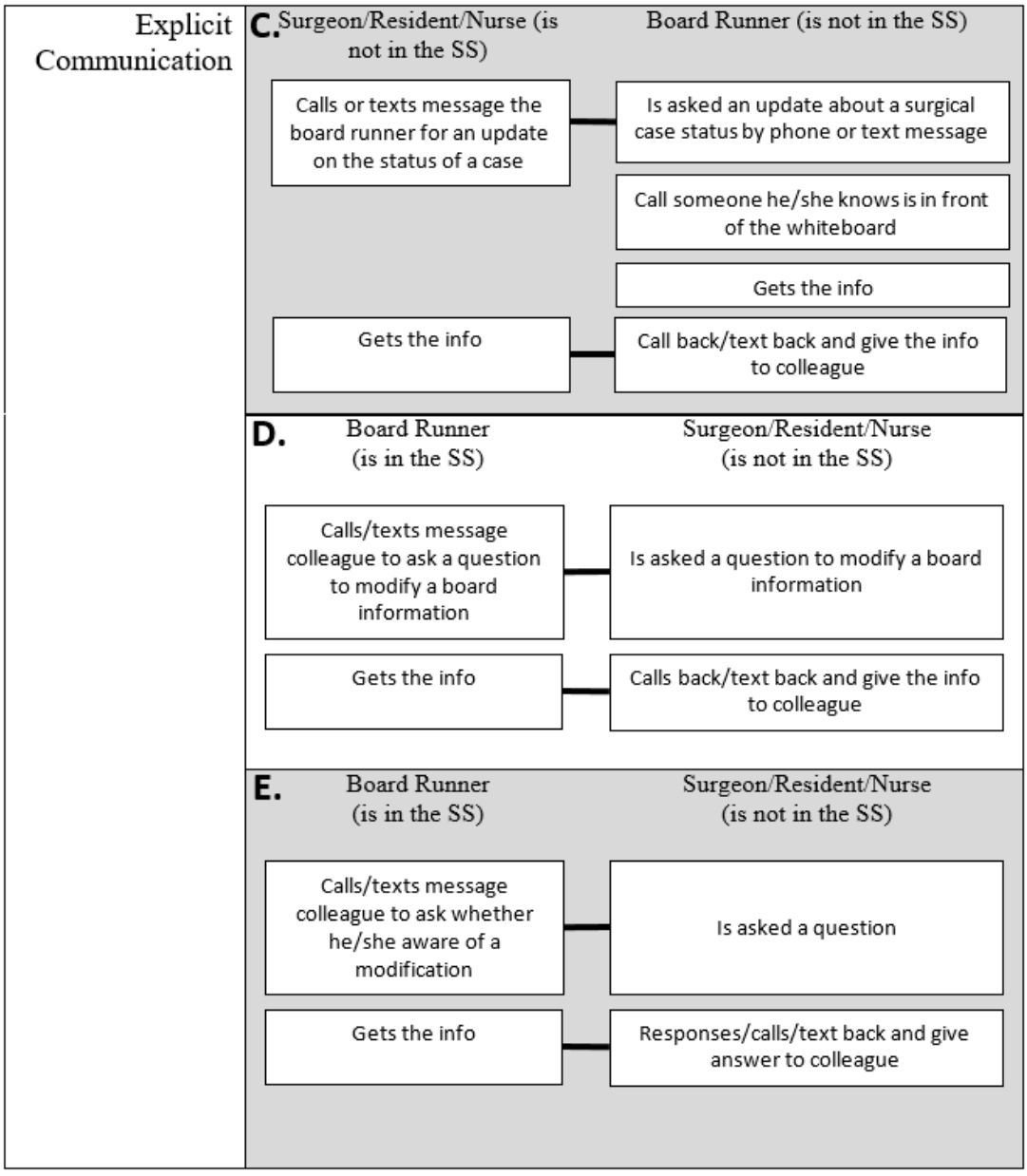
Table 8 represents the analysis of collaborative mechanics [129] between the surgical suite staff, in the surgical suite and outside, synchronously and asynchronously. We interviewed a specific resident to build these scenarios. We focused here on collaboration where at least one stakeholder is not physically in the surgical suite. Table 8 shows on the left the different collaborative mechanics associated to the different scenario in the right column. The right column details the actions and the back and forth interactions between the left and right stakeholders of the scenarios. It indicates whether the stakeholder is physically present in the surgical suite or not.

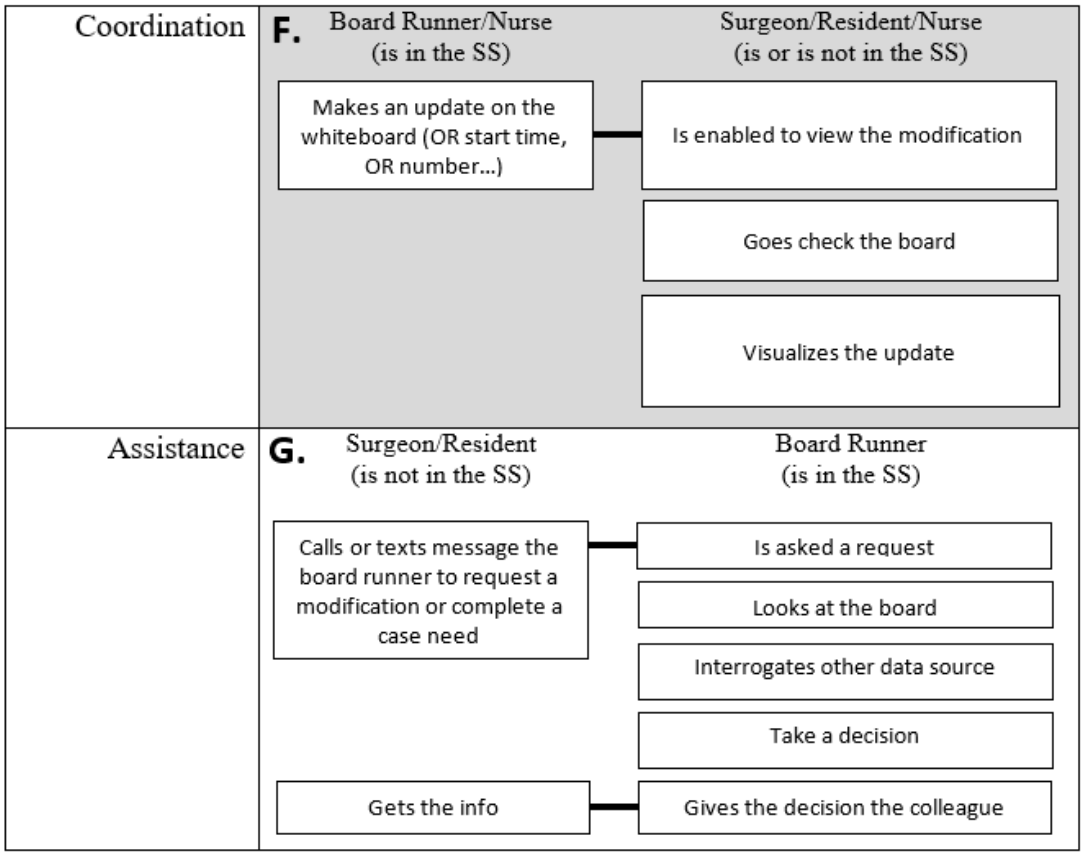
Scenarios A, B, C, D and G involve synchronous collaboration and interrupting additional persons to get information about the surgical schedule. Up to three persons will be interrupted at a time to give the information to one, because the information on the whiteboard is not mobile.

Scenario F is an asynchronous communication, which allows the staff to read the new information. However, they do not receive a notification that the change was made.

Table 8. Analysis of collaborative mechanics between the surgical suite and the "outside world" that we focused on (SS: Surgical Suite).




Explicit Communication
C.
Surgeon/Resident/Nurse (is not in the SS)
Board Runner (is not in the SS)
Calls or texts message the board runner for an update on the status of a case
Is asked an update about a surgical case status by phone or text message
Call someone he/she knows is in front of the whiteboard
Gets the info
Gets the info
Call back/text back and give the info to colleague
D.
Board Runner (is in the SS)
Surgeon/Resident/Nurse (is not in the SS)
Calls/texts message colleague to ask a question to modify a board information
Is asked a question to modify a board information
Gets the info
Calls back/text back and give the info to colleague
E.
Board Runner (is in the SS)
Surgeon/Resident/Nurse (is not in the SS)
Calls/texts message colleague to ask whether he/she aware of a modification
Is asked a question
Gets the info
Responses/calls/text back and give answer to colleague



In addition to observations and contextual inquiries in the surgical suite, five interviews with S2, S3, S8, S9 and BR2 (see Table 4) were necessary to identify the interaction features we needed to design to support scenarios A, B, C, D, E, F and G.

This analysis led to the development of a smartphone application that would be a continuum of computerized system needed for the surgical suite. It will be further developed in the chapter 6 “Interaction design & Implementation”.

5.5. Analogies between air traffic control and surgical flow management

Airport control towers are comprised of air traffic controllers that oversee the landing, take-off and taxiing of airplanes. En-route centers are comprised of air traffic controllers that manage their

respective airspace. We propose hereafter the results of a high-level analogy in terms of environment and resources management.

5.5.1. Critical environments

Civil aviation and hospitals' surgical suites share common concerns: working around the clock, collaborative work, emergency situations, interruptions, incidents, situation awareness, safety and security, wide range of collaborating trades, strict procedures, resource management [50,53,112].

In civil aviation, studies have tried for many years to model human activity and to insert more and more automation with only partial success [6,7]. Instead, the trustworthiness of the system comes not only from its individual parts (hardware, software or people), but emerges from the process of checking and crosschecking each other's activity [3,37,50,88,145]. Designing new systems that improve safety and capacity is thus difficult since it requires to unveil concerns and subtle but important details that might be hidden by this emergence.

The surgical suite is a critical environment. Patients are in critical conditions when they arrive, and the surgical procedures are never without risk. Extreme precautions are taken by surgeons and the whole surgical team in terms of infection propagations, awareness of patient status during surgery, needles and compress counts and more.

Hence, both air traffic control and the surgical suite manage a flow of persons in a critical environment. The surgeon, anesthesiologist and nurse can be compared to the pilot. The board runner and manager can be compared to air traffic controllers.

Figure 46. Surgeons in an OR (left). Cockpit of the A330 (right). Picture credits: left - Pexels (Vidal Balielo Jr.), right – airbus.com.

5.5.1.1. *Standards*

In Air Traffic Management, air traffic controllers and pilots have a standardized background such as Crew Resource Management training [193], regulations via the European Aviation Safety Agency [194] and International Civil Aviation Organization (ICAO) [195] such as the air-ground communications phraseology (ICAO Annex 10) or Air Traffic Management regulations (ICAO doc 4444).

In the hospital, among the same roles (surgeons, nurses, anesthesiologists), the stakeholders have standardized trainings for surgical procedures (CME programs via the ACCME [196]) and sets of good practices such as "The Red Book" [83] via the American College of Surgeons (ACS), but the hospital is less standardized regarding management of patient flow.

5.5.1.2. *Capacity*

The airspace is packed with planes. Between optimum trajectories and popular destinations, the same routes are followed by all airlines. It results in airplanes following each other on the same routes and altitudes. Hence, the role of air traffic controllers is to make sure the sky capacity is optimized i.e. the highest numbers of flights are performed for a given area within the acceptable level of safety – anticipated and preventing collisions. Regulations impose separations minimums between planes, vertically and horizontally. Given the speed and the size of a plane compared to another one, other separations might be implemented.

The surgical suite, with given resources, can manage a certain number of patients. The most patients a surgical suite treat the better, but there is a maximum number of patients that can be safely handled at a time. Emergency departments are in the front line with these issues.

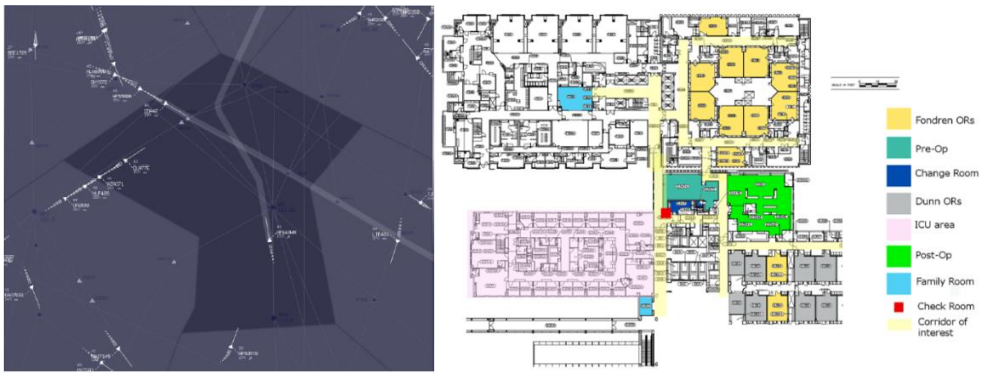


Figure 47. On the left, radar image used by air traffic controllers representing the airspace they oversee (Source: [173]). Right, the layout of a surgical suite at Houston Methodist hospital.

5.5.1.3. *Scarce resources*

Air traffic controllers typically work by pairs at a workstation including a dynamic radar image of their airspace and flight strips (digital or paper-based). When the flow becomes heavy, managing many flights at the same time become difficult for only two persons. Hence, if a third or fourth controller are available an additional controller can be added at a workstation already comprising two or three controllers.

In the surgical suite, resources are limited, most of all in emergency departments. There is often a need for more doctors, more nurses, more machines, more tests, etc. The surgical suite staff manage their resources to accommodate the surgical patient flow and it can become difficult to achieve. When delays start to accumulate because of a lack of resources, surgeries start to be canceled, the surgical staff become frustrated and patients' health is at risk. Again, an optimized flow might foster safety.

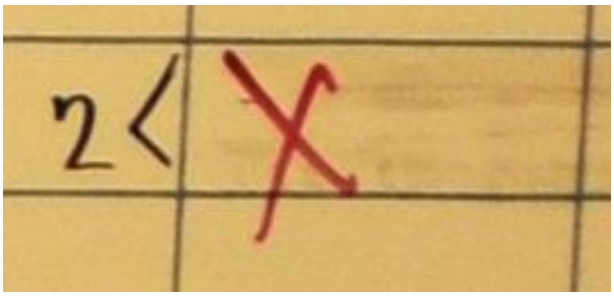


Figure 48. On the whiteboard, this indication tells the surgical staff that two staff are missing for OR number 2.

5.5.1.4. *Collaboration*

The collaboration between two air traffic controllers at the same workstation is omnipresent. Together, the controllers manage their airspace, make decision, contact the pilots and coordinate their tasks. An efficient collaboration among them is necessary to the management of flights. For instance, when flights are represented with paper strips, they write on the papers and give them to each other. There is a lot of synchronous but asynchronous communication, for tasks that can be performed later. Communication is significant between the air traffic controllers and the pilots via the radio and datalink systems.

Collaboration in the OR is omnipresent, as the surgeon is not the sole person performing the surgery: the nurses, residents and sometimes technicians or medical device company

representatives participate to the surgery. Sometimes there is even two surgeons or more that are performing the procedure. Communication is mostly synchronous, but the nurses anticipate surgeons' moves and know what instruments they are going to need. Collaboration is as important outside of the OR as inside. In the surgical suite, several healthcare providers will take care of the patient. A patient's journey in the surgical suite can overlap a nurse shift and communication during the shift transition is critical. From the pre-operating room, to the OR, to the post-operating room, the patient will receive different types of care requiring synchronous and asynchronous communication. For example, the nurse will leave notes in the patient binder for the next nurse to read them later.

Interruptions are a similar problem in ATC and in the hospital field. Interruptions create undesired disruptiveness: partial information should accompany any type of disruptive notification to let the user decide whether or not it is worth interrupting the task [82]. Partial information can be a visual cue of a pending task, with an indication of its level of priority [82]. In the hospital, significantly more nurses make medical errors when they are interrupted than when they are not [133].

5.5.1.5. *Instrumented activities*

To support the workflow, the two air traffic controllers use the dynamic radar image, paper or digital strips, other visualizations and the radio. Their activity is more and more digitalized, for example with the apparition of datalink to support text message exchanges between the air traffic controllers and the cockpit instead of speaking over the radio, thus allowing asynchronous communication. Flights are reified into paper/digital strips that contain all flight properties.

In the OR, the procedures were initially only performed with manual instruments. Nowadays, more and more robots are used to help the surgeon and to offer more accuracy. For instance, the Da Vinci robot supports laparoscopic procedures to operate more precisely than with the traditional manual laparoscopic tools. Out of the OR, in the rest of the surgical suite, the activity is instrumented. The hospital system is widespread and contains information such as scheduling information and patient's information, which are digitalized and usable via terminals. The surgical staff coordinates with direct communication but text messages and phone calls. Finally, the surgical whiteboards are used to give an overview of the surgical suite state and make updates on the scheduling and patients' requirements.

Figure 49. Left, an air traffic controller workstation comprising two controllers working together. Right, a surgical suite whiteboard supporting the collaborative work of several nurses and a board runner.

5.5.1.6. *Contingencies*

Air traffic controllers face multiple times unforeseen situations. For instance: preventing a collision, emergency priority to a plane due to technical or medical issue in the plane, emergency landing, difficult landing due to weather, overcrowded airspace, supplemental clearances to pilots that are different from the usual ones because they did not work in a first place, changing a route because the pilots say "unable because of the weather", etc. In each of these cases, the controllers must coordinate with the pilots and other controllers to deal with the situation.

In the surgical suite, contingencies are daily situations. An emergency patient arrives and must be treated right away, missing documentation, delayed staff and equipment or lab result, etc. The board runner and charge nurse must accommodate with unforeseen event to ensure the surgical flow. When a surgery is delayed, it can impact the whole surgical flow and delay every procedure for the rest of the day. To keep the surgical suite running, the whole surgical team must coordinate and make plans.

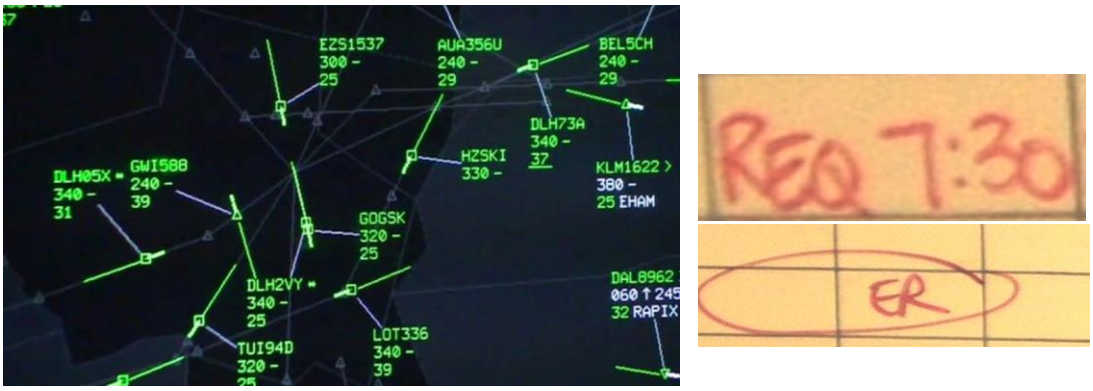


Figure 50. Left: a radar image with several planes – each represented by a green square, on this image the there is an intense traffic and the controllers oversee the separation limitations to avoid collisions (Image credit: bbc.com). Right: emergency situations represented on the whiteboard of the surgical suite – a patient is coming from the emergency department and a specific time is required for surgery (all written in red).

5.5.1.7. *Concepts analogies*

We will compare a flight to a surgical case (including the patient). Both have a beginning and an end in time and space and the objective is to reach destination while having a safe journey. A plane can be compared to an OR: a plane fits a mission, a type of flight. ORs support different surgical cases. The OR staff tries to separate groups of OR that will deal with specific types of surgeries. We compare the Duty supervisor ("Chef de salle"), who is in charge of the ATC center and its air traffic controllers, with the Board runner, who is in charge of the surgical suite and its staff. Finally, controllers/pilots can be compared to surgeons/anesthesiologists/nurses as they are the operators, have similar collaborative activities and face life-threatening contingencies.

5.5.2. Tools and representations analogies between air traffic control and surgical flow management

While being managing traffic in two completely different worlds, air traffic controllers and surgical staff have similarities in the tools they use and the representation of traffic elements.

Figure 51. Top: radar image of the air traffic controller, displaying the flights in the sector. Source: [197]. Bottom: Paper strips giving an overview of the flights and their orders. Source: [198]

Figure 52. Large whiteboards used in the surgical suite to follow the surgical patient flow and manage the resources. Right: electronic board displaying the EHR scheduling information to be used in combination with the whiteboard.

5.5.2.1. *Situation overview*

In ATC, the controllers use dynamic radar image to have an overview of the airspace. It shows the planes, their physical (horizontal and vertical) and time separations, taking in account the speed. The radar shows predicted trajectories and help anticipate collisions.

The surgical suite whiteboards and the hospital system contains all the surgical suite information. The whiteboards give an overview of the operations and are more updated than the hospital system.

ATC has at its disposal the "secondary radar" i.e. a localization and identification system that allow real time information to appear on dynamic radars image, via a transponder. The surgical suite does not dispose of such real time information; the patient location is more or less guessed or the staff makes call to get the information; the OR state is not available out of the OR so the staff must enter inside the OR to ask or see where the procedure is at; the equipment nor the staff are tracked within the hospital; etc.

5.5.2.2. *Representations of the traffic elements*

A flight is represented in ATC by either an icon on the radar image, paper strips on a board in front of the air traffic controllers, or digital strips in the computer system.

We compare paper strips to each line of the surgical suite whiteboard, which corresponds to a surgical case. In both cases, these elements are manually updated or annotated with pens and mobiles on the support: paper strips can be picked and moved, lines on the whiteboard can be erased or added. Flights have an identifier; the whiteboard lines have the patient's name. In the same idea, a flight has a status, the surgical whiteboard gives the status of the surgery (patient arrived in pre-operating room, patient in the OR, surgery canceled, etc.).

Figure 53. Top image, a paper strip representing a flight. Middle-top image, a line on the whiteboard representing a surgical case at the Houston Methodist Hospital. Middle-bottom: a "patient strip" from [104] and Bottom: a "patient strip" from [184].The four can be written on with a pen.

5.5.3. What we learnt with ATC

Many similarities exist between ATC and the surgical environment at the high conception level, but they both have similarities down to the tools and representations of the traffic. Many design guidelines from ATC research projects could therefore be applied to surgical suite patient flow management.

In the MAMMI project [50,171,173], the authors' assumption is that improving collaboration will have a positive impact on the safety of the air traffic and its capacity. The system follows 3 design guidelines which can inspire us to build the design principles for a computerized tool to support surgical flow management:

- *M1*. *Reify actions into objects*: Digital objects represent actions or physical objects. They can be manipulated and allow for task reallocation.
- *M2*. *Enable partial accomplishment of actions*: A task can be partially performed and can signify to a colleague that it needs to be completed.

- *M3*. *Provide as much feedthrough as possible*: Having mutual awareness of teammates' actions foster safety and collaboration.

From Digistrip [116], we extracted 3 graphical design techniques to favor collaboration and awareness:

DG1. *Texture or color gradation to code information*: Colors can be used in many other ways than for state coding. Textures can be subtle reminders of possible users' actions.

DG2. *Different fonts to convey information*: it is possible to distinguish system-computed data and user input data through the font (computer vs handwritten).

DG3. *Animation to facilitate transitions*: as much as graphical design helps display information in better ways, animations in interfaces are useful to help understand state changes.

5.6. Identification of usability requirements from the scenarios and necessary features for a new surgical suite management system

We hereafter identify the 6 usability requirements following the pattern "To [*achieve goal*], OnBoard shall allow [*user*] to [*perform task*]" (see in Table 1) [70]. The requirements reflect the importance of supporting medical staff collaboration by design [136]:

R1. *Enriched surgical flow*: to get up-to-date information and benefit from relevant automated support, OnBoard shall allow users to visualize the surgical flow data enriched with additional information from the cyber-physical infrastructure.

R2. *Multi-users and multi-roles*: to face high workload situations, foster fluidity and benefit to anyone, OnBoard shall allow several users with different roles to interact with it simultaneously.

R3. Teammates' activity: to create mutual awareness, OnBoard shall provide users with means to be aware of teammates' activity.

R4. *Communication and Coordination*: to regulate the surgical flow, OnBoard shall allow users to communicate with each other and coordinate actions.

R5. *Dynamic change*: to face unexpected events, OnBoard shall allow users to change the surgical flow dynamically.

R6. *Work adaptation*: to appropriate technology, the OnBoard system shall allow users to continuously create and adapt new work practices.

The requirements to support central location activities are *R1*, *R3*, *R5* and *R6*. The requirements to support direct interactions between people to solve a problem are *R2*, *R3*, *R4* and *R5*.

Most scenarios include an activity to perform on the whiteboard. The central location of the whiteboard allows the scenarios to happen. The non-mobility of the information is at the same time a strength: to get people together in a central location to directly exchange, and a weakness: people must take the time to physically go to the whiteboard or must call someone to ask about the whiteboard information. The lack of mobility of the whiteboard information is a recurrent bottleneck within the analysis of the user context (cf. Sc15, Sc16).

From the interviews, observations and establishments of scenarios, we were able to identify 24 features for supporting the surgical flow management activity (see Table 9).

Table 9. Synthesis of surgical flow management feature needs.

ID	Feature	Justification
F1. Support for central location activities	***Associated requirements to the features:*** **R1. Enriched surgical flow, R3. Teammates' activity, R5. Dynamic change, R6. Work adaptation**	
F1.1	Edit cases representation	Sc3, Sc4, Sc5, Sc6, Sc9, Sc10, Sc11, Sc13, sc17
F1.2	Visualize a full case	All scenarios
F1.3	Remove a case representation	Sc3, Sc6, Sc17
F1.3	Allergy to latex caution	Sc8, Sc3
F1.4	Name alert caution	Sc8, Sc3
F1.5	Special needs for a patient/surgery information	Sc11
F1.6	Import information from the hospital system to the whiteboard	Sc3, Sc6

F1.7	Support staff breaks representation	Sc10
F1.8	Support patient location representation	Sc4, Sc5, Sc17
F1.9	Support case status representation	Sc4, Sc5, SC17
F1.10	Support cases re-organization	Sc3, Sc7
F1.11	Support surgical suite state representation	All scenarios
F2. Direct interactions between people to solve a problem	***Associated requirements to the features:*** **R2. Multi-users and multi-roles, R3. Teammates' activity, R4. Communication and Coordination, R5. Dynamic change**	
F2.1	Support communicating with colleagues	Sc8, Sc3, Sc1, Sc7
F2.2	Export/Extract information from the whiteboard	Sc10, Sc15, Sc16, Sc14
F2.3	Support staff assignments	Sc18, Sc19
F2.4	Carry information away from the surgical suite	Sc1, Sc2, Sc15
F3. Performances & Integration in hospital	***Associated requirements to the features:*** **R6. Work adaptation**	
F3.1	Quick interactions – Quick feedback	Transition in technology – installation in operational context
F3.2	Software reliability **– *if digital system***	
F3.3	Hardware reliability **– *if digital system***	
F3.4	Easy to clean up	Surgical suite environment
F3.5	Not in the way	Surgical suite environment – patients' beds circulating in the information hall
↓***Associated Requirements:*** **R2. Multi-users and multi-roles↓**		
F3.6	Appealing and engaging	Transition in technology – installation in operational context
F3.7	Usability criteria (effectiveness-efficiency-user satisfaction)	

F4. Cross-interactivity with the CPS		***Associated requirements to the features:* R1. Enriched surgical flow**
F4.1	Linked to the OR sensors of the cyber-physical system **– *if digital system***	Bring automatic data
F4.2	Linked to the hospital system – EPIC **– *if digital system***	

F1.6, F2.2 and F2.4 are the main reasons why a traditional whiteboard is not the optimum solution to surgical suite flow management. F4.1 and F4.2 could not be fulfilled by a traditional whiteboard-based system. F1.6, F2.1, F2.1 and F2.4 suggest incorporating a mobile application.

5.7. Summary and perspectives

The surgical suite whiteboards are usable tools to support collaboration and give an overview of the surgical suite state. From interviews with the surgical staff and observations of the surgical suite, we identified 19 scenarios of whiteboard use that can be divided in two categories:

- Central location activities
- Direct interactions between people to solve a problem

The staff reported in questionnaires being satisfied with the whiteboard and they rely on it to perform their daily activities. The surgical suite whiteboards are physical devices at a specific location with crucial information. They thus serve as a meeting point and foster face-to-face communication.

We have identified 5 high level requirements based on the scenarios of use of the whiteboard and tuned from the MAMMI requirements:

- *R1. Enriched surgical flow*
- *R2. Multi-users and multi-roles*
- *R3. Teammates' activity*
- *R4. Communication and Coordination*
- *R5. Dynamic change*

- *R6. Work adaptation*

From the scenarios, we extracted 24 features necessary for a new surgical flow management system.

The replacement of the traditional whiteboard by an electronic one aspires to bring better information to medical staff but may jeopardize collaboration and adaptation. Therefore, we used a user-centered design approach to keep the collaborative aspects and flexibility of the current tools. For whiteboards to be removed/replaced, we strongly believe a significant effort must be made in term of human computer interaction to leverage their assets better and replace them with a system fitted to the surgical staff. As mentioned by Bardram et al. [23] in their design principles for a surgical touch screen, the system should augment, rather than automate, users' activity. The challenge is henceforth to gather and implement the benefits of whiteboards and computers systems together.

6

INTERACTION DESIGN & IMPLEMENTATION

The related work and the user analysis we performed showed that the power of the traditional whiteboard dwells in its flexibility, which can be jeopardized by computerization. Therefore, we oriented the design of a collaborative computer support for the surgical suite workflow towards a large electronic interactive whiteboard, with direct manipulation of objects [89]. The result is OnBoard, an application for a large multitouch surface that proposes whiteboard-like features, enhanced by interactions that could be only provided by computer-support. OnBoard follows specific design requirements and principles identified thanks to the user context analysis and the study of related work. In this chapter, we detail the user interactions allowed by OnBoard, and the relevant implementation challenges. We first describe the design principles we followed to design the user interactions [136] and finally the 26 Interaction Features (IF) designated as "IF+number" in Table 12.

Hereafter is a recall of the requirements of OnBoard (see Table 10):

Table 10. Reminder of the requirements of OnBoard.

ID. Title	Description
R1. Enriched surgical flow	To get up-to-date information and benefit from relevant automated support, OnBoard shall allow users to visualize the surgical flow data enriched with additional information from the cyber-physical infrastructure.
R2. Multi-users and multi-roles	To face high workload situations, foster fluidity and benefit to anyone, OnBoard shall allow several users with different roles to interact with it simultaneously.
R3. Teammates' activity	To create mutual awareness, OnBoard shall provide users with means to be aware of teammates' activity.
R4. Communication and Coordination	To regulate the surgical flow, OnBoard shall allow users to communicate with each other and coordinate actions.
R5. Dynamic change	To face unexpected events, OnBoard shall allow users to change the surgical flow dynamically.
R6. Work adaptation	To appropriate technology, the OnBoard system shall allow users to continuously create and adapt new work practices.

6.1. Design considerations

In this section, we present the design principles that guided the design of the interaction features.

6.1.1. Design principles

We determined design principles to implement these features in a new surgical flow management system [136]. Leveraging on usability guidelines [49,124,125], CSCW principles [60] and from the analogy with ATC (MAMMI) [50,116], our user analysis and the related work study on touch surfaces benefits, we determined and followed 5 design principles (summary of design principles and requirements in Table 10):

P1. *Multi-touch*: Use a large interactive vertical multi-touch surface to support multi-user interaction. This principle was selected to support the benefits of multitouch large surfaces studied

in the related a work and in the analogy between ATC activities and our user activity study in the surgical suite.

P2. *Reify:* Reify actions and real objects into virtual objects. Since objects are displayed on a shared surface, their manipulation may enable accountability. Based on the whiteboard's observations, many objects from the whiteboard could be reified and enhanced to promote a better usability.

P3. *Partial:* Enable partial accomplishment of actions. An action can be separately prepared, checked and accomplished by different users, thus offering seamless task allocation. This principle results from the related work and from the whiteboards observations where users do not always fully accomplish actions on it but leave unknowns visible on the whiteboard (for example: the information that a staff is missing for an OR).

P4. *Feedthrough:* Provide as much feedthrough as possible. Since activities must be accountable, it is important that appropriate feedback provide an opportunity for teammates to observe one another's actions. This principle supports mutual awareness and synchronous and asynchronous communication improvements.

P5. *Robust:* Interactions must be tailored to work efficiently in a high-pressure environment. OnBoard should be robust enough to be used in a real-setting or offer fallback. This principle is instrumental in our success to install OnBoard in the surgical suite for real-world testing.

We borrowed technology probes principles [90]:

TP1. *Flexibility*, *Open-ended and co-adaptive*: Technology probes must be open-ended with respect to use, and users should be encouraged to reinterpret them and use them in unexpected ways.

TP2. *Real-world*: Technology probes must work in a real-world setting. Therefore, the main technological problems must be solved for the technology probes to serve their purpose.

TP3. *Instrumented*: Technology probes collect data about users and help them (and us) generate ideas for new technology. Logging allows researchers to create visualizations of the use of the probes, which can be discussed by both users and designers.

We also borrowed graphical design techniques from Digistrips [116]: *DG1*. *Texture or color gradation to code information*, *DG2*. *Different fonts to convey information*, *DG3*. *Animation to*

facilitate transitions: as much as graphical design helps display information in better ways, animations in interfaces are useful to help understand state changes.

The combination of requirements and design principles acted as a driving force in the design process.

In the next sections, we detail the interaction features and the implementation challenges.

6.2. OnBoard system overview – A large surface in a semi-public cyber-space *(supporting R2 and R6 and satisfying P1)*

OnBoard (see Figure 54 and Figure 55) runs on a large multitouch surface (84", 4k, 60 Hz, Inglass technology – capacitive & infrared) in the surgical suite corridor (IF1. Surface and Space, see Table 12). The corridor is a semi-public and central area: the surgical staff meets there because of the presence of the whiteboard, especially during turn-around between operations. It is a place of information sharing and verbal communication. The 84" surface is vertical in landscape orientation and is as large as one of the two whiteboards of the surgical suite. The surface is multitouch, large enough so that 3 people can stand in front of it. The resolution is high enough to allow both close-up and 5 meters-apart reading.

The main layout of OnBoard user interface consists in reproducing closely the current traditional whiteboard used by the surgical team to manage cases (Figure 41 and Figure 55). OnBoard is composed of three main parts. The central part is a vertical list of white, horizontally-elongated strips that reify surgical cases and allow rescheduling activities and additions of notes. On the right part, a vertical list displays groups of staff members to support staff management and assign them to ORs. The banner at the top contains a toolbar with various tools such as magnets, ink color and width and an undo button.

The general philosophy of OnBoard is the direct manipulation of objects [89] such as case strips, magnets and staff magnets. Objects can be physically moved on the whole board and their content can be modified. OnBoard constantly updates the representation with the information from the OR sensors, and is updated by the users via the touch screen. A mobile phone app was prototyped to interoperate with OnBoard. *[R2: multiusers; R6:adapt; P1:multitouch]*

Figure 54. Three nurses training on OnBoard.

We thus offered a system that is very similar in terms of use and layout to what the users are used to have. Such an approach guarantees a similar usability. In addition, it can be a safety measure. Indeed, the traditional whiteboard supports the workflow and it is possible that we do not know all the reasons why it works so well. In a critical environment, radically changing a system is a risk that can lead to fatal consequences. It differs with a non-critical environment, where radically changing of system can be accepted because it allows an adaptation and learning time and can tolerate errors.

We used three kinds of electronic board: a Sharp HD (64”), an InGlass 4K (84”), and a Microsoft Surface Hub 4K (84”). The Sharp HD was used at the beginning of the thesis, for development purposes. We quickly discovered that its definition was not high enough for proper handwriting and its resolution was not enough to include all cases. Houston Methodist thus afforded the InGlass 4K screen, while ENAC acquired a Microsoft Surface Hub. The InGlass was eventually deployed, while the Surface Hub could be used to test and compare the quality of the interaction.

The software is principally based on the JavaFX library. It integrates a reimplementation of SwingStates to cope with JavaFX events [10]. The software architecture comprises 9 implementations of state-machines, 14 objects in the Model and 40 visual objects in the. It was developed on a Windows 10 operating system, with a NVIDIA Quadro K2200 graphic card. In the following, we provide information on the implementation of the interactions, for the sake of replicability.

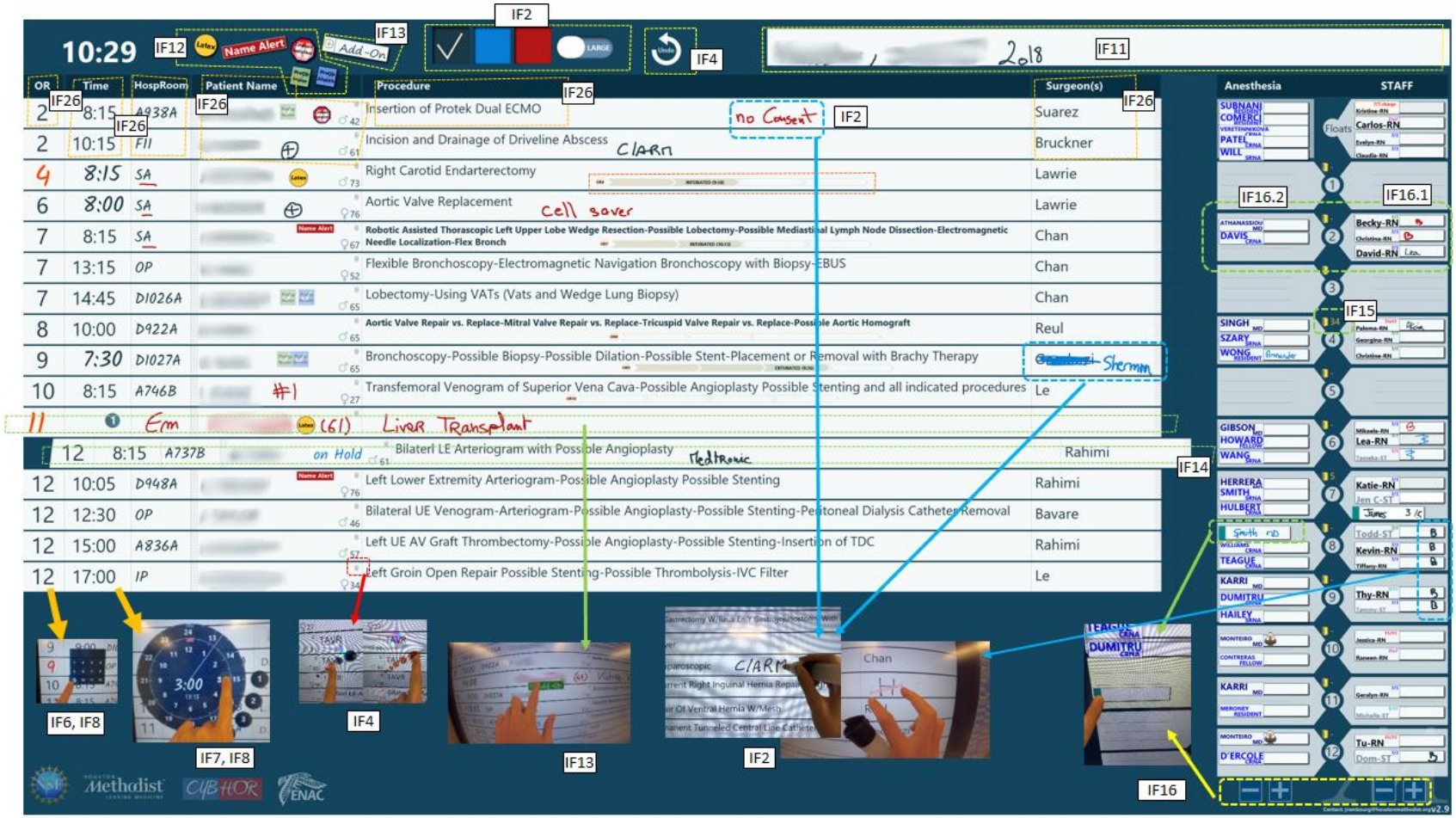


Figure 55. Overview of layout and interaction features (IF see Table 12) of OnBoard.

6.3. Writing/Erasing almost everywhere *(supporting R1, R3, R4, R5, R6 and satisfying P1, P2, P3 and P5)*

Like the traditional whiteboard and for the sake of flexibility, we preserved the ability to write and erase on the electronic board.

6.3.1. Writing

We proposed several ways to interact with the surface: fingers, gloves and different types of pens (see Figure 56) (IF2. Handwriting/Erase). Users can write on objects such as cases and staff magnets. We inserted empty areas to provide additional zones of writing, one at the top of the surface and one that can be hidden behind the staff list (F11. Notes area).

Figure 56. Left: User writing on OnBoard. Right: The different types or pens used by the surgical staff during design walkthrough sessions.

After testing the different types in design walkthrough sessions, the surgical staff promoted the use of traditional dry-erase markers that have no ink in it. One advantage is that the "noise" made by a marker is preserved and participate to make people around the board aware that something is being done on the board (P4 Feedthrough). Another advantage is that writing on the board is very smooth with such a pen, whereas writing with plastic/rubber/microfiber pens is less comfortable. Indeed, they do not "glide" smoothly nor make annoying tapping noise.

6.3.2. Erasing

We designed and implemented a multitouch erasing interaction based on the area between two or several fingers. The eraser is represented by a line joining the fingers together. Users can select the eraser size by moving one's fingers away or closer from each other. By dragging the fingers on the screen, one erases the text which has been overflown (see Figure 57). Users can see what will be erased thanks to the dimming of the color of the overflown items *[DG1. Color]*.

The participatory design sessions with the staff led to customize a traditional physical eraser with four points of contact, allowing them to erase electronic items with a physical object, and bringing back some tangibility. For the Inglass multitouch surface, we simply cut the foam of the eraser as shown in the top picture/images in Figure 58, as a touch is recognized by the display no matter what is touching the surface of the display. For the Microsoft Surface Hub, we glued conductive fabric on each of the eraser extremities and we wired the device with thin cooper wires linking the hand to the conductive fabric (see bottom images in Figure 58). As the Microsoft Surface Hub is a conductive only technology, we had to link the electricity coming from the hand to the conductive fabric to make a connection. The idea is to use the four corners of a traditional dry-eraser to simulate touches on the display. We consider that if any touch within a certain range next to another touch is smaller than a certain treshold (that must be calibrated according to the size of the surface and hand's size), it means that the user is erasing. We then create an erasing shape which will collide with digital objects in the interface as the user moves the eraser on the surface (see Figure 57 and Figure 59). The collided shapes'colors are dimmed, and are definitely erased with a fading animation *[DG3. Animation]* when the user lifts the eraser at the end of the gesture.

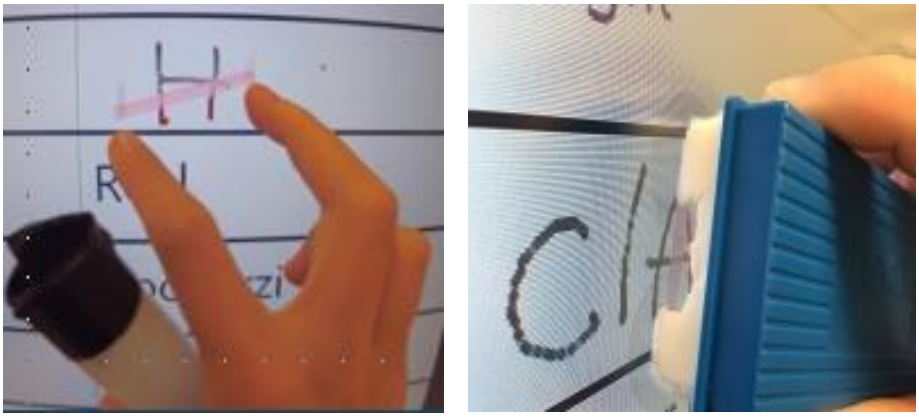


Figure 57. "2-fingers" erasing (middle) and "2-points" erasing (right).

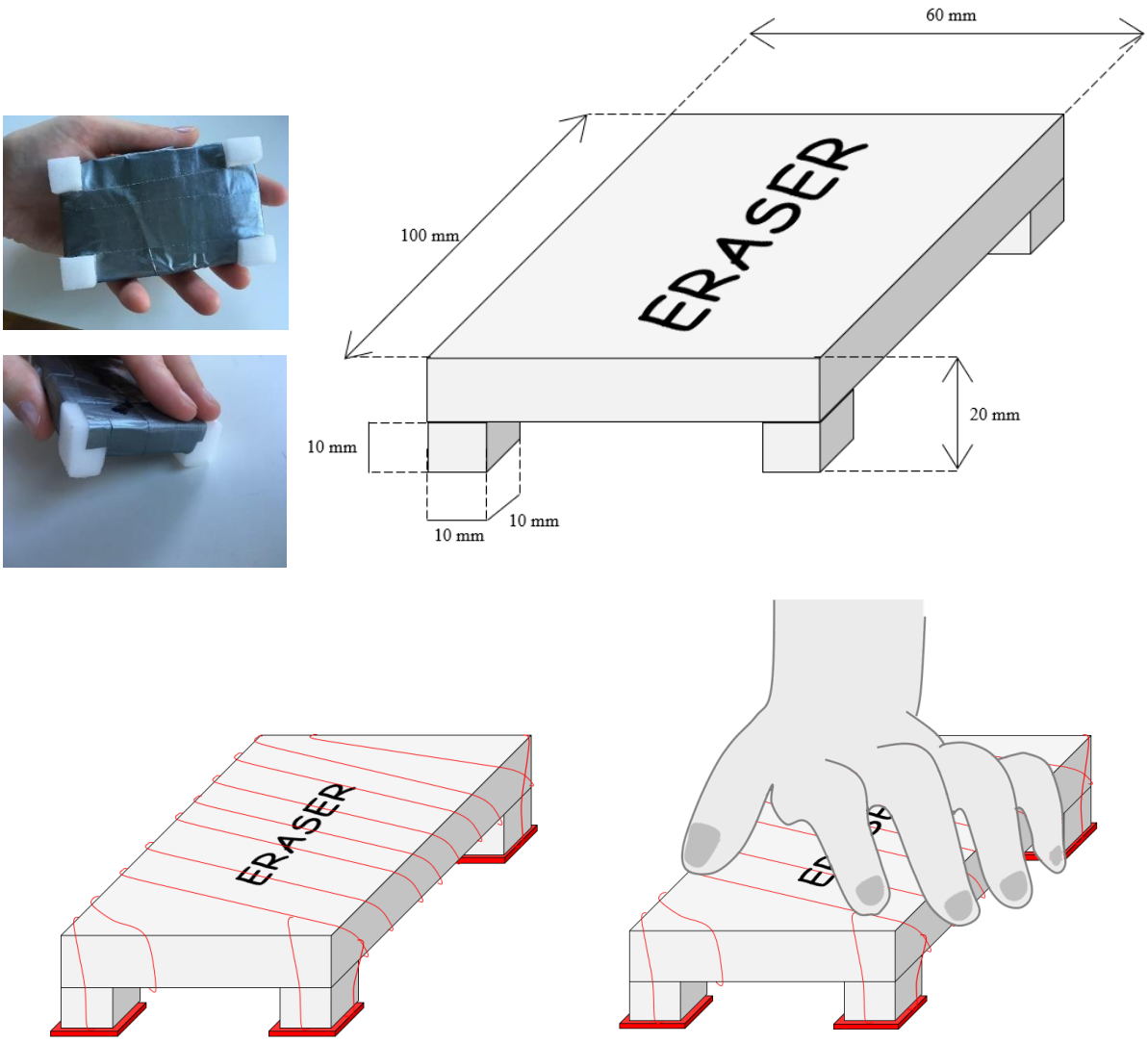


Figure 58. Pictures and drawing of the eraser concept. Top pictures: for Inglass/Infrared touch displays. Bottom: wired with copper and conductive textile (in red) for capacitive screens.

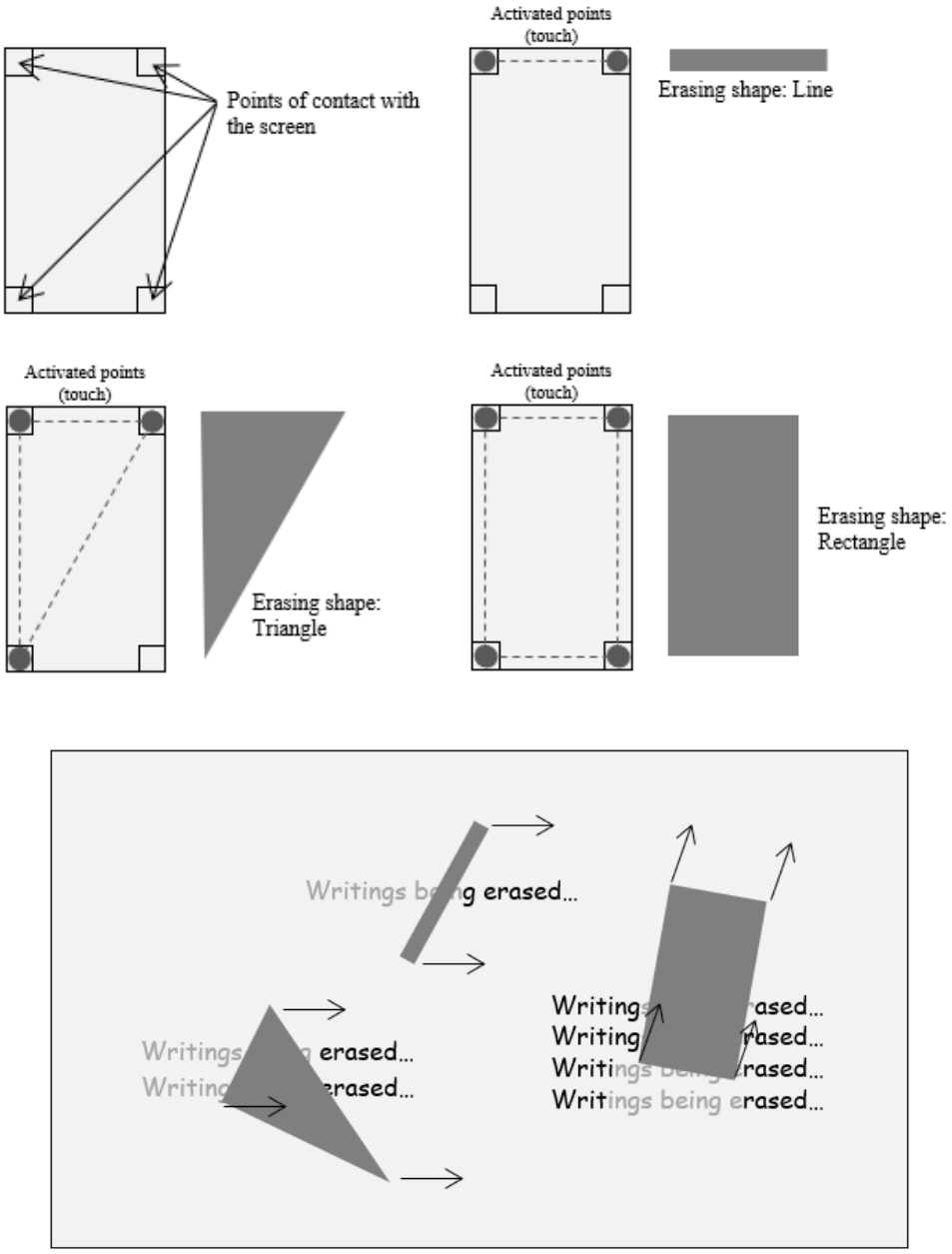


Figure 59. Details of the contacts points for the eraser and associated shapes. Text in light gray: what was erased by the eraser shape after moving the shape over the text.

6.3.3. Implementation of the writing/erasing interactions

We developed multitouch interactions to support writing and erasing activities by the user on the large display. This multitouch is managed with a reimplementation of SwingStates [10]. This reimplementation allows to bridge SwingStates originally meant for the library Swing for Java with JavaFX. JavaFX events are therefore redirected to state-machines (see Figure 60, Figure 61 and Figure 62) specifically designed for supporting JavaFX events.

```
EventHandler<TouchEvent> MOVE = new EventHandler<TouchEvent>() {
    @Override
    public void handle(TouchEvent event) {
        // within strip width
        if (event.getTouchPoint().getX() > list.get(1)
                && event.getTouchPoint().getX() < (list.get(list.size() - 1) + 50)) {
            // not around trash
            if (event.getTouchPoint().getX() > list.get(3)
                    || event.getTouchPoint().getX() < (list.get(3) - 20)) {
                hwsm1.handleEvent(TouchEvent.TOUCH_MOVED, event);
            }
        }
        event.consume();
    }
};
```

Figure 60. Sample of the code redirecting the JavaFX events to the state-machine.

```
/*********************************************************************************
 ********** WRITING 1 user ******************************************************
 *********************************************************************************/
public State W1 = new State() {
    Transition press_new = new Transition<EventType<TouchEvent>, TouchEvent>(TouchEvent.TOUCH_PRESSED) {
        @Override
        public boolean guard() {
            return (evt.getTouchPoints().size() < 3) && !isDistanceSmallEnough(evt.getTouchPoint(), finger1);
        }

        @Override
        public void action() {
```

Figure 61. Sample of code within a state-machine, here in "1 WRITER" state.

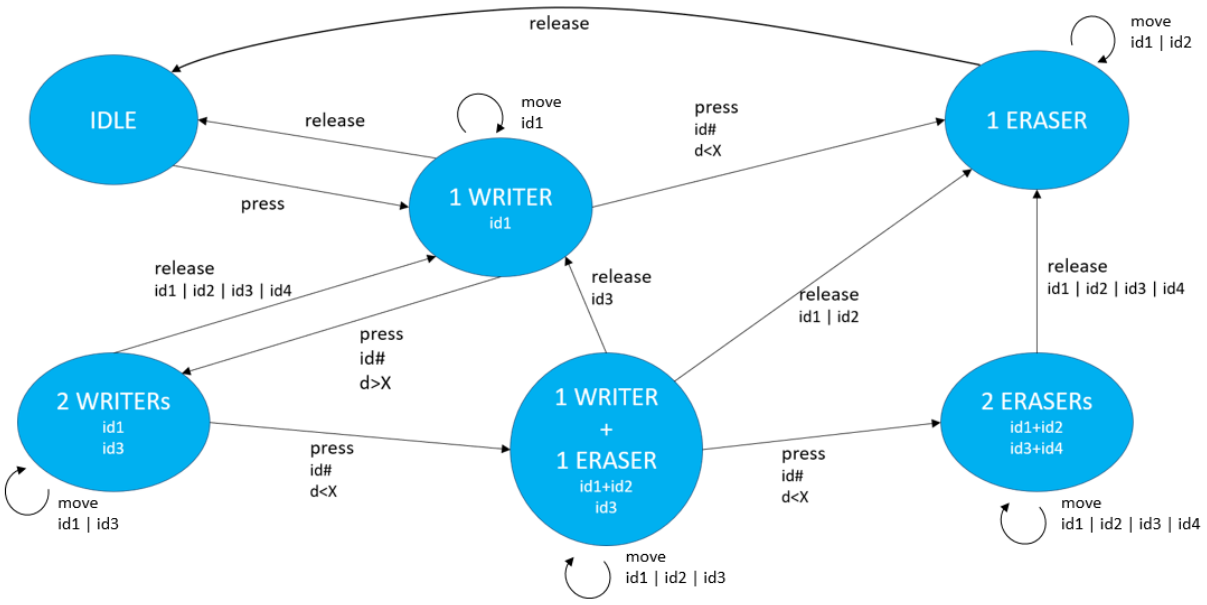


Figure 62. Multitouch state machine to support the writing and erasing activities at 1 or 2 users for this prototype.

In Figure 62, the text with each arrow is the necessary action to transfer from a state to another one. We assumed that more than 2 users at a time on the same surface was uncomfortable and rarely observed. Hence, OnBoard supports two users simultaneously only for the writing-related activities. However, the other interactions can support simultaneously as many touches as the display can support (JavaFX events management).

On Figure 62 "id" represents a "touch id" which is the number that identifies a touch event on the screen. “d” represents the distance between a touch id and the new touch performed on the screen. If the distance is smaller than a threshold that must be calibrated according to the size of the screen and a hand’s size, the state-machines will consider that there is no new user and that this touch belongs to the same user. It makes the system enter an “eraser” state instead of a “writer” state. However, if “d” is larger than the threshold, the state machine will consider a new user and will add a writer in the system. It leads the system to allow two users to write on the display.

The writings are “glued” to a specific strip i.e. with the strip’s coordinates. These coordinates must be calculated when the writings are glued to the strip and when the user is trying to erase them with their fingers/eraser by creating a selection zone that enters in collision with the writings. Such

development required careful algorithm and interaction programming, e.g. we had to resort to QuadTrees to optimize the collision detection for erasing.

The QuadTree as implemented in OnBoard manages the space of the scene on which the surgical case strips lay (see Figure 63).

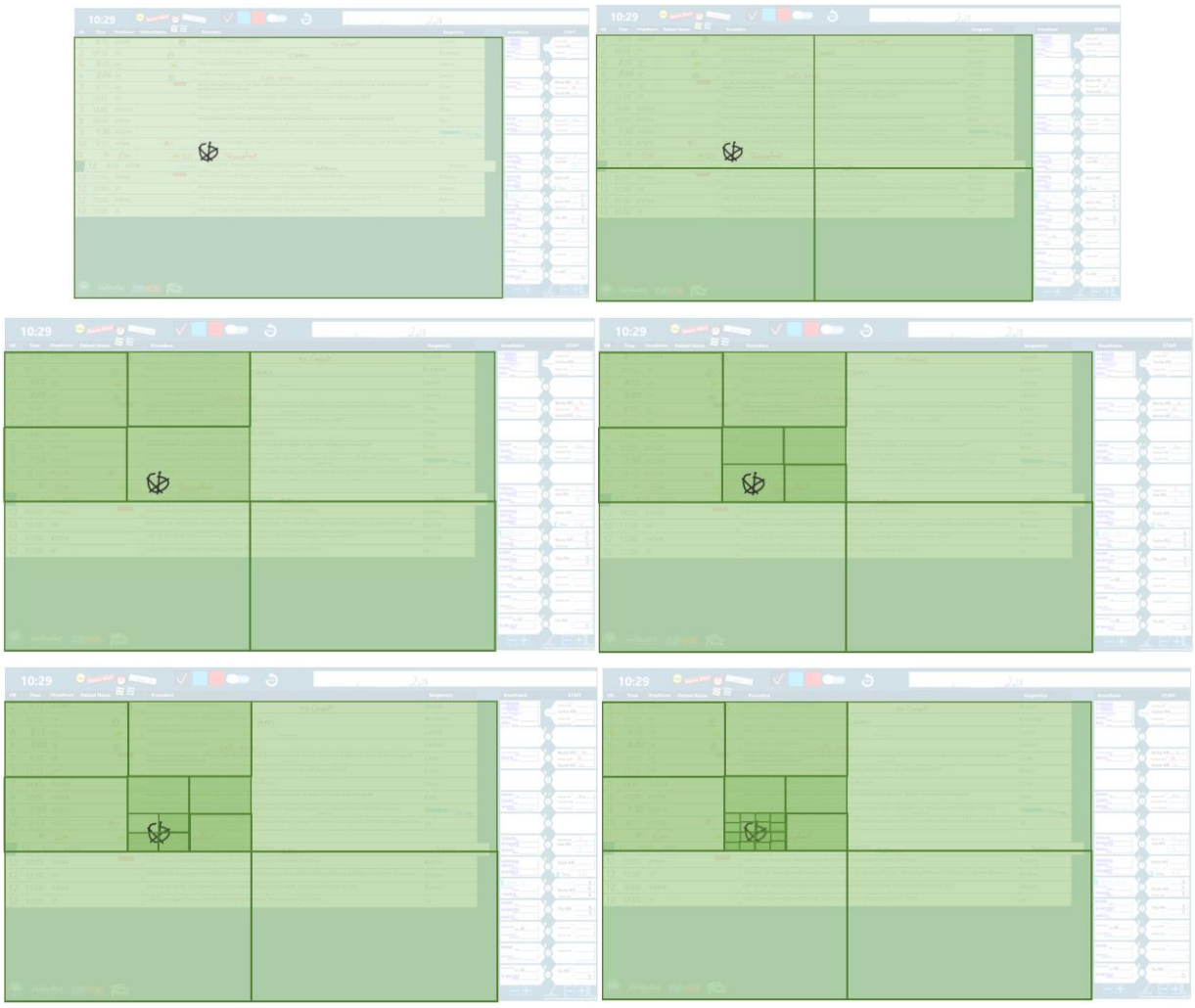


Figure 63. Representation of the QuadTree implemented and parameterized for OnBoard. The black strokes represent the erasable strokes that the QuadTree will store

We parameterized the QuadTree to dynamically and recursively subdivide into four quadrants up to 5 levels, as the size of the smallest quadrant corresponds to the height of a strip. The size of erasable objects can be reasonably contained within this range. Each quadrant is a new QuadTree.

When an erasable shape is added to the scene (by the user writing on OnBoard), it in inserted in the initial QuadTree, which will generate if necessary smaller QuadTrees.

When a user is erasing, the quadrants which coordinates correspond to the coordinates of the erasing shape activate and search for erasable shapes/strokes contained in the data structure of the QuadTree (see Figure 64). This system allows a significantly improved optimization of the search for colliding shapes in the 2D scene.

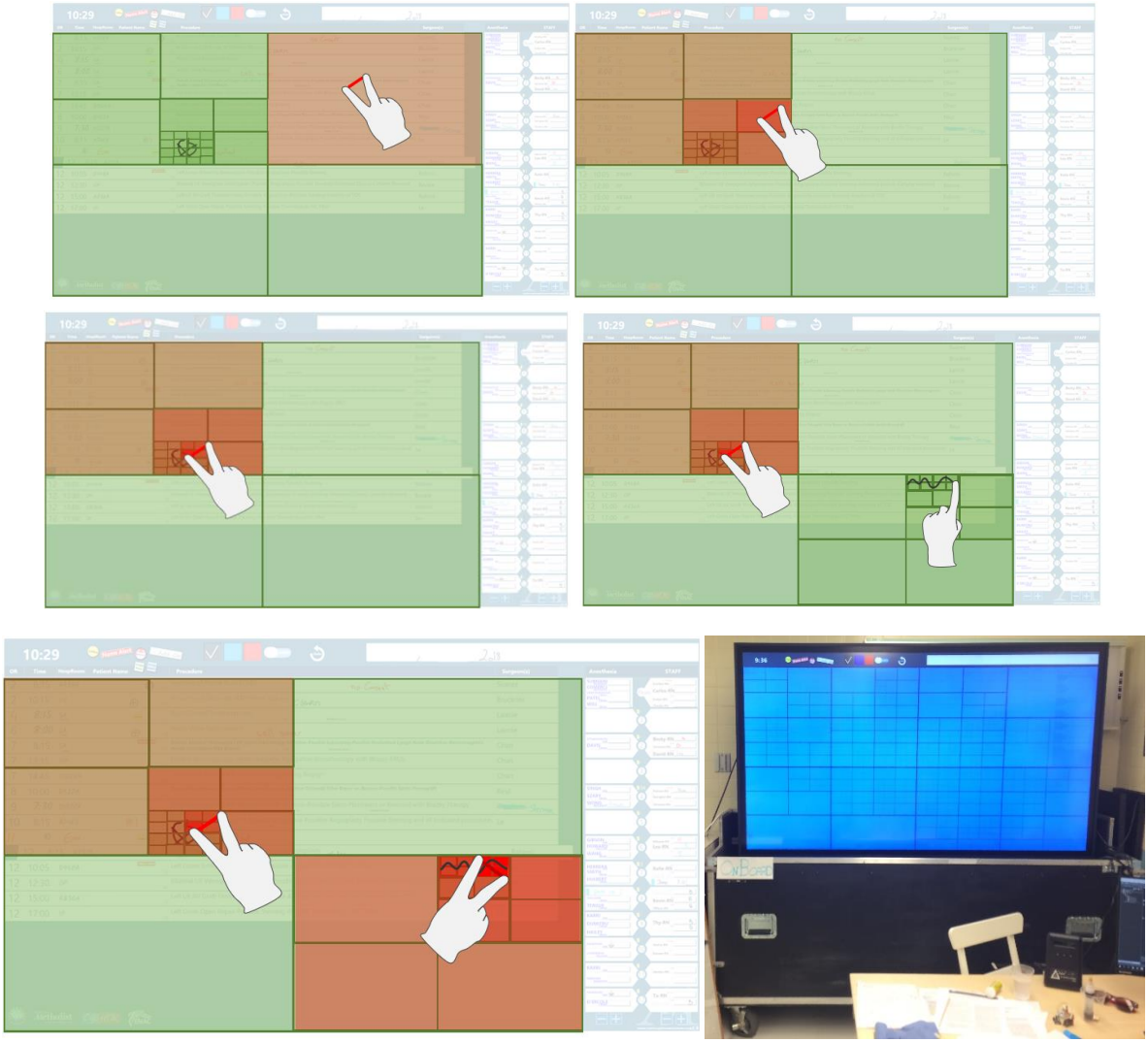


Figure 64. Search of the smallest existing quadrants (containing erasable shapes) which contains the coordinates of the erasing shape. Up to 2 users. Bottom-right: OnBoard with the QuadTree division visualization activated.

We never observed more than two users using the whiteboard at the same time, possibly because the physical space makes it difficult. We limited the writing/erasing interactions in OnBoard at two users at a time as it seemed reasonable in terms of use, and as it was already borderline in terms of speed of feedback of the display to support two users erasing at the same time. Even when there was only one user erasing, the system would become slow when a lot of shapes were drawn on the display, inducing too many calculations of collisions for the system.

6.4. Surgical case management *(supporting R1, R4, R5 and satisfying P1, P2, P3 and P4)*

A surgical case is represented by a long strip containing the following information: operating room id, scheduled time, hospital room id, patient name, procedure, surgeon name. The information mimics that of the actual board.

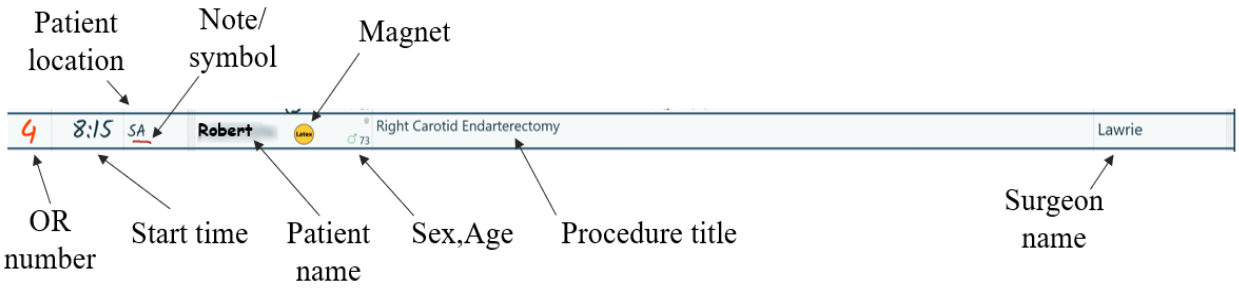


Figure 65. A surgical case as represented on the whiteboard.

6.4.1. Adding informative magnets

Magnets exist on the traditional surgical suite whiteboard. They warn (or alert) about potential dangers for the associated patient or are just informative. During participatory design sessions, the staff oriented the design of "alerts" toward digital magnets. The staff proposed new magnets for notes they often write on the whiteboard (for instance, "latex allergy"). A design problem was to determine how many magnets we should implement, as a lot of them were proposed. Implementing and using too many magnets might weaken the expected magnets ability to draw the attention on something specific, even though they are recurrent. After discussions during participatory design

sessions with various staff, we decided to implement four magnets: latex allergy, name confusion, contact isolation, and pre-op done (see Figure 66) [IF12. Magnets].

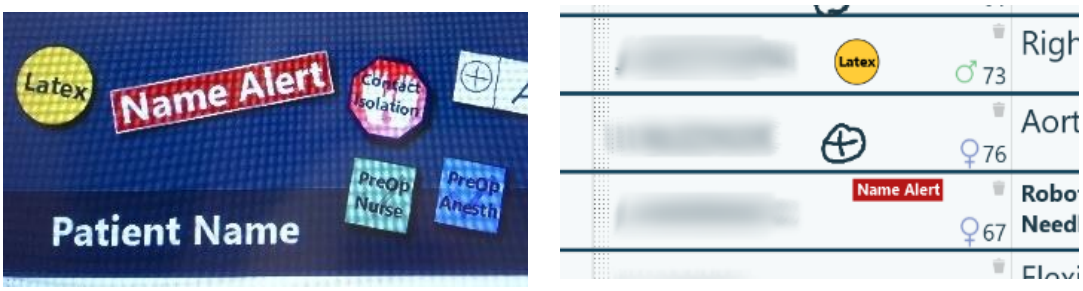


Figure 66. Strip magnets.

Magnets can be associated to a strip: the magnets are taken from the "magnet tool box" at the top of the screen and dragged and dropped on a strip. This feature is directly inspired from the way DunnOR surgical staff manage their cases i.e., adding physical magnets on the whiteboard. A state-machine (Figure 67) controls how the magnets are moved and on which part of the board they are released: if on a strip, the magnet is "glued" to the strip and will follow it when it is moved.

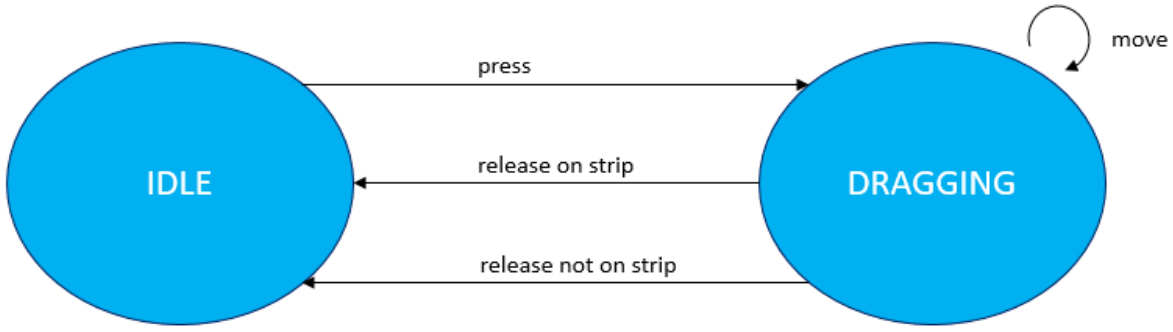


Figure 67. State-machine controlling the interactions with the magnets versus the strips (Latex Allergy – PreOp – Name Alert – Contact Isolation).

These magnets can be deleted by being "thrown away" with a quick swipe while holding the magnet. To implement this effect, we determine the distance between the last two touch points, and if the distance is large enough it means that a quick "throw away" movement has been performed.

[R1: enrich; R4: coord; R5: dynachange; P2: reify; P4: feedthrough]

6.4.2. Re-arranging cases

During interviews and participatory design sessions, users mentioned that re-writing a surgical case on the traditional whiteboard was inconvenient: to move the surgical case elsewhere on the whiteboard they would have to totally erase it and then re-write it. With the re-arranging case feature, users can modify the vertical layout of strips on the board, by dragging them up and down (see Figure 68) [IF5. Arranging cases layout]. They usually choose to order them by OR number, then by start time number. We wanted to leave this totally free so that any surgical suite culture could be applied.

Figure 68. Re-arranging case layout.

To differentiate between the start of a move and the start of handwriting, we implemented a spatial mode: the user must touch on a "grained" textured zone to start a move. At the end of the movement. The application computes the height of the touch to determine where the strip should be released in the layout, for instance, in between two cases already present. Feedback, which is key for such micro interactions [150], is displayed when the strip moved and released (in between two other for instance). An animation gradually moves all the strips to make room for the new one. This feature helps understand where the strip was inserted, as inspired from Digistrip [115].

[R1: enrich; R4: coord; R5: dynachange; P2: reify; P4: feedthrough]

6.4.3. Shifting case

Users can "visually" extract a case from the flow by dragging and shifting a strip to the right (see Figure 69) [IF14. Shift case]. This feature was designed with no targeted use in mind. We wanted to observe what use could be done of it, as in the technology probe approach [*TP3. Co-adaptive]*.

This idea came from the related work on the MAMMI prototype and on actual ATC stripboard practices [173].

[R1: enrich; R3: teammates; R4: coord; R5: dynachange; P4: feedthrough]

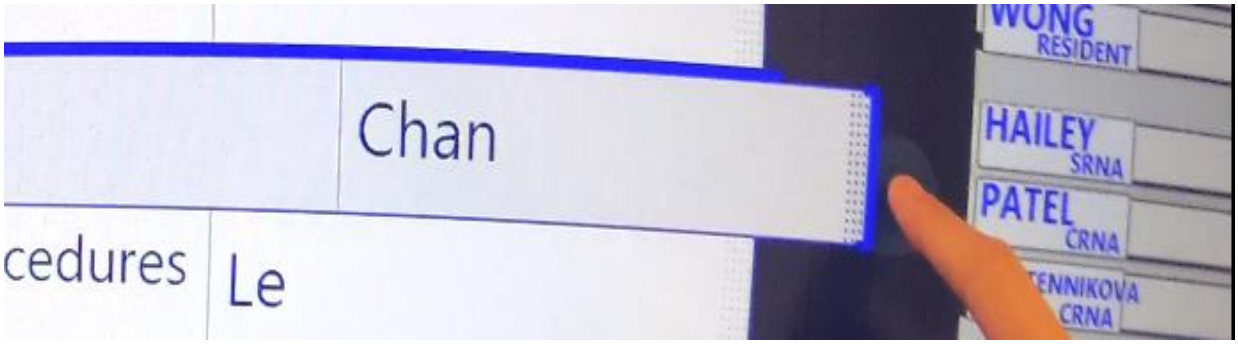


Figure 69. Shifting a case to the right.

6.4.4. Adding emergency cases

Along the day, add-on surgical cases can be added on the board (IF13. Add-ons), for instance for emergency cases.

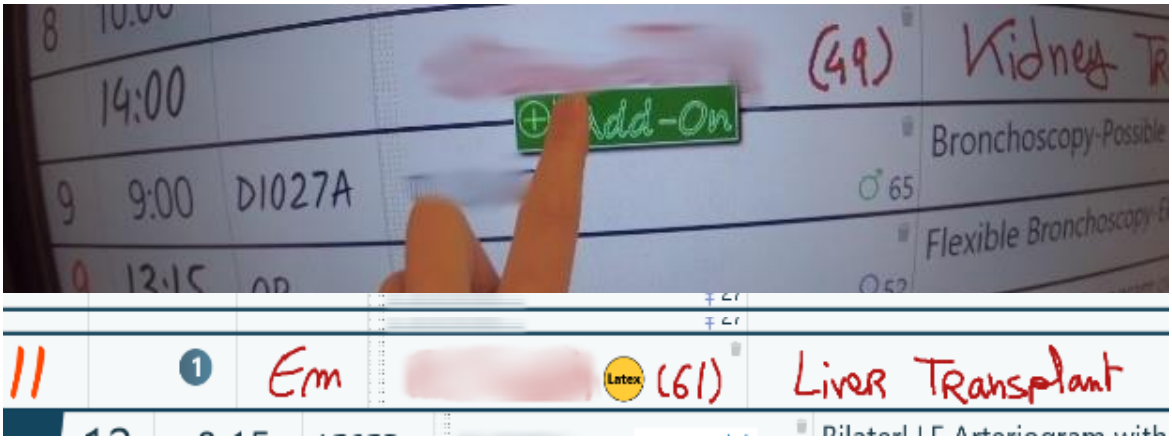


Figure 70. Insertion of add-on cases in OnBoard.

During interviews and observations, we identified that physically adding a case in the flow on the whiteboard was a problem due to the lack of space, like moving the cases from one place of the whiteboard to another. We designed an interaction that relies on the reification of an add-on case

into a magnet. When dragged, the ad-on turns into a blank surgical case. The user drags the add-on (see Figure 70) and drops it between two trips or at the bottom of the screen. Like the re-arrangement of existing strips (see section 6.4.2 “Re-arranging cases”), when an add-on is inserted in the flow, an animation separate all the strips to make room for the new one.

[R1: enrich; R4: coord; R5: dynachange; P1: multitouch; P2: reify; P3: partial; P4: feedthrough]

6.4.5. Cancelling and deleting cases

A case can be cancelled [IF3. Cancel case] without being removed from the board by pressing on the “trash” icon. A red triangular wave and a CANCELLED text is displayed on top of it to mimic strikethrough: this enables the staff to make sure that everybody is aware that the case has been cancelled (see Figure 71) (observations at DunnOR).

Figure 71. Canceling a case.

A case can be totally deleted and removed from the board (IF4. Delete case + undo/redo), by pressing the trash icon, then dragging all the way to the bigger trash through each bubble, then releasing (see Figure 72). This interaction brings safety in the deletion of a case, which is considered a very critical action. This action must be done only when the staff estimates that the patient left the surgical suite. Would a mistake be made, or would the patient come back into the OR, the staff has the possibility to “undo” the deletion and bring the representation of the case (the strip) back on the board by pressing on the “undo” icon at the top of the screen.

[R1: enrich; R3: teammates; R5: dynachange; P1: multitouch; P2: reify; P3: partial; P4: feedthrough]

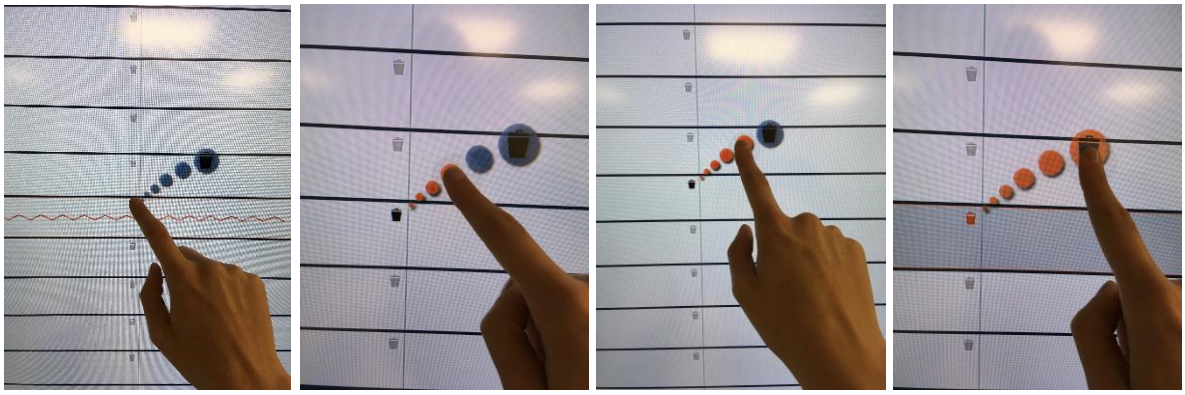


Figure 72. Delete a case from the board.

6.4.6. Writing recognition for OR number

Recognizing the change of OR number is important to the surgical suite managers because it provides data about the suite's schedule. We explored writing recognition for the choice of the OR number on a case. The purpose was to let the user handwrite *[R1: enrich]*, while being able to inform the system on the newly OR number chosen for a surgical case. Users are intolerant to recognition error and it is difficult to get a bullet-proof hand-writing recognition system even for entering simple information such as an OR number, with a variety of people having different handwritings. We thus designed some interactions to ensure that the OR number has been recognized correctly.

Here, the user writes the OR number in the OR box on the strip (see Figure 73). When the user draws on the surface, all the coordinates of the points are saved. When the user releases the pen (or his finger), the list of coordinates is sent to the Windows Optical Character Recognition (OCR) system via a the Ivy software bus [38]. The system sends the results back to the interface. The computer then displays, via a box under what was written, the best proposition according to its recognition algorithm (1 or 2 propositions). To validate the recognition, the user must select the proposition by clicking in the box, which will make the computer replace what was manually written by a computer font. One can notice that the chosen computer font chosen has a "script style" as we want to preserve the visual hint that a human made a modification. Would the user not select a proposition, the box fades away and leaves the previous writings unchanged.

Figure 73. Writing recognition to change the OR number associated to a case.

If the user wants to input an OR number containing two figures (e.g., OR 12), the users first write a “1”, select the “1” recognized by the system, draw a “2” next to the “1”, and select the “12”.

This feature was appreciated and raised interest from the BR since when the computer recognizes the OR number, it replaces the hand-writing with a more readable computer font. However, most users during design walkthrough sessions would make the comment that this is a “long and complicated” interaction for something as simple as changing a number. Most users during design walkthrough sessions, thinking about using it in the clinic, stated that it would be much easier and understandable by other staff members if they could press and drag and drop on a number and not use recognition. We therefore designed another solution, based on the selection in a list of OR numbers laid out in transient dialog box (see Figure 74).

6.4.7. Changing procedures scheduling

OR number and start time for a case may vary regularly according to the other cases and external factors such as turnover between two cases, or surgeon availability. OnBoard allows these changes (IF6. Change OR number and F7 start time) (see Figure 74). To modify the start time, users need to press the current start time and drag the hand of the clock along the inner clock (for AMs) or the outer clock (for PMs). The text of the new start time appears with a handwritten font to specify that a user changed it. As users sometimes do not know the new start time and just need to give an idea of the order of the cases, we added the possibility to drag to numbers (1-2-3-4). This feature illustrates how OnBoard enable users to provide partial information in a flexible way.

[R1: enrich; R4: coord; R5: dynachange; P3: partial; P4: feedthrough]

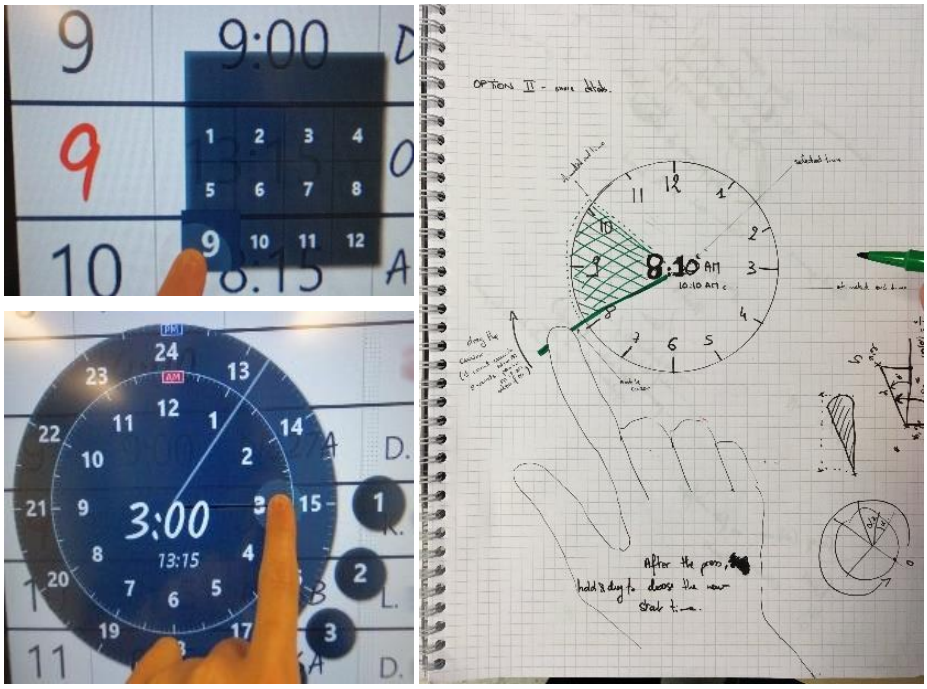


Figure 74. Modification of OR number (top-left) and start time clock (bottom-left). Design idea of the clock showed to users during a participatory design session (right).

The OR number modification is a simple JavaFX press/move/release events listening on the object "ORchoiceModule". The object "ClockModule" converts the angle where the user is dragging into a time (no time, pm or am) according to the distance from the center. The white handle represents the previous selected time, helping the user to start his/her dragging interaction. The user usually thinks "This case will need 30 more minutes to be finished, so I need to delay the start of this case here by 30 min". Instead of having to make an absolute choice, the user is allowed to make a choice relative to the former time.

6.5. Staff management *(supporting R1, R4, R5 and satisfying P1, P2, P3 and P4)*

The surgical staff management is performed in the right part of the interface (see the two columns on the right of Figure 55). We consider here "staff" as the anesthesiologists, the nurses and the surgical technicians. The surgeon is represented on a surgical case strip as he/she is usually not changed (except for emergencies).

6.5.1. Staff representation

An important part of the job of the board runners is to assign staff to ORs and procedures. In DunnOR surgical suite, they are manually written on the whiteboard. In FondrenOR surgical suite, the surgical staff has magnets to represent their names. All the interviewed staff commented willing to have magnets for the staff assignment as it is often the same names that are used because the team does not change often. To do so, every staff of the day has a magnet with his/her name as his/her representation on the right of the board (see Figure 75) (IF16. Staff magnet). These magnets can be moved up/down on the right part of OnBoard to assign them to OR numbers. New staff magnets can be created by pressing the "+" at the bottom-right of the screen and edited with a pen (see Figure 75). Any staff magnet can also be deleted (for instance if a staff has left) by dragging the magnet to the "-" at the bottom-right of the screen.

[R1: enrich; R4:coord; R5:dynachange; P1:multitouch; P2:reify; P3:partial; P4:feedthrough]

6.5.2. Surgeon occurrence

Nurses are often associated to a surgeon team and perform surgeries with the same surgeon. Staff reported in interviews that if they were able to quickly see what their schedule looks like, it could improve the nurses' efficiency. Hence, we designed an interaction consisting in pressing on the surgeon name, which highlights all the cases performed by the same surgeon (see Figure 76) (F10. Surgeon occurrence). This feature allows users working with this surgeon to have a quick overview of all the patients they will work with.

[R1: enrich; R4: coord; R5: dynachange; P2: reify; P3: partial; P4: feedthrough]

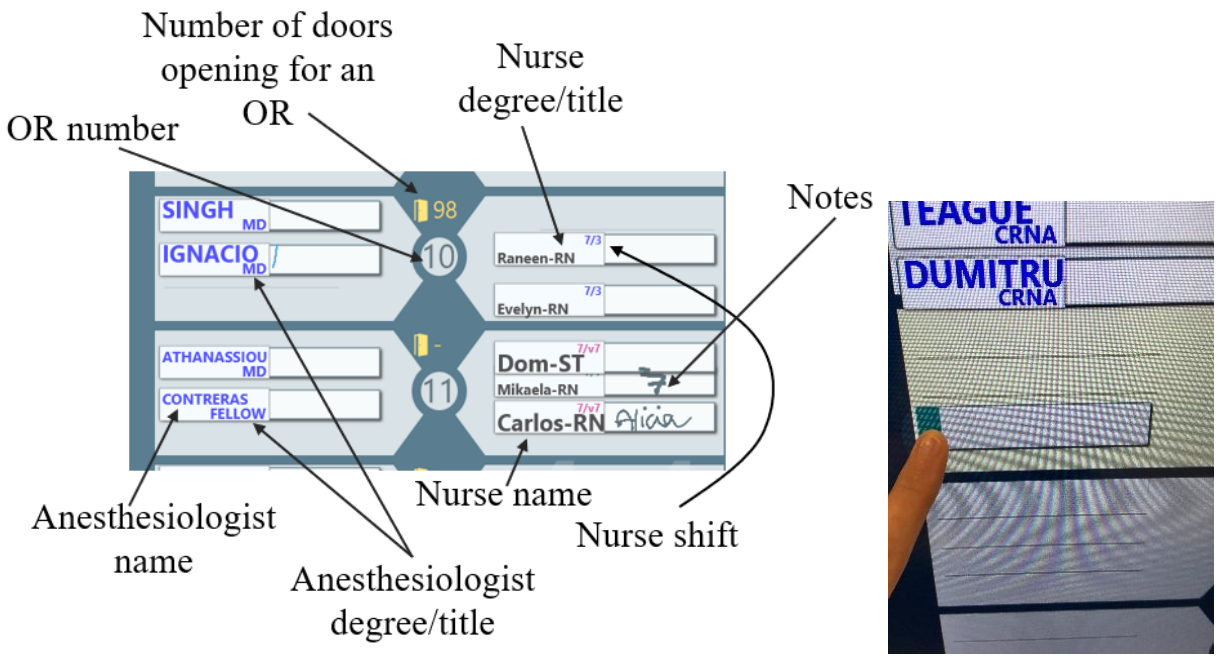


Figure 75. Staff magnets and assignments to ORs. Left image: In the left column is the anesthesia staff and in the right column is the nursing staff. Right image: New staff magnet.

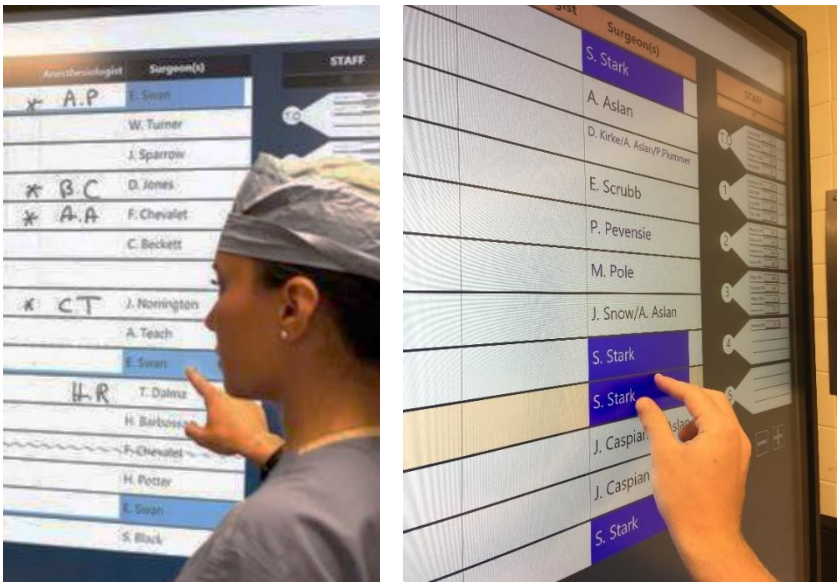


Figure 76. Surgeon occurrence feature.

6.6. Integration and Cyber-infrastructure *(supporting R1)*

This section details the necessary features that were implemented to prepare OnBoard for the deployment and its connection to the SmartORs.

6.6.1. Pre-editing and loading the surgical schedule

At the end of the day, the board runner prepares the schedule for the following day by filling up a set of preformatted spreadsheets containing the details of the elective cases (start time, OR number, patient name, procedure name, surgeon name), the details of the surgical staff (nurses and surgical technicians names, shift) and the details of the anesthesia staff (name and job-role). In the morning the following day, the board runner loads the schedule in OnBoard (IF17. Load schedule). Digitally prefilling the sequence of cases is an asset for board runners, as it prevents from the necessity to transcribe by handwriting the information already available in the hospital system, thus avoiding pain and potential mistakes. In the future, the hospital system might be able to directly fill OnBoard: however, it is not possible now for security and License Agreement-related reasons.

[R1: enrich]

6.6.2. Operating room real time state

The cyber-physical system comprises sensors in every OR to capture OR state in real-time: it detects if the patient is in the OR, if the anesthesia machine is on/off and the number of door openings during the procedure. The OR state information is displayed on the board through timelines (see Figure 77) (IF9. Mobile OR timeline). The timelines display: “Patient IN” – “Intubated” – “Extubated” and “Patient OUT” with “(time of event)”. This information is interesting for the staff: it allows them to anticipate and make decision based on accurate data. For instance, when sees that the patient is extubated, he/she can call post-operating room staff and announce that the patient is coming soon. This prevents from resorting to a displacement in the OR susceptible to nosocomial infection.

[R1: enrich; R3: teammates; R4: coord; P2: reify; P4: feedthrough]

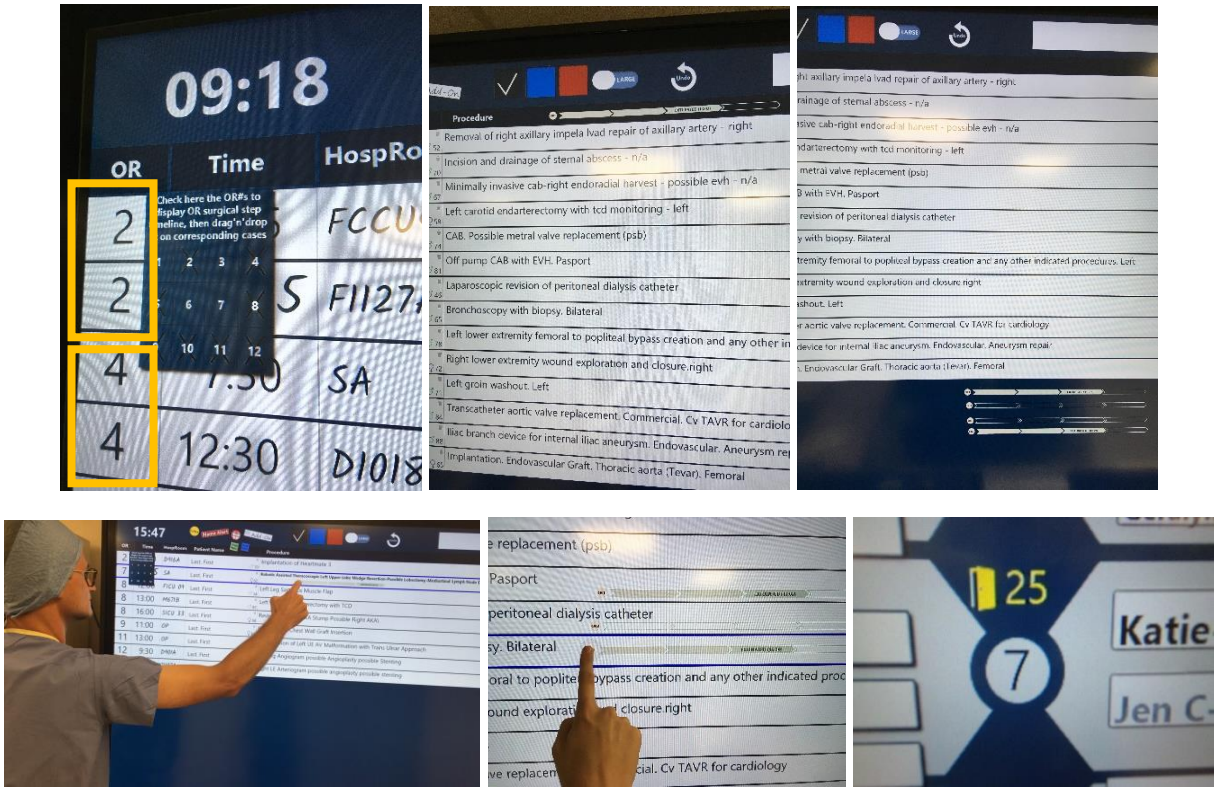


Figure 77. Real-time OR state timeline. Top-left: in the orange frame, the surgical cases that will be performed in the same OR but at different times – a press on the OR column opens a menu to choose which timelines the user wants to display. Top-middle and right: the timeline can be put anywhere in the interface. Bottom-left and middle: the timeline can be put on a surgical case, as the user knows which patient is in which OR. Bottom-right: Display of the number of door openings per OR.

Multiple cases on the board are supposed to occur in the same OR (obviously not at the same time) (see picture top left, in the orange frames, in Figure 77). However, the sensors are not able to decide which case is which, as the cases can be arbitrarily rescheduled and there is no patient tracking. Thus, we decided that the timeline be drag-and-droppable (see Figure 77): the board runner can manually attach the timeline to the case running in the OR. Such feature is an example of how interaction by an informed user might compensate from deficiencies of a partially-implemented or erroneous cyber system.

[R1: enrich; R3: teammates; R4: coord; P2: reify]

6.6.3. Doors openings

The CPS acquires in real time the number of times a door is opened for a procedure in an OR. OnBoard displays this information on the right part of the screen, where OR are represented with numbers (see Figure 77) (IF15. Number of times OR door is opened during a procedure). The number of doors openings is a measure of the infection risk, and we wanted to see if the visibility of this information together with that of the operation state would change staff habits.

[R1: enrich; R3: teammates; R4: coord; P2: reify; P4: feedthrough]

6.7. Mobile phone application *(supporting R4, P4)*

We designed and developed a mobile phone application to enable the staff to pick information from OnBoard when connecting with the phone and carry information about cases within the hospital (IF18. Phone app).

6.7.1. Engaging the staff with a Pinch & Drop interaction for remote collaboration

A comment coming from almost all the interviews, was that the users, independently from their job-role, was to be able to have access of the whole board on their phone. However, during interviews, while listening to what information they need to receive on the phone, we realized that the need is restrained most of the time to the handful of cases they are responsible for during the day (at the exception of the board runner who oversees all the cases).

We refrained from proposing too many interactions in the mobile app, as it might have hampered the use of OnBoard and have a negative impact on shared awareness. Additionally, patient information privacy is a critical concern in the hospital; sending all the information potentially to everyone is not secure. Therefore, we decided to develop the prototype in such a way that the only information to be added on the phone was the one chosen during the day by the users, through an interaction allowing a restrained selection of cases.

Figure 79 shows the layout of the application on the phone.

First, the user must press and hold on the green button on the mobile app. This button turns red if the connection with OnBoard is allowed. The user then performs a Pinch & Drop on the board (see Figure 78). Pinch & Drop is an interaction technique derived from pick-and-drop [142]. The idea

is to pinch a case strip from the board with two or three fingers and then to touch the screen of another device as if the object was dropped. The user then receives the case on the phone in his/her list of cases and becomes a “Follower” of the case in the system. Once a user is a Follower of the case, he/she can follow its updates in real-time by receiving notifications on the phone without being in front of the board anymore. A blue chip appears in the procedure title box of the surgical case and displays the number of followers. A user can see all the followers of a case by pressing on the blue chip (see Figure 80).

This interaction has some interesting properties for a use on the board. First, as with the pick-and-drop, the pinch movement reminds the physical action of pinching an object to take it away, so it fits in the concept of taking away a piece of information. Moreover, this is an interaction that is performed on OnBoard, creating mutual awareness about who is become follower of cases.

[R1: enrich; R3: teammates; R4: coord; P2: reify; P4: feedthrough]

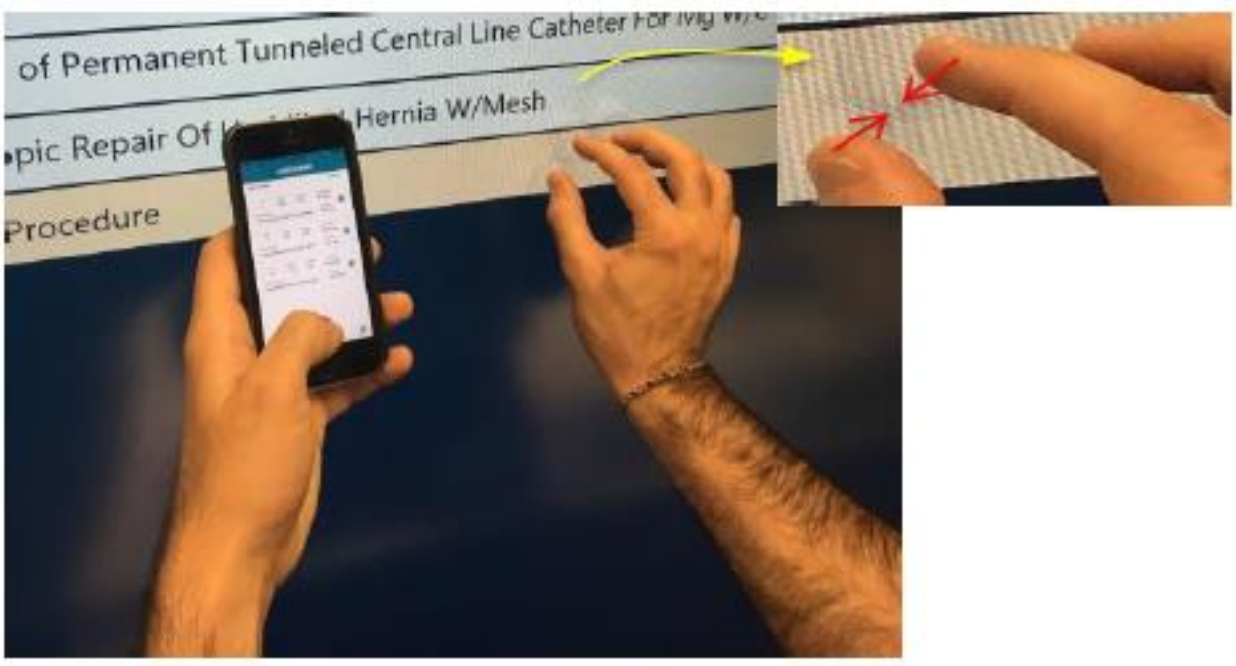


Figure 78. Pinch & Drop interaction.

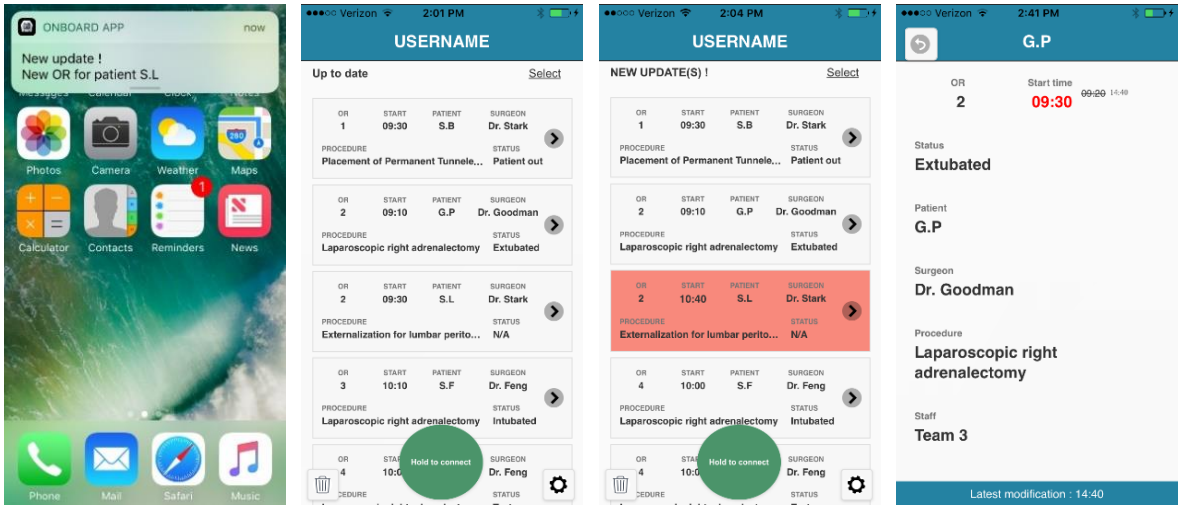


Figure 79. Several layouts of the phone app. This apps shows the cases the users subscribed too, plus the different updates and alerts.

6.7.2. Onboard and mobiles phones through meaningful push of information

New information on OnBoard (the main interface) triggers an update on the mobile app, and possibly an interruption of the activity of the mobile user. According to the content of a new information, the level of disturbance of the interruption should be different. We first added partial information in the notification to allow the user to better determine the level of priority of the update. We then decided that the board runner making the update on the board can decide the importance of his/her modification.

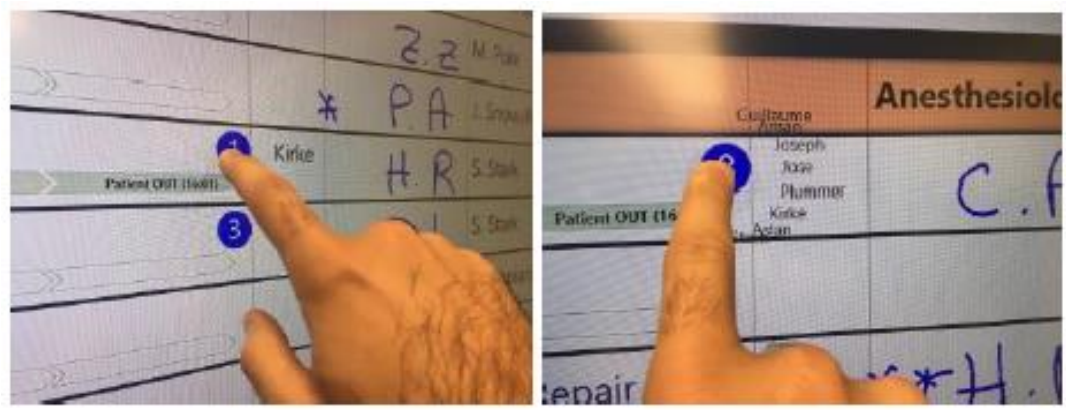


Figure 80. Followers visualization on the board when press and hold on the blue chip.

We defined two levels of priority of update: high or low. To turn his/her update to a low priority level of update or a high priority update, the user drags the strip to the right “pushing the information outside”. The corresponding notification is shown to the followers on their phones, according to the level of priority [160], from visual highlights to audio rings and vibrations (see Table 11).

Table 11. Levels of priority of the update and view on the mobile app and OnBoard.

Priority level	OnBoard interaction	Mobile app updates style
None		
Low		
High		 + ring + vibration

6.8. Safety and technology probe aspects *(supporting R1, TP2, TP3)*

Safety is a primary concern in critical settings such as hospitals and implies constraints on software reliability. As the information on the board is critical, it is not possible to afford a crash or a freeze. While we did not expect that the hospital management would fully replace the traditional whiteboard with OnBoard at once, we took special care to mitigate the robustness risk.

We tried to harden the interactions and code robustness, so that the board would not crash or stick in an unusable state even if misused. The OnBoard software automatically saves it state every 30s. In case of failure, the user can re-launch the application and load the last save. Furthermore, the application takes screenshots automatically every 30s and saved them on a shared drive on the network. This has several uses:

- Following remotely the use of OnBoard in real-time (Social Science goals of technology probes) and making sure the system is running correctly.
- Archive of the use of OnBoard for analysis on the long-term (idem).
- A safety function (IF19 Plan B)

The safety function consists in being able to quickly display the last visual state of the board if it shuts down unexpectedly and would not restart. We envisioned a system comprised of a printer connected to the shared drive, transparent sheets in the printer, and a connected button. The user would press the button, the system would grab the last screenshot from the shared drive, print it on the transparent sheet that the user would put on a traditional overhead projector on a cart. Thus, the last screenshot would be projected on the wall or a traditional whiteboard and would display vital information, or even enable board runners to write on top of it as they already do with the current system (see Figure 81).

The initial information on cases are input in an Excel file prior to the launch of the application. At the start of the application, the system loads this file and fill OnBoard. In this file, each line corresponds to a case. This file will be modified all day automatically through the application. When modifications are made to a case (for instance, the OR number was changed by a user), this file is updated. The file contains all the strokes drawn/erased on the board, per case. Therefore, one can know what was written on the board. As said before, if the software crashes or the computer, one could re-launch the software with the latest version of updates from this file. Even the order of strips on the board is recorded. The application records all user interactions.

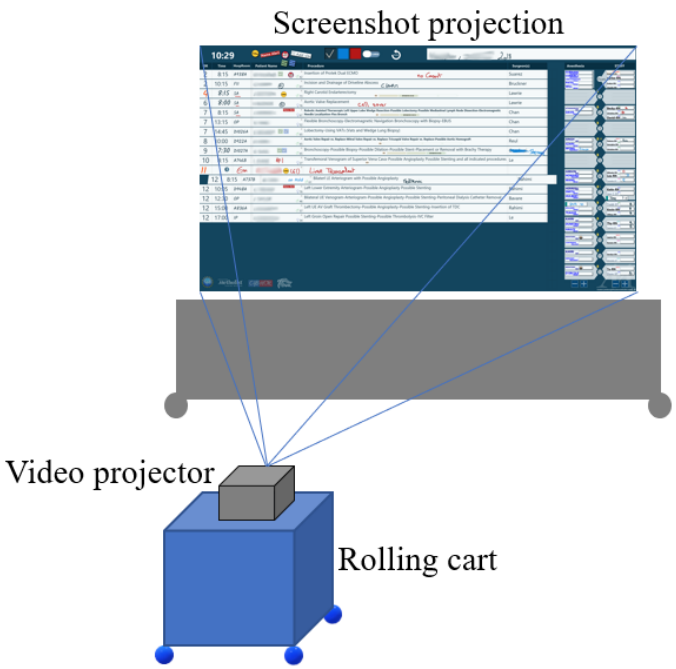


Figure 81. Plan B: a projector on a rolling cart displaying the last screenshot of OnBoard on a whiteboard sheet dropped-down from the top of OnBoard.

OR number	Start time	Status	Modified start time	Patient Name	Procedure
1	7:30	Not Starte	0:00	E. Swan	Laparoscopic Gastric Pacem
1	12:00	Not Starte	0:00	W. Turner	Appendectomy. Laparosco
1	13:00	Not Starte	0:00	J. Sparrow	Laparoscopic Partial Gastre
3	7:30	Not Starte	0:00	D. Jones	Transplantation Liver
5	7:30	patientEX	9:35	F. Chevalet	Appendectomy. Laparosco
5	13:00	Not Starte	0:00	C. Beckett	Laparoscopic Recurrent Rig
5	14:00	Not Starte	0:00	J. Norrington	Laparoscopic Repair Of Ver
6	7:30	Not Starte	0:00	A. Teach	Placement of Permanent T

Figure 82. Extract of the initialization excel file to be filed to launch the application. It contains the schedule of the surgeries of the day (start time, patient, surgeon, procedure etc.). These files can be either filled manually (what was deployed for tests), either filled automatically from the hospital system in future possible developments in collaboration with the hospital.

6.9. Usability inspection results *(TP2. Real-world)*

The robustness of interactions with OnBoard is critical for a deployment in the surgical suite at the usability level (*TP2. Real-world*). We summarize in this section the results of the usability inspection sessions that focused on how to prevent errors from the users while interacting with OnBoard, and how to recover from errors if any.

6.9.1.1. *Error prevention*

The purpose of these usability inspections was to anticipate the slips that users could make. The first one is inadvertently deleting an element. To delete a strip, we created a two-steps deletion system, requiring an additional effort from the users to reach a full deletion. For deleting a magnet, the swipe interaction is not as easy to perform. The second mistake is the wrong placement of a strip or magnet. Hence, we placed a visual indicator to help the users foresee where the element will be positioned if released. Another mistake is the wrong selection of a new time or OR number. We created many feedback on the status of the selection. For instance, the hand of the clock to choose a new start time follows the user finger to help indicate the selection. The interaction to delete a strip is complex and requires additional effort from the user to be performed, protecting the user from deleting a strip without having the intention to do so. Finally, we must prevent inaccurate handwritings. Therefore, we improved the look and feel of the writings to fit to the pen or finger tips to the closest.

6.9.1.2. *Error recovery*

The purpose of these usability inspections was to allow maximum flexibility by being able to "undo" a lot of actions. To recover from a wrong deletion of a strip, a user can "undo" this action and recover all former strips one by one. To recover from inputting a wrong time/OR number, the user can always change this data with the tools available. A wrong positioning of a strip can be fixed by easily changing its position and moving it up or down in the list. To undo wrong writings, a user can erase what he/she wrote. If the board runner forgot to input a patient the previous day, a new strip can always be edited. Finally, if the user forgot to input a staff, a new staff can always be edited.

6.10. Summary

To design OnBoard, we used UCD methods including participatory design and design walkthrough with a total of 12 surgical staff. We designed an environment of management of the surgical workflow on an 84 inches, 4K, multi touch surface, vertical, multi users. We designed 26 features for this environment, 19 were sent in the version for deployment.

More features and ideas were proposed by designers and staff than the 26 that were developed, as such a large surface and collaborative design environment really favors brainstorming and the generation of ideas. For instance, we considered using tokens, physical object that could be dropped on the screen, as additional means of interaction [119]. However, our system is vertical, and cannot use such tokens, unless gravity is compensated by a viscous system (static electricity or magnets).

OnBoard was design to be deployed in the surgical suite. Via the feedback of users, we could determine what features would be used by the variety of surgical staff, which is a very heterogeneous population and who has no will for learning complex interactions (the example of the writing recognition with user confirmation was a good one). As we will see in the next section, we realized anything with more than 2 fingers was immediately rejected with a comment "nobody will ever remember to do that", except the writing/erasing feature. We overall limited our interactions with direct manipulation and combinations of drag'n'drop, contextual menus, one and two fingers interactions and buttons. Writing/Erasing interactions are possible with two people simultaneously, which is the maximum number of people that can comfortably be up-close to the board at the same time. All other drag'n'drop interactions are multi users.

Our contributions are:

- The design and development of OnBoard, a large multitouch, multiusers, surface, designed for appropriation by the surgical staff.
- Specific interactions for surgical suite management: surgical cases representation and manipulation, alert magnets, staff magnets, OR state representation, doors openings representation, add of emergency cases in the scheduled flow, writing/erasing of notes about surgical cases, assisted filling of the whole board, logs of schedule modifications.
- A 2-fingers (or multiple shapes) erasing method, including a physical eraser device.

- A mobile app connected to OnBoard with a new pinch'n'drop interaction.
- Mobile OR state timelines, that can be dragged'n'dropped on surgical cases or elsewhere in the interface.
- Specific safety features: erasing with a continuous gesture, multiple feedback, case deletion undo, fallback projection system

OnBoard environment copies to some extend the traditional whiteboard by allowing the same type of object direct manipulation: free writings, erasing and magnets. It reifies existing concepts: whiteboard-like features, surgical case lines and staff magnets. These six imitations/reifications favor user appropriation of the technology. Each feature comprises a certain amount of micro interactions [150] with subtle feedback and error prevention.

We summarize OnBoard features and match them with design principles in Table 12. Table 13 summarizes how the design principles serve the requirements. The interaction features fulfill all the needs that are summarized in Table 9 and add new features.

Table 12. Summary of OnBoard interactions features (IF) and their match with our design principles. "Case" refers to "surgical case". In grey: the features that were not deployed for the clinical trials.

Design Principles → / **Interactions Features ↓**		**P1.** Multi-touch	**P2.** Reify	**P3.** Partial	**P4.** Feedthrough	**P5.** Robust
IF1	Surface & Space	x				x
IF2	Handwriting/Erasing	x		x	x	x
IF3	Cancel case	x	x	x	x	
IF4	Delete case + undo/redo	x	x		x	x
IF5	Arranging case layout	x	x	x	x	
IF6	Change OR number	x	x	x	x	
IF7	Change start time	x	x	x	x	
IF8	Handwritten style fonts		x		x	
IF9	Mobile OR timeline	x	x		x	x

IF10	Surgeon occurrence	x	x		x	
IF11	Notes area	x	x	x		
IF12	Magnets	x	x		x	
IF13	Add-ons	x	x		x	
IF14	Shift case	x	x	x	x	
IF15	Number of times OR door is opened during a procedure				x	
IF16	Staff Magnets	x	x		x	
IF17	Load schedule					x
IF18	Phone app		x		x	
IF19	Plan B					x
IF20	Board content saves					x
IF21	Security					x
IF22	Rewind		x			
IF23	External selector		x	x	x	
IF24	Patient tracking				x	
IF25	Camera inputs		x	x	x	
IF26	Case strip				x	

Table 13. Design Principles to serve Requirements.

Design Principles ↓	**Requirements ↓**					
	R1. Enriched surgical flow representation	**R2.** Multi-users and multi-roles	**R3.** Teammates' activity awareness	**R4.** Communication and Coordination	**R5.** Dynamic changes	**R6.** Work adaptation
P1. Multi-touch	X	X	X		X	
P2. Reify	X	X	X	X	X	
P3. Partial	X		X	X	X	X
P4. Feedthrough		X	X	X	X	X
P5. Robust					X	X
TP1. Design for appropriation, Open-ended, Co-adaptive	X	X	X	X	X	X
TP2. Real-world		X	X	X	X	X
TP3. Instrumented						X

7

DESIGN EVALUATION & DEPLOYMENT IN THE SURGICAL SUITE

This chapter reports on the results of the design evaluations and of the deployment. We detail the sessions of design walkthrough and the conditions of deployment of OnBoard in a real surgical suite of 12 ORs for 2 months. The SmartOR sensors were deployed in 6 ORs and connected to OnBoard during the deployment. The system ran through a total of 300 procedures.

7.1. Design walkthrough - Evaluations

We conducted four sets of design walkthrough sessions with 12 staff of DunnOR and OPC (see Table 4) to refine the features and the overall design. This included overall 5 board runners, 4 of them with a nurse background and 1 of them with a secretary background, 6 surgeons and 1 nurse.

We had full authorization to access the surgical suites of the hospital to observe and interview the staff, but we were strongly limited by legitimate restrictions with respect to testing in operational conditions of our prototype's versions, as the surgical suite is a critical environment and not a place to experiment all sorts of new systems. While we were waiting for authorization to install our full

system in the surgical suite when ready, we recreated simulated conditions close to the reality: a fake surgical suite corridor within the hospital, with surgical staff of DunnOR, OPC and other suites (see Table 4), As surgical staff are very busy and do not have much time to participate in the study, each session was designed to fit within 30min.

We performed design walkthrough sessions with 12 surgical staff (see Table 4), with 13 separate sessions (see Table 14). These design walkthroughs were performed on prototype versions of OnBoard. We present hereafter the different walkthrough sessions and their impact.

Table 14. Participation of staff to design walkthrough sessions (see Table 4).

Design walkthrough session	Participants	Session focused on OnBoard design only	Session focused on the mobile phone app design in connection with OnBoard	Session includes groupware	Prototype version
Session 1	BR1, BR3	x			V1
Session 2	BR2	x			V1
Session 3	S2	x			V1
Session 4	S6	x			V1
Session 5	S7	x			V1
Session 6	BR1, BR3	x			V1.5
Session 7	BR2		x		V2
Session 8	S8		x		V2
Session 9	S9		x		V2
Session 10	S2		x		V2
Session 11	S3		x		V2
Session 12	BR2, N1		x	x	V2
Session 13	BR4, BR5		x	x	V2

We present hereafter the different walkthrough sessions and their impact.

7.1.1. Part 1 – Design walkthrough on OnBoard only, on version 1 of the prototype

Version 1 of OnBoard was designed as a technology probe, and as such it contained very few features (see Figure 83): write, erase, add and move cases up and down on a background. The hardware used was a Sharp HD 64" infrared touchscreen. We did an analysis of this first prototype to evaluate what should be implemented next, and how the users were reacting towards this electronic whiteboard compared to the traditional whiteboard.

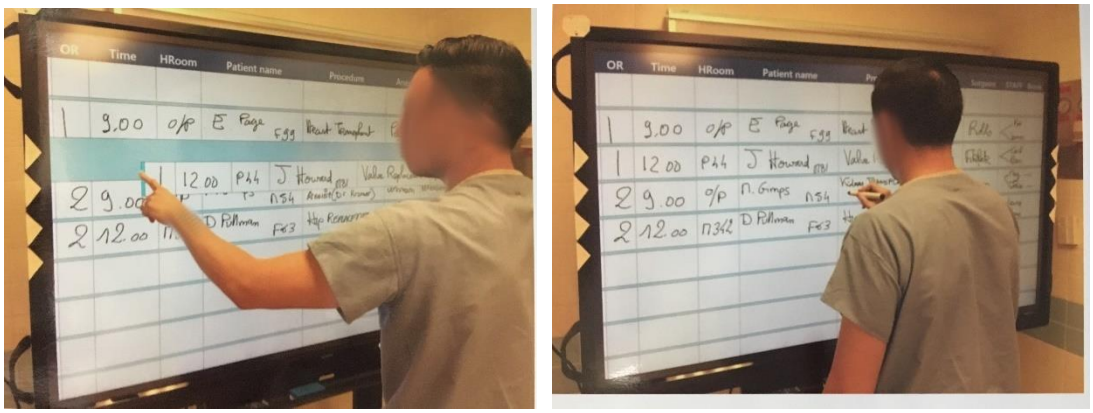


Figure 83. Design walkthrough with a surgeon on prototype v1 of OnBoard.

During the very first sessions 1 to 5, we asked the staff (n=6) to perform 9 relevant tasks (see Table 15) representing daily activities they do on the whiteboard. They were briefly introduced (2min) to the few features of the prototype.

For each of these scenarios, we recorded:

- The success or failure of the performance of the task (effectiveness).
- The way the user performed the task.
- User's satisfaction by asking to answer, "How difficult was the task?" on a scale from 1 to 5 (satisfaction). We recorded free comments from users and questions asked during and after the task (see example of evaluation sheet in Figure 84).
- The time to perform the task (efficiency).

Table 15. Summary of tasks along which ones we performed design walkthrough of OnBoard prototype version 1.

Task	**Description** (Context: the user is in front of OnBoard, already launched, displaying the schedule of the day)
1	Insert in the board the case that is written on this document.
2	Modify the staff for this operating room.
3	Signify on the board that the case that was in OR2 is over.
4	Inform other staff of the date of edition of this schedule and that there are 10 cases for this day.
5	Signify on the board that the patient in OR1 is allergic to latex.
6	Inform the surgical suite that the case in OR3 has started.
7	Signify on the board that the patient programmed for OR4 has been "sent for".
8	Edit the case to signify the progression of the surgical case status.
9	Signify that two patients have similar names.

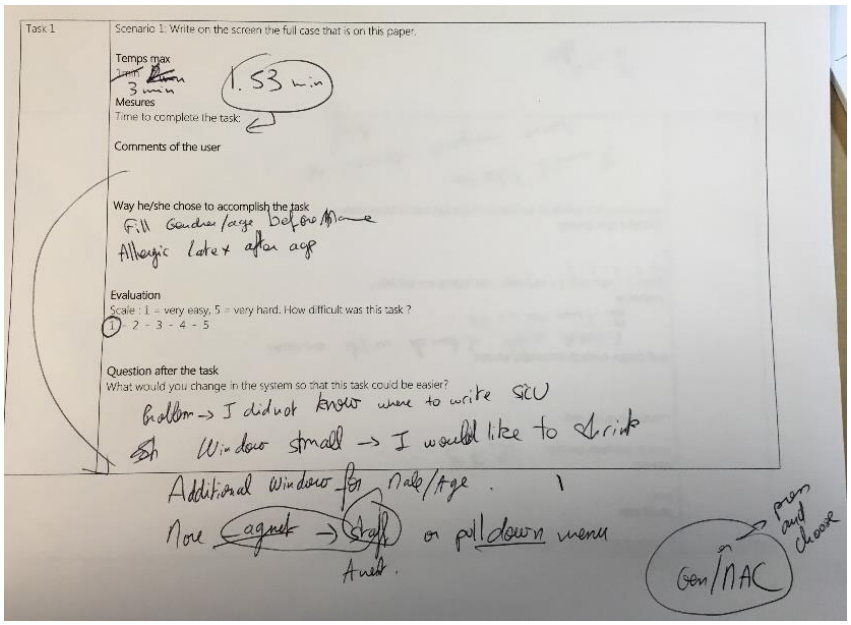


Figure 84. Evaluation sheet during design walkthrough.

The difficulty for each task was on average assessed to 1.7 out of 5 (1 being very easy and 5 being very hard). 92% of the time, participants were able to perform the tasks. Each task received on average 1.7 propositions of change.

These sessions resulted in numerous direct exchanges. The discussions allowed us to see the problems of the prototype and have further discussions about how to improve the design of the electronic whiteboard. For instance, we realized that the process of preparing the board with all the surgical cases for the next day could be automatized or done on a personal computer, as it is a work done by one person only. The idea of having magnets were proposed as some staff saw it in other surgical suites. Many objects were displayed too small.

7.1.2. Part 2 – Design walkthrough on OnBoard only as a team and System Usability Scale (SUS) questionnaire, on version 1.5 of the prototype

On version 1.5, we added to the baseline of version 1 some additional features to be tested: magnets, possibilities to change writing colors, a separated section for staff management, time display, more free notes space, cancelation, automatic surgical timeline information and an undo feature.

During session 6, we asked the staff (n=2, board runners) to perform 10 relevant tasks as a team (see Table 15) representing daily activities they perform on the whiteboard. These tasks were similar to the ones asked during Part 1, with variations due to the need to walk through the new features with the staff.

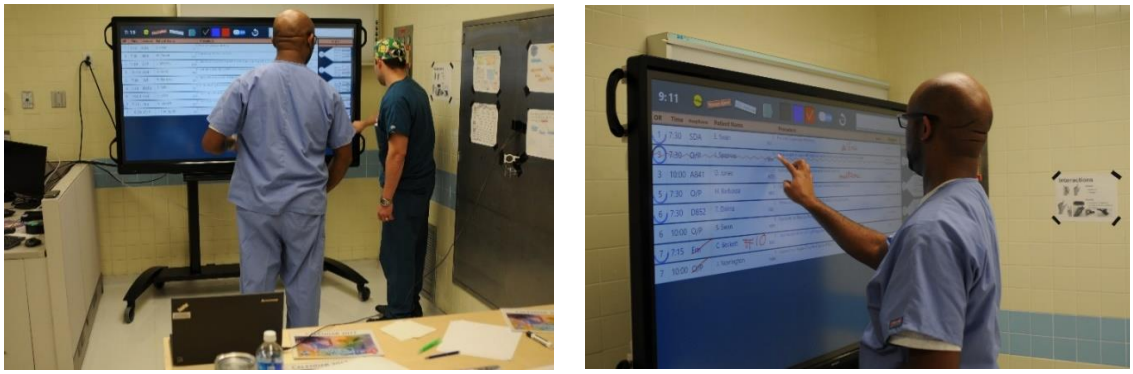


Figure 85. Design walkthrough with two board runners on prototype v1.5 of OnBoard.

Table 16. Summary of tasks along which ones we performed design walkthrough of OnBoard prototype version 1.5.

Task	**Description** (Context: the user is in front of OnBoard, already launched, displaying the schedule of the day, without the staff information)
1	Assignment of surgical staff to all the cases.
2	Signify that Patient Beckett has arrived in PreOp, Bed #10
3	Staff Loya is leaving. Reorganize staff.
4	Signify that Case #2 in OR1 is canceled.
5	Arrival of 2 new staff to replace staff Penny and staff Emma.
6	What equipment is required for Dr Snow for his patient Swan's procedure?
7	Phone call: Question – What is the status of the surgery of Dr Stark, patient Beckett?
8	Staff of OR3 left to take a break.
9	Read, insert and schedule an add-on case from a paper document.
10	Signify that the case of Dr Scrubb, patient Jones, is NOT canceled anymore – still operate at 10:00.

As the staff participated in Part 1, they were already familiar with the technology. We added 2min of additional explanations for the new features. The participants had a background task to perform (answering a Christmas quiz with growing difficulty) to stay busy while asked to perform the tasks. They were asked to perform the 10 tasks, and at the end to answer a System Usability Scale (SUS) questionnaire about their experience.

The participants used 100% of the features of OnBoard to perform the tasks, with a success ratio of 95%. The SUS questionnaire resulted in a score of 80 (a SUS score >68 is considered "above average" [2])

This session allowed us to verify the usability of the new features, and how to improve them. For instance, the writing/erasing started to be slow when there were a lot of writings on the board. We realized that the hardware chosen was not optimum: the screen was too small to display enough surgical cases in a real surgical suite and the infrared touch technology was inadequate as the touch detection would be too inaccurate for writing activities.

7.1.3. Part 3 – Design walkthrough on usability with a smartphone app connected to OnBoard, on version 2 of the prototype

We used an individual design walkthrough method [131] to evaluate the interaction between OnBoard and the mobile phone app and how a single staff deal with these tools. During the sessions 7 to 11 we asked the staff (5 persons, independently from each other's) to perform 8 tasks on the smartphone app (see Table 17). For these sessions, the prototype is version 2, and was deployed on a larger screen (an 84" versus 64" for the initial prototypes see Figure 87) to match the size of a traditional whiteboard in used in the hospital and offer as much space as possible to write comfortably. This version offers additional features compared to the former version: it comprises all the smartphone app related features. It comprises interaction feedback improvements such as animations of moving items and fading of deleted items.

We were using a Wizard of Oz technique to simulate the connection between OnBoard and the smartphone app. OnBoard would play the animation of pinch'n'drop when the user pinched a case to drop it on his/her phone (see Task 3 in Table 17). The feedback of success of the interaction was given to the user but was not sent to the phone. To simulate the arrival of data on the phone, we connected the phone to an online server on which we could change the data from another computer. The phone would receive the notification of change with the new data when activated.

Table 17. Summary of tasks along which ones we performed single user design walkthrough of the smartphone app prototype.

Task	Description
1	*Context*: The app is in foreground. *Question*: Let's say the user is Mr. Stark, a surgeon. He must perform a surgery in OR2 at 10:40am, so he subscribed to the case just before him in OR2. Tell what the current status of the case before his case is.
2	*Context*: The app is in foreground. *Question*: Tell the patient's initial of your patient of 10:40.
3	*Context*: The app is in foreground. *Question*: Tell the full procedure of the surgery of 09:20 (the full procedure is too long and visible only on the detailed view or on landscape mode).
4	*Context*: The app is in foreground. *Question*: Tell if the start time of the surgery of 09:20 has ever been modified, and if yes when the last modification was.
5	*Context*: Ask the user to come back on the main page and to check his email on the phone. The app is in foreground, arrival of a new update with a level of priority "+". *Question*: which value has been modified and what was the previous value?

6	*Context*: The user goes in front of OnBoard with his/her smartphone app. *Question*: Pick up a case you want from OnBoard to get it on your phone.
7	*Context*: The app is in foreground, arrival of a new update with a level of priority "–". *Question*: which value has been modified and what was the previous value?
8	*Context*: The app is in foreground. *Question*: Delete the case of Dr. Feng from OnBoard.

For each of these scenarios, we recorded:

- The success or failure of the performance of the task (effectiveness).
- The way the user performed the task.
- User's satisfaction by asking "How difficult was the task?" with an answer on a scale from 1 to 5 (satisfaction). We recorded free comments from users and questions asked during and after the task (see example of evaluation sheet in Figure 86. Individual design walkthrough record sheet example.).
- The time to perform the task (efficiency).

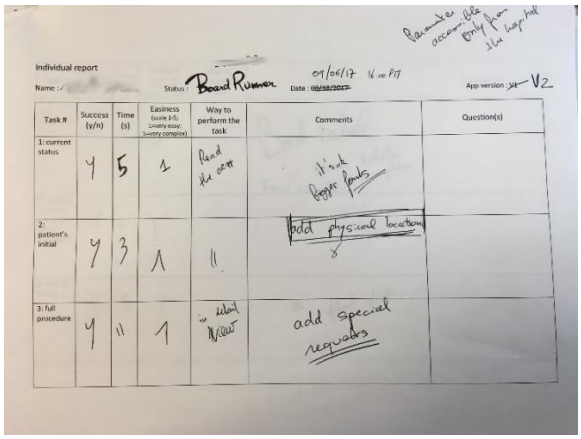


Figure 86. Individual design walkthrough record sheet example.

The difficulty for each task was on average assessed to 1.6 out of 5 (1 being very easy and 5 being very hard). 86% of the time, participants were able to perform the tasks. Each task received on average 0.7 proposition of change in the comments. The average time to perform a task was 9 sec.

These sessions included an ideation seance at the end of each one, with propositions from the users to improve the app. For instance, increasing the size of all writings in the app was demanded by every staff. The staff reported that the pinch and drop interaction was very difficult to perform,

and most of them failed at first try. Some users reported that with more training, they would have better performance with the pinch'n'drop interaction, but others stated that this interaction would never work in the surgical suite and that nobody would learn or remember it. A staff did appreciate the difficulty/novelty of the interaction, it made him feel that "only trained people could know about this feature and therefore use it, it is like a protection".

After the design walkthrough that was more focused on the phone app, the users commented on the new version of OnBoard itself. The request for a larger size was supported by all users, who felt that now OnBoard could be a real candidate to support the surgical flow.

7.1.4. Part 4 – Groupware design walkthrough on usability with a smartphone app connected to OnBoard, on version 2 of the prototype

We used a groupware walkthrough method [129] to evaluate the interaction between OnBoard and the mobile phone app, and how to deal with those tools as a team.

7.1.4.1. *Participants*

The minimum setup of participants consists in a Board Runner (BR) and a Nurse working in the same surgical suite. We went through two runs: the first one (1h) with a BR and a Nurse, playing respectfully their job-roles, the second one (2h) with two BR – one playing the role of a BR and the other the role of a Nurse.

7.1.4.2. *Experimental design*

The experimental setup consisted of a control room and a family room. Before starting the experiment, the exercise was presented to the participants for a couple of minutes, with a 5min training on OnBoard and the smartphone app. The evaluation consisted in the sessions 12 and 13 (see Table 14) where we asked the staff (4 persons, see Table 14) to walk through the 5 tasks (see Table 18) to collect feedback from the users. Two runs of evaluation with the two different teams are reported here.

For each task, we recorded (see example Figure 88):

- Time
- How it was carried out
- Problems if any. After elicitation, we told participants to assume the problems were fixed, and told them to resume.

We stopped after each task and ask the following questions:

- *Effectiveness*: does the interface provide the means to perform correctly the task?
- *Efficiency*: would the group make the effort required to perform the task?
- *Satisfaction*: would the group be motivated to do this task? Would they be satisfied with the outcomes?

Figure 87. On the right, surgical staff during a groupware walkthrough. These pictures allow comparing the size of the prototype v1 of OnBoard (right, 64") with the version 2 (left, 84"). Users had no hesitation saying they preferred the bigger one.

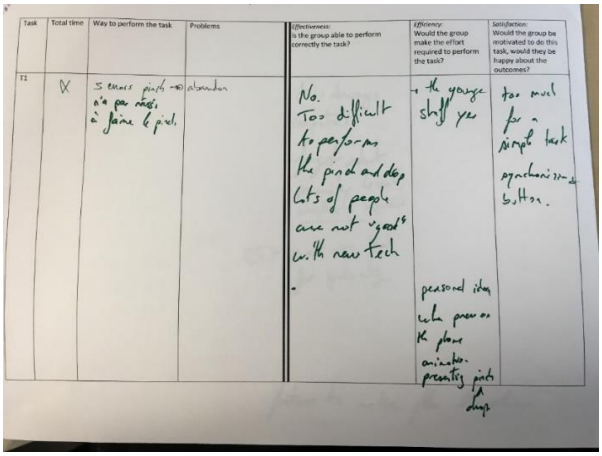


Figure 88. Groupware design walkthrough record sheet example.

At the end of both sessions, the participants stayed to brainstorm on the system, proposed ideas and exposed other problems. Even after improving the pinch'n'drop feedback and animations,

some users still felt uncomfortable with the interaction. They proposed other types of interaction to replace it such as checkboxes to select the cases one would like to follow on their phones.

Table 18. Summary of tasks along which ones we performed groupware walkthrough of the smartphone app prototype.

Task	Description Task	Description Subtasks
T1	Pinch and Drop a case.	Subtask ST1.1: Get close to the board, open the mobile app then press and hold green button.
		Subtask ST1.2: Perform the pinch and drop action on a case on the board. Release green button after.
		Subtask ST1.3: Verify that the right case was transferred to the mobile phone app.
		Subtask ST1.4: User leaves the room.
		Subtask ST1.5: User talks to the family of a patient about report on a surgery.
T2	Modification of the same case.	Subtask ST2.1: user comes to the board and modifies the OR number on the same case (between 1 and 9).
		Subtask ST2.2: Change the level of priority of changes to “high”.
		Subtask ST2.3: user checks who is following the cases.
T3	Update notification on mobile phone app.	Subtask ST3.1: user realizes when he/she received a notification
		Subtask ST3.2: user decides whether/when he/she can interrupt current task.
		Subtask ST3.3: user visualizes content of the notification
T4	Check if the follower saw the modification.	
T5	Discussion about the board runner decision.	Subtask ST5.1 – individual: user comes back to the board
		Subtask ST5.2 – collaborative: user waits for BR to be available to discuss
		Subtask ST5.3 – collaborative: user and BR discuss whether the modification should be modified or kept

7.1.4.3. *Results*

The main remaining issues concerned the interaction between OnBoard and the smartphone app: performing the Pinch & Drop is complex. Some people think it is usable and others do not (*T1*). The action is simple but according to the hand and finger size, the strip would need to be much bigger, which is problematic because we want to display a lot of strips on the board. Some participants feel that this interaction is fun but too complicated compared to the purpose of the task and that nobody would remember. A nurse said: "only the young nurses might make the effort", indeed this person made 3 attempts before succeeding in performing the Pinch & Drop. However, other participants who achieved the interaction said: "the fact that it is a little complex would prevent undesired people to transfer cases on their phone".

The concept of determining on the board the importance of a modification and therefore the level of priority was much appreciated. Shifting the strip to the right seems complex for certain participants: "why do we do something so complicated again?" (*T2*, see Table 18. Summary of tasks along which ones we performed groupware walkthrough of the smartphone app prototype.). Other participants enjoyed the fact that even on the board itself one can see that the case received a special notification is useful: "It is great that from the monitoring area we can remember that the notification was sent with a special level of priority".

Working through these problems and brainstorming with the participants, we could determine some redesigns:

- Communication: As the participants understood that for the next prototypes there would be the possibility to share a whole strip, including manual writings on it, they immediately thought that they could write on it a question to each other and the response "Oh so whatever I write on the strip would be sent out to the phones? I could write *I need the Surgeon to identify the patient NOW*? This is perfect". This comment (*T3*), combined with the desire that we recorded during early interviews and participatory design with other surgical staff, confirms that our method encouraged users to be inventive and allowed us to observe the flexibility of OnBoard to activity needs (*R6*. *Work adaptation*).
- Team awareness: The participants pointed out that they would love to be able to push cases to other users' phones app (*T1*). "In case they forgot it" or "to help". The owner of the mobile phone would thus not be the only person responsible for his/her awareness: other people may help.

- Security of access: Some participants were worried (T5) that the easiness of moving strips up and down and change OR number is “too easy to perform” and that therefore some staff could be tempted to make modification without the approval of the BR. We therefore thought about a way to unlock the board with the staff badges to allow inputs on the board to people with authorization.
- Stop the Line: An important scenario never mentioned before, appeared when the participants were thinking about the mobile phone ringing/vibrating to notify them of a change. Sometimes the BR or a Nurse needs to “Stop the line” (called “Hold on”). It means that something is unclear for a patient and the staff must stop the process and fix the problem. For instance, there are many times where the patient is brought to a room whereas someone knowing that the room is not available yet could have stopped it before the patient is brought in front of the room. All the participants agreed on the fact that shifting the strip to the right makes it “stand out” from the rest of the strips (*T2)* and shows that “This case is not in the normal flow anymore” (*T2*). This feature might fit the “Stop the line” scenario.
- Connect to other boards: Some participants mentioned that there should be a way to connect the boards of the different surgical suites, as they sometimes exchange staff/patients. Connecting the different surgical suites better would improve the management of resources of the hospital. The smartphone application is considered a welcomed expansion.

7.2. Deployment

Even with full authorization to access the surgical suites of the hospital to observe and interview the staff, we were of course (and as it should be) strongly restricted in the deployment by the fact the surgical suite environment is critical and had to be at no time an obstacle to the operations of the surgical suite and patient care. This notably slowed us down a lot for testing in real settings our prototype, but we were able to install the system 2 years and 5 months after the beginning of the project, in 12 ORs, for 2 months. The system ran through a total of 300 procedures [136].

This section describes the condition of deployment of OnBoard in the surgical suite FondrenOR (see Table 4). Figure 90, Figure 91, Figure 92 and Figure 93 illustrate the use of OnBoard during its deployment in the surgical suite.

7.2.1. Linking OnBoard with SmartORs on the hospital network

The schema in Figure 89 describes how we integrate OnBoard within the cyber-physical system. OnBoard is linked to the sensors of the cyber physical system installed in every OR the hospital network, communicating by text files in a shared drive.

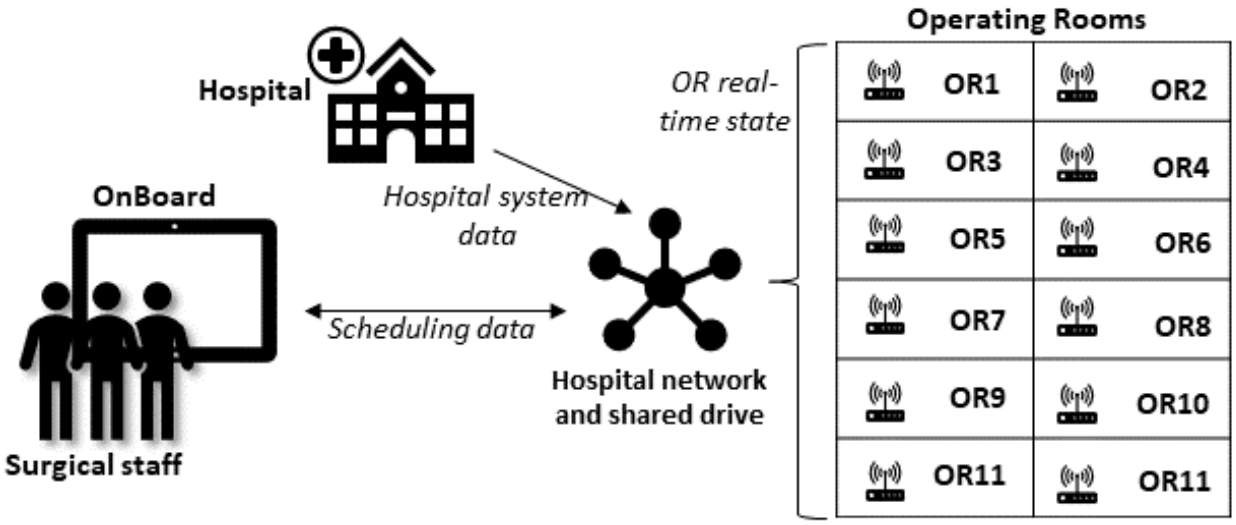


Figure 89. Architecture of the system comprising the SmartORs and OnBoard.

This shared drive is hosted on the hospital network. The sensors (SmartOR sensors) are driven by RaspberryPis that are on the hospital network. The sensor data analysis (signal and image processing) is made on a computer that then sends, still on the hospital network, the updates to the text files on the shared drive. The OnBoard application constantly watches these text files and when a modification is made, OnBoard updates itself with the new content. The text files can seem a primitive way of storing data. However, this solution allowed us to create a very flexible data storage and data sharing system that can be modified easily manually by even a novice. These files are used for the initial loading of the day surgical cases, and for the sensors' updates. On the other hand, we use these files to save logs of the use of the system such as writings coordinates, modifications of schedules etc.

All communications are performed via this shared drive, nothing goes on the cloud or out of the hospital network. Therefore, we overcome the problem of cybersecurity with this system. For many computer systems that host data on the cloud, it is very challenging to integrate with hospital systems if they manipulate Protected Health Information (PHI), they must comply with regulation

such as the Health Insurance Portability and Accountability Act (HIPAA). This act sets the standard for private patient data protection. Such systems must have physical, network, and process security measures in place and follow them to ensure the compliance.

7.2.2. Participants

The surgical team of FondrenOR comprises 124 persons: average of 10 surgeons per day, 15 anesthesiologists., 2 board runners (BR), 40 nurses, 14 surgical technicians (ST), 10 perioperative nursing assistant (PNA), 12 anesthesia technicians (AT), 21 certified registered nurse anesthetists (CRNA) and (+2 high school interns at the end of the study).

Among them the 2 anesthesiologists, 2 BR, 2 nurses (including a BR) were deeply involved in the study. The 2 BR volunteered to use OnBoard and encourage others to do so. The 2 anesthesiologists provided feedback on the use of the board by the anesthesia staff.

Figure 90. (Left) Two nurses are discussing the schedule a nurses assignement's using OnBoard as a support to the discussion. (Right) the traditional whiteboards that kept being used in parallel of OnBoard.

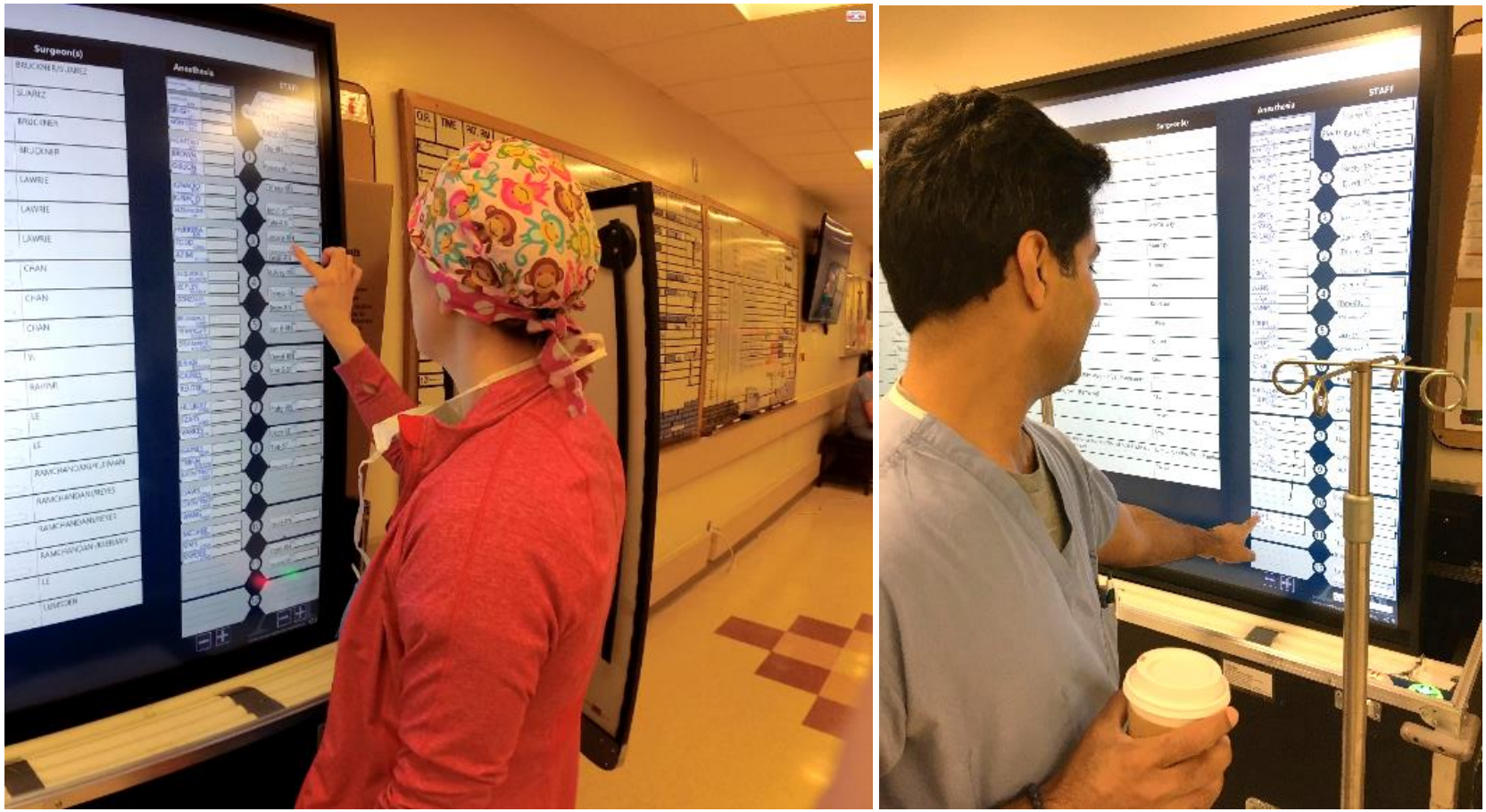


Figure 91. (Left) Charge nurse re-arranging the nurses' assignments on OnBoard during the deployment at the surgical suite. (Right) Anesthesiologist chief re-assigning the anesthesia staff to ORs.

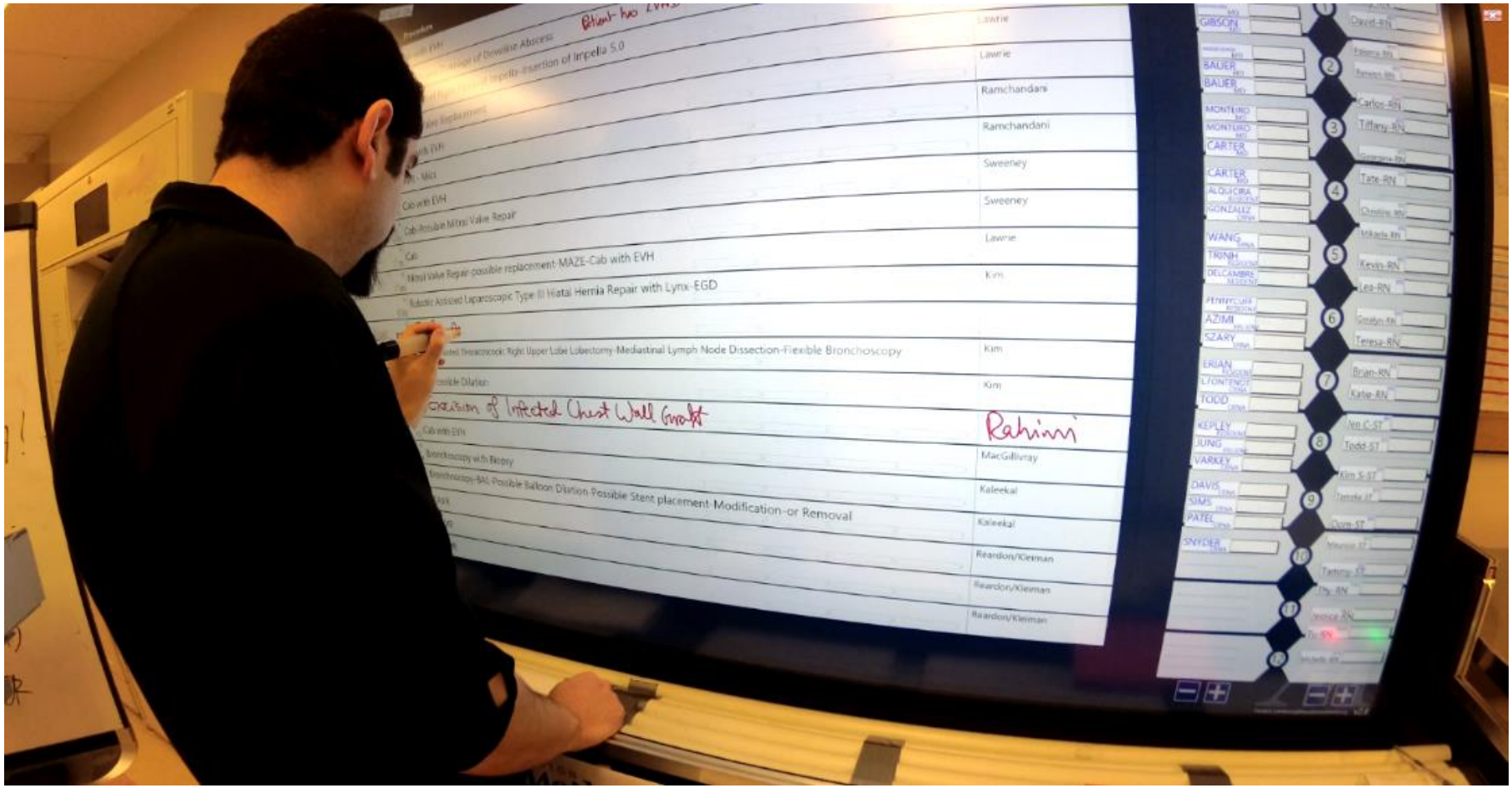


Figure 92. Board runner adding an emergency case on OnBoard during the deployment.

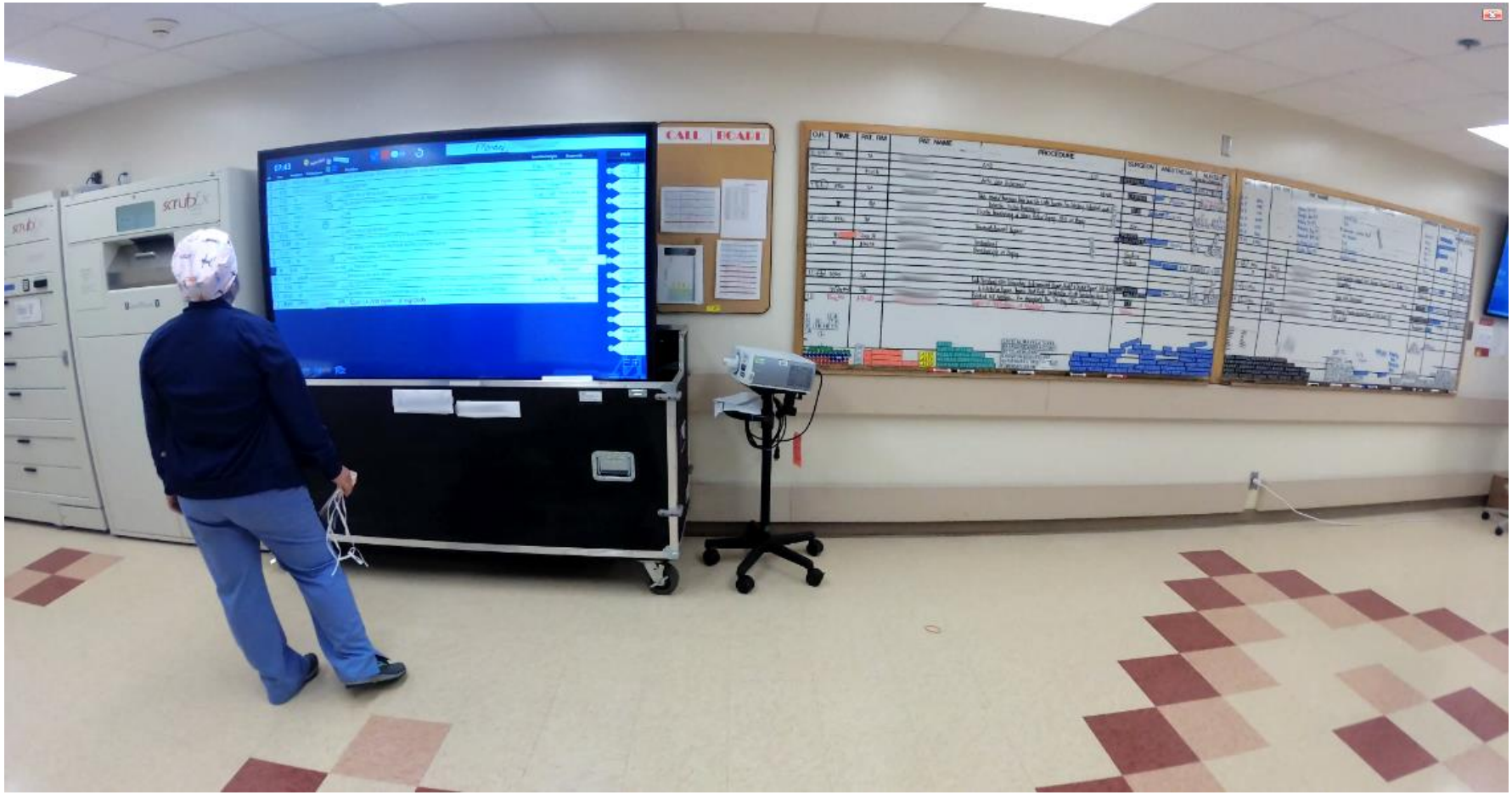


Figure 93. A nurse looking at information concerning the start time of a surgical procedure during OnBoard deployment.

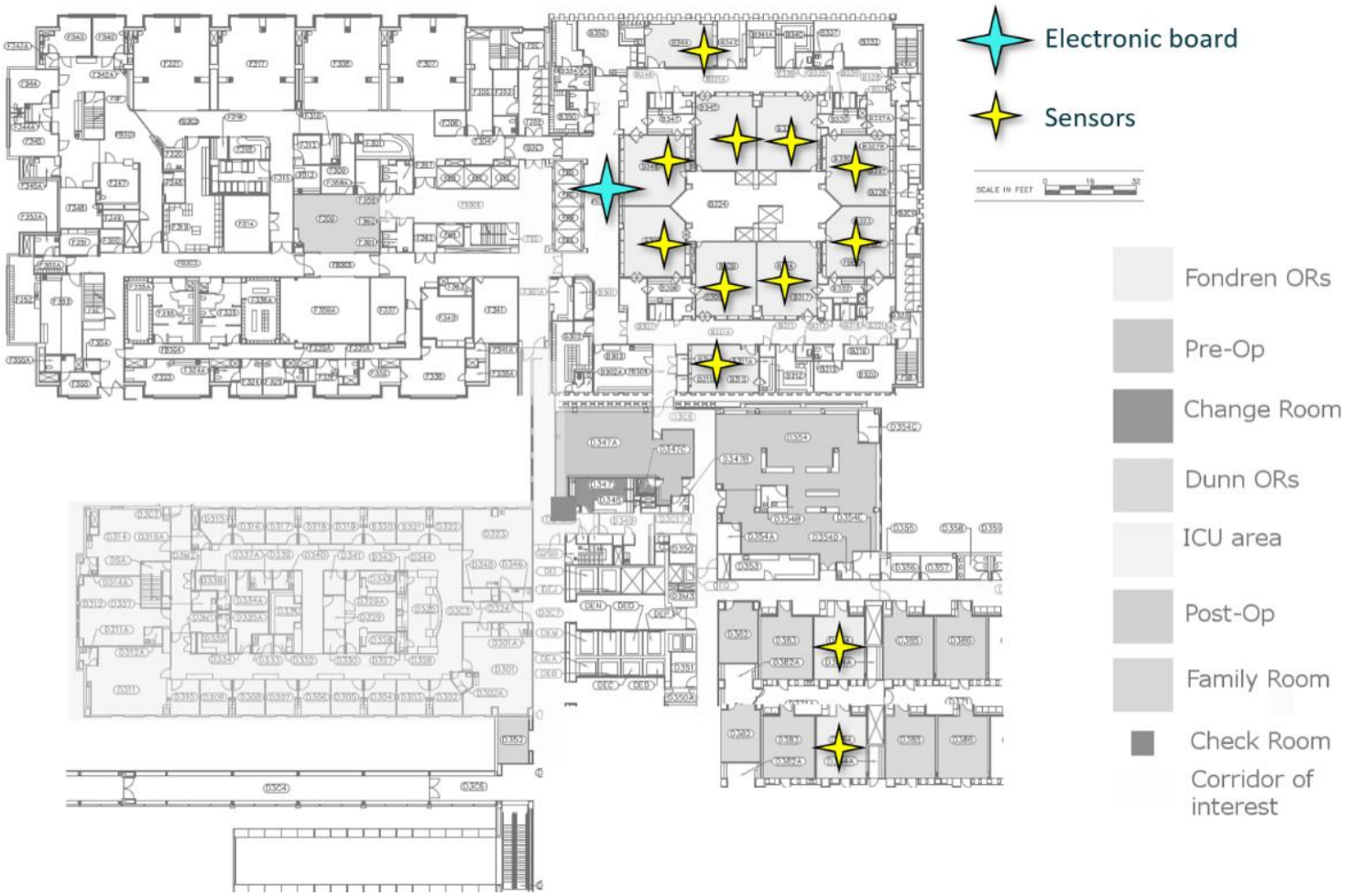


Figure 94. FondrenOR map and the placement of the OR sensors and OnBoard (Electronic Board.

7.2.3. Equipment & setting

We deployed OnBoard in FondrenOR and the activity sensors in the 12 ORs of the surgical suite FondrenOR (see Figure 90, Figure 91, Figure 92, Figure 93and Figure 94).

OnBoard was installed in FondrenOR right next to the whiteboards, in the corridor (see Figure 94). OnBoard is running on an 84" 60Hz multitouch 4K display, on a computer installed on a cart, connected to the intranet network of the hospital. Every users' input on OnBoard was recorded in a CSV file on a shared drive of the hospital network as soon as the input was performed. In addition, OnBoard took and stored screenshots of itself every 30s for further analysis. The sensors systems were installed in the 12 ORs of FondrenOR prior to the study. The communication between OnBoard and the sensors systems were made via csv files on the shared drive located on the hospital network. OnBoard was watching the CSV files and reloaded them whenever the sensors modified them.

The software version of OnBoard deployed for testing did not comprise all the features developed. We kept it as simple as possible to favor a quick appropriation in the clinic. The following features ***not*** deployed for clinical testing:

- Writing recognition of the OR number.
- Mobile application.

7.2.4. Training

The main users (2 BR and 2 other nurses) quickly tested and formally trained on the last OnBoard version during 10min prior to the installation.

7.2.5. Procedure

The Board Runners were asked to make updates first on the whiteboards and then on OnBoard for safety reasons. We are aware that this represents supplemental work for the boardrunner, that the traditionnal whiteboards would "compete" with OnBoard, and that it would bias the experiment. However, we were not allowed to replace the traditionnal whiteboards.

OnBoard was used mostly from 7.00am to 3.00pm (time during the involved BRs were working), Tuesdays through Thursdays and occasionally Mondays/Fridays/Week-ends. OnBoard was mostly used between 7.00am and 12.00pm as mornings are typically busier than afternoons.

A member of the research team was present the first two weeks every morning from 7.00am to 11.30am and often during an hour at around 2.00pm, at the time of the afternoon shift. She was also present twice a day during the rest of the study, from 9.00am to 10.00am and from 2.00pm to 3.00pm. She updated OnBoard during the deployment to improve its usability or robustness. Most of the software updates were made in the evening when the surgical suite was less busy. She would also answer occasional questions about OnBoard to curious members of the surgical team that were not directly involved with its use.

7.2.6. Data collection means

During the study, we collected various data, including videos/photos (that were subject to patient privacy restrictions), observations, and interviews in the surgical suite when the staff had time, questionnaires and logs.

We used the technology probe method to get inspiration, create new features or better understand the surgical flow needs. Many features and ideas came from talking with the surgical staff in their environment, in front of OnBoard. The fact that OnBoard was physically in the surgical suite changed the users' way of seeing it and they started to have much more ideas of features than during the participatory design sessions with the first team in the laboratory.

7.2.7. Results

We present here the results of the deployment of OnBoard in FondrenOR surgical suite.

7.2.7.1. *Different teams*

The participatory design of OnBoard was performed with surgical teams (DunnOR and some staff from a third surgical suite), which are different from the surgical team that used the board during the study (FondrenOR). Even if they share the same goals and concern, every surgical suite has its own culture and specificities. Nevertheless, the first design allowed the FondrenOR team to perform most of their daily activities with only minor customizations due to a slightly different way of managing anesthesia and staff. The rest of the interface was satisfying to the FondrenOR team, which allowed us to deploy the system at their facility to run the study. This suggests that OnBoard is not too specific to an OR suite.

We also ran training sessions with nurses. They consisted in a 10min session in a laboratory environment and a 30min class with all the nurses. The nurses were able to perform most of the

interactions. Furthermore, the main users did not report difficulties to perform the interactions during the study. This suggests that OnBoard interactions are not too difficult to learn and to perform.

7.2.7.2. *Successful management of surgical cases*

OnBoard enabled the staff to visualize updates and make the necessary case modifications. The BR were able to load up to 21 cases per day on the electronic board during the 2 months of study in the surgical suite. Users provided comments such as "Easy to use, clear information" (Board Runners), or "The board gives the ability to have a better visual work flow assessment" (Anesthesia staff). A nurse also commented "I love this electronic board because I love our whiteboard, and it is a good compromised between what we already use and the hospital system".

However, a single OnBoard can display 21 cases only for one day: if there are more cases, the supplemental ones are hidden until there is room again. There were a few days when the board runner had to load 22+ cases on the board (the surgical suite usually uses 2 whiteboards, but we could provide only 1 electronic board).

We observed that OnBoard transcended the whiteboard in the following dimensions:

1. *Flexibility*: the staff appreciated and benefited from the flexibility offered by the addition of emergency cases (or no-elective cases), and the ability to insert it anywhere, move it around and change its OR number and its start time. The reification of physical objects into digital instruments (strips, magnets) enabled users to move elements faster (no need to erase a case and rewrite it completely elsewhere – action that is also prone to human copy errors) while preserving flexibility. We observed partial accomplishment of action when inserting a new case in the flow during an emergency. The user would bring the add-on magnet to the bottom of the list for instance, creating a whole empty strip. The user would then start to fill patient name, procedure title and surgeon name, leaving the OR number and start time of the procedure blank. Indeed, the user did not know yet in which room nor at what time he could schedule this emergency case. Case shift was also straightforwardly adopted and appropriated: FondrenOR team used this feature to signify a "hold on" on a patient, meaning that the surgeon requested that everything about this patient must be stopped until further notice.

2. *Semi-public overview*: OnBoard preserved a collocated access of the whiteboard by remaining a large, central information surface. Users found the overall visualization clearer than the

whiteboard when written with computer fonts (once we increased the size after a request from the staff), affording a better shared overview. However, it is not possible to conclude on the effective support of mutual awareness from OnBoard alone, since the traditional whiteboards were still in place and filled up with the same information for safety reasons.

3. *Cross-Interactivity*: OnBoard displays new types of information coming from the sensors and enables the BR to quickly load all cases for the day from a spreadsheet file. Board Runners and Anesthesia reported being more able to anticipate and deal with the surgical flow by having a better idea of the status of the procedure. They also reported less need to physically enter the ORs to check the state of the surgery if they have the information on the electronic board. The mobile timelines helped them compensate the system for not being fully automatic.

7.2.7.3. *Staff management adaptation*

Associating staff (anesthesia and nursing) with ORs is as important as case management: who will work in what room after the shift, who already took his/her break, who will replace who etc. To do this, the team from DunnOR only relies on hand writing on the whiteboard. We designed magnets with this surgical team during participatory design to improve efficiency.

When we installed the system at FondrenOR with the second surgical team, we observed that they already use magnets for the staff. Indeed, we were able to automatically load everyday all the surgical staff with their shift information by creating individual magnets. However, we observed that digital magnets lack flexibility, compared to tangible. The staff was not able to signify some information the exact way they were doing it: for instance, rotating by 90° a staff magnet (Figure 95) to signify to others that this person is covering another person during his/her break (as observed with the DunnOR team). Also, the fact that all magnets stay at any time on the board was difficult for major re-organization of staff activities: with tangible magnets, the BR can pick them up, keep them in hand or in the pocket, and then place them on the whiteboard. With OnBoard, the BR could only drag and drop them. This suggests that these magnets need improvements on their design to reach the level of flexibility of tangible magnets. The staff asked for more "personalization" of "their" magnets, as they represent themselves. We quickly deployed an avatar system that was much appreciated (see Figure 96).

Figure 95. Example of use of tangible magnets on the whiteboard at FondrenOR.

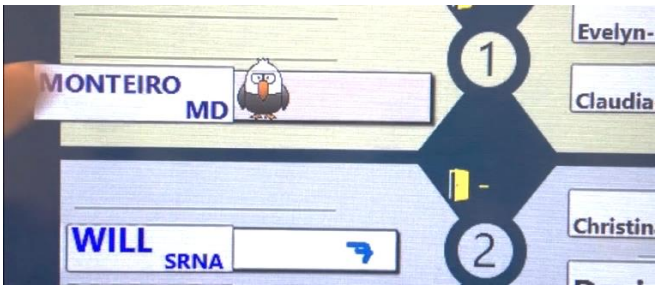


Figure 96. Personalization of staff magnets with an avatar.

7.2.7.4. *Handwriting fosters flexibility*

The ability to free-write/erase anywhere on OnBoard is an addition to the electronic whiteboards in the literature. Indeed, writing adds extensive flexibility and allow users to support actions that were not planned by designers. We observed the ability of the users to write/erase notes on cases and magnets, just like they would on the whiteboard. For instance, the inability to rotate by 90° a staff magnet was compensated by writing on the magnet the name of the person that is covering for the other person. The users also used it to fix an error from the users at the launch of the application: a wrong surgeon's name input (see Figure 97). This suggests that providing handwriting on OnBoard mitigates some of its limits.

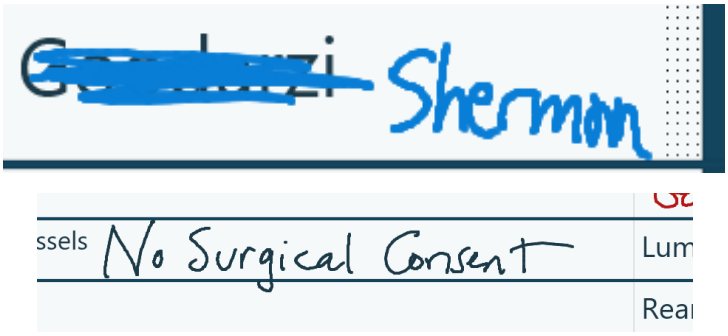


Figure 97. Manual writings and creative corrections on strips.

The three colors (black, red, and blue), were mostly used with the same purpose as on the whiteboard: black for regular information, blue for anesthesia information, red for special/important notices. On Figure 97, the modification made was on the surgeon name was made in blue: an Anesthesia staff noticed the problem and he made the modification with “the anesthesia (blue) color”.

As said before, users found the computer font “clearer” than handwriting. Indeed, the quality of the graphic rendering of handwriting may have an impact on users’ satisfaction. JavaFX only provides event coordinates rounded to the closest integer. The result was that the writings seems wobbly. The users were particularly annoyed by the rendering during a day when they filled OnBoard entirely with writings (Figure 98).

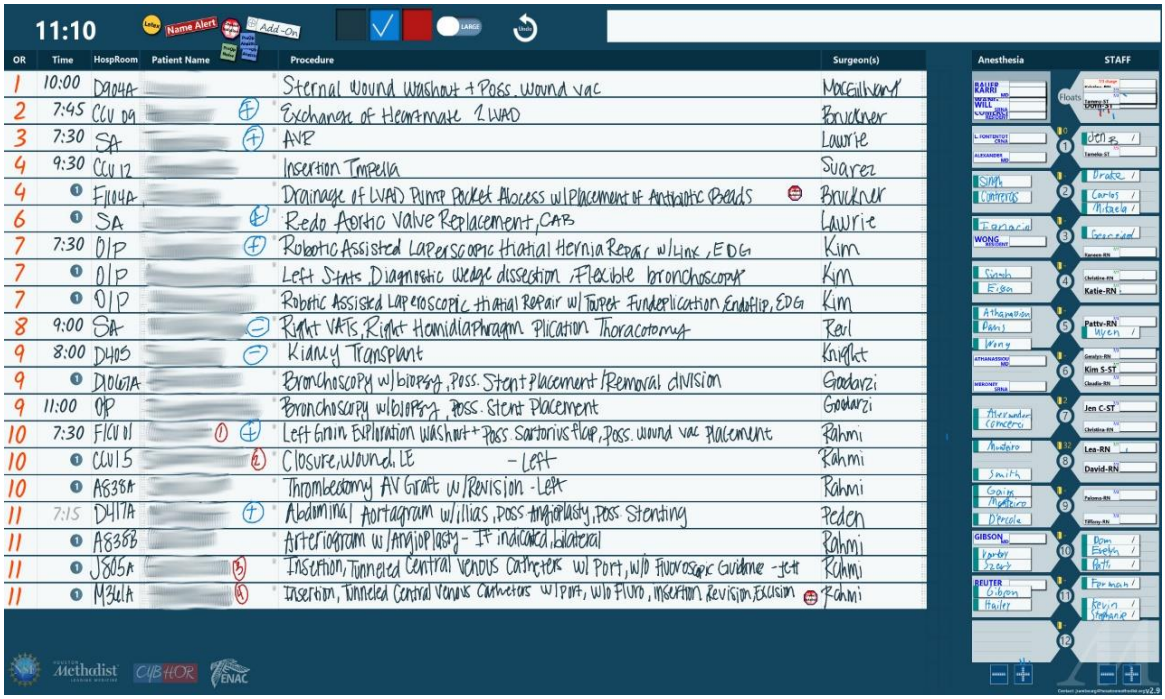


Figure 98. OnBoard manually filled with the surgical schedule.

7.2.7.5. *Synchronous and asynchronous collaboration among surgical staff*

We observed that the positioning around the boards (whiteboard and electronic board) are similar at FondrenOR and DunnOR. Many people gathered in front of the board to check the information they need: two people talking about a patient using the board as a support; one person making a change on the board; people gathering in front of the board just waiting; people texting information

from the board to someone; people taking notes on paper from the board etc. However, conversely to DunnOR, people at FondrenOR tend to write on the whiteboard one person at a time only, while having more asynchronous communication. Some collaboration patterns were observed e.g. the updates made by a board runner were later read by other staff (change of ORs number, change of cases order, staff information). We therefore could observe that OnBoard, even if it can support two users at a time, was principally used by one person only. This might be because people wanted to be cautious with the technology and were worried to break it.

Still, every person of the different surgical suites has their own objectives and uses the whiteboard/OnBoard to achieve it. Anesthesiologists write to inform other anesthesia staff of the anesthesia team organization, the charge nurse writes for the nurses, nurses update cases state etc. Overall, every displayed information may have a value for anyone who can read it and has value to be displayed to everyone. The large size of OnBoard both provides space for putting information and, as a semi-public screen, draws the attention of the staff.

7.2.7.6. *Collaboration between surgical staff and design team*

We were able to test on the fly new types of interactions during the study, based on our own observations or requests from the staff. The first request consisted in customization due to the fact the participatory design was done with a different team: the creation of an anesthesia information space on the board with another color, so that the anesthesia team could be linked to an OR instead of a case. Two additional magnets "Pre-Op Anesthesia Done" and "Pre-Op Nurse Done" were provided to mimic FondrenOR staff practice on the traditional whiteboard. The second type of request came from the visibility of the public displays in general and many people asked right away for bigger font, as well as different colors to differentiate people by their job-roles on the board. We got a request of customization of a staff magnet (representing a person), with an avatar. The third type of requests was functional. We were asked first to remove a note area that potentially could be hidden: the staff was worried that important things could be written on it, then hidden and overlooked. We were asked if we could make it easier to follow staff magnet assignments to ORs while moving them up and down, which we did by highlighting the OR number when hovering with a staff magnet. Another request was to "make a copy by clicking on a staff magnet". Indeed, some people, represented by a magnet, must be assigned to several ORs. We answered quickly by loading directly in the morning several magnets of the same person.

The request to connect the electronic board to phones was made many times by every job-role staff, emphasizing the need for information mobility. The prototype of the phone application was designed to explore this need. All these changes and additions suggests that our methods succeeded in fostering rich exchanges and offering new design perspectives.

Finally, we noticed three documents that were left on the cart of the electronic board during the study, one among them with clear intention to be found and reused later (an anesthesia staff calendar). We observed that a lot of paper notes were taken from the board, but also that things were written on the board from paper notes. This suggests that there is a need for even more flexible ways of inputting on and outputting from the board (see chapter 8).

7.3. Summary

In this section, we summarize the results of the design evaluations and of the deployment at the surgical suite FondrenOR.

7.3.1. Design evaluations

We used design walkthrough to validate and evaluate interactions and the usability of OnBoard. The design walkthrough sessions revealed a variety of usability problems and new design ideas. They allowed us to go from version to version and iterate to improve the usability of OnBoard. The latest version of OnBoard was considered usable and deployable in the surgical suite by all the users of the final design walkthrough, for the support of surgical cases, staff, and their management. The increase in size of the hardware and the improvement of micro interactions and of the writing/erasing features were key to its deployment.

More than with just interviews and observations, the participatory design sessions and walkthrough allowed us to include the users directly in the design process. These sessions allowed us to revisit our designs and improve them following users' failures/successes and advice. It allowed us to create a better link with the user and prepare for deployment.

7.3.2. Deployment in FondrenOR

The prototype (including the sensors) was deployed in real settings in a surgical suite at Houston Methodist Hospital, cardio-vascular department (FondrenOR). This suite comprises 12 ORs, for 2 months and ran through a total of 300 procedures.

We gathered data about the use of OnBoard in real settings and used technology probes principles to improve the system during the evaluations (*TP1. Design for appropriation*/*Open-ended*/*Co-adaptive, TP2. Real-world* and *TP3. Instrumented*.). Several features were designed during the deployment and integrated before the end of the deployment.

Observations and interviews "in the wild" showed that users were able to get up-to-date information from the sensors (*R1. Enriched surgical flow representation*), especially through the timelines, with the help of their direct manipulation to correct sensor deficiencies. We did not observe high workload situations and several users interacting simultaneously (*R2. Multi-users and multi-roles*). However, several roles (surgeons, anesthesiologists, nurses) were able to use OnBoard, thanks to handwriting.

We did not evaluate the level of mutual awareness (*R3. Teammates' activity awareness*) and how interactions may contribute. The large surface displaying coordination artifacts (surgical cases and staff) with hand writing everywhere is definitively a suitable means to support communication and coordination (*R4. Communication and Coordination*). Direct interactions to change time, fix incorrect information and add new cases in the flow allowed users to face unexpected events (*R5. Dynamic changes*). Finally, users were able to appropriate technology (*R6. Work adaptation*), with the use of colors, handwriting and object shift. However, we observed that some users are still reluctant to technology, turning away from using OnBoard. We learnt from these sessions how to improve the design of OnBoard and how to foster design for appropriation.

Many aspects of OnBoard revealed being very flexible for deployments. The initial load of cases for the day using simple excel files is one: the BR was able to quickly adapt what was written in his/her agenda to the current situation (when the schedule was loaded on OnBoard). Therefore, even if this feature was there as a temporary solution before a total automation between OnBoard and the hospital system, it revealed itself very resilient. Another flexible aspect was the writing/erasing feature. The ability to write anything allows the users to cope with any situation

that was not foreseen by the designers. This suggests that fulfilling requirement *R6*. *Work adaptation* is key to the success of deployment for such system.

Despite the numerous constraints due to the critical environment and the heterogeneity of surgical staff, the system was accepted in the surgical suite by the staff and they participated until the end. The staff participation in the design increased during the deployment, as it was more exposed and put in context. We believe that the effort of building the system with the staff played a big role in its acceptation when we moved it to the surgical suite, as it was not a system "imposed" to them. After we moved the system to the surgical suite, numerous ideas were proposed by the staff: first because more people got to interact with it, second because seeing the system in real condition helped generating ideas and seeing problems directly. After this deployment, we moved the system back to our offices and decided to try out the implementation of new ideas generated during the deployment.

7.3.3. Limitations

As the whiteboard was always being filled first for security reasons, OnBoard was sometimes not perfectly up to date due to the staff getting busy (many cases and concerns to take care of at the same time, emergencies…).

We observed that overall, staff do not "fully" trust electronic displays, as they are used to be failed by them (cf. hospital systems). Therefore, when a staff was looking at something on the electronic board, he/she was often led to check the information on the whiteboard. We believe OnBoard could build a better trust over time with more use.

There remain usability issues, and the OnBoard application is not robust enough to completely replace the traditional whiteboards. Furthermore, OnBoard is not linked to the hospital system and the smartphone application was only tested in simulated environment.

On the technical level, OnBoard visual feedback while writing or erasing are still slow, despite the optimization made with a QuadTree data storage architecture of the shapes locations. More computing power could solve the problem, but we believe there is still many optimizations that could be implemented. Furthermore, OnBoard was designed to be used by two people at a time maximum. We could improve the implementation of the interactions to allow more than two users at a time.

Another limitation is the customization of OnBoard. Surgical suites have different cultures and ways to perform the surgical flow management. We could see that, despite a lot of similarities between the different surgical whiteboards studied in the literature and at the Houston Methodist Hospital, there still are many differences. For example, some surgical suite whiteboard displays the procedures by OR number vertically instead of horizontally. Another example is the transparent whiteboard used in Boston. Finally, some whiteboards use only magnets whereas other whiteboards mostly use writings.

Hence, further development of the software would be necessary to make it a potential tool for everyday use in multiple surgical suites.

8

UBIQUITOUS COMPUTING FOR THE SURGICAL SUITE

Computers will be integrated in everyday life in every aspects [177]. However, one must consider the consequences on team coordination. The introduction of new automation should engage the designers in considering the negative effect on team coordination [180]. Indeed, automation can decrease situational and mutual awareness, and change roles and responsibilities of the members of the team [52,147]. Hence, creating a ubiquitous computing for the surgical suite must focus on this problematic.

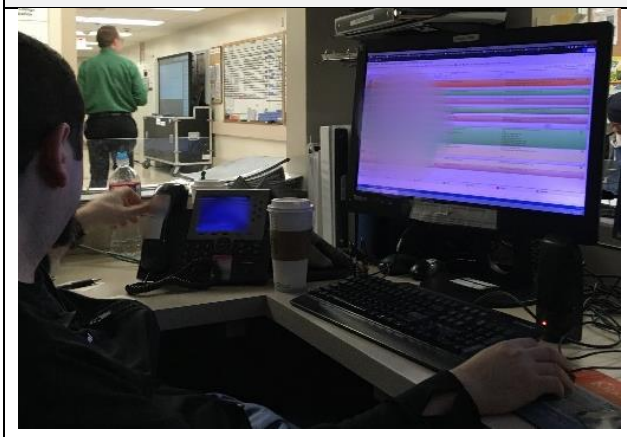
We developed OnBoard as a platform that could be the central element of other coordinative artifacts, just like the whiteboard is the central coordinative tool combined with phone calls and paper notes.

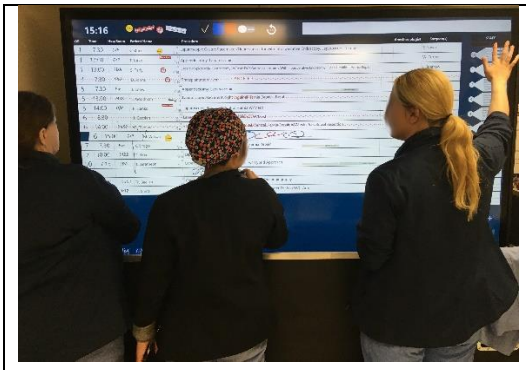
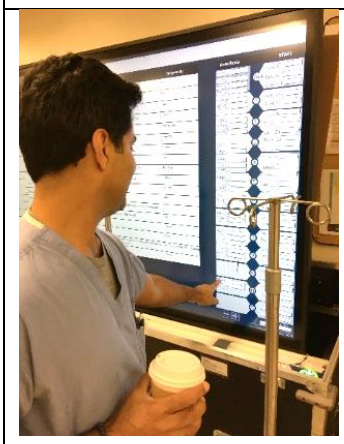
8.1. OnBoard in the perspective of the Cyber-Physical System

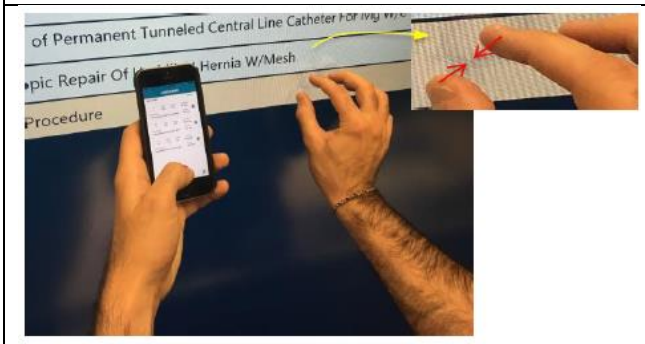
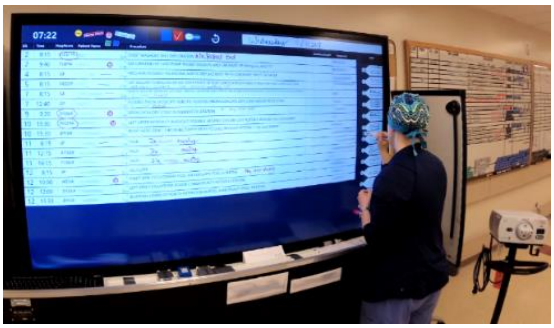
At first sight, OnBoard might be considered as an output system, displaying SmartOR sensors data and surgical suite schedule from the EHR. An effective information visualization can help

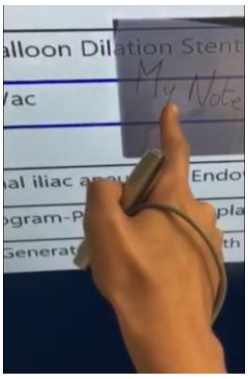
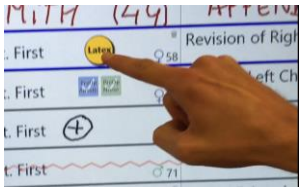
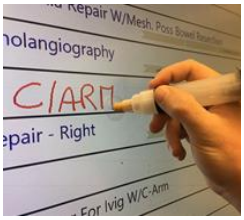
providers to explore and analyze EHR data for patient treatment and clinical research [143,157,176,182]. However, the innovation brought by OnBoard is not the visualization but the interaction design and its support for collaboration. Interactive features not only turned OnBoard into an input tool but also into a coordination tool. Table 19 presents how a typical workday would unfold with OnBoard and the CPS.

Table 19. Use cases of OnBoard in the perspective of the Cyber-Physical System.

Picture	Use case
	The day before, the board runner uses an excel file on his/her desktop to load the schedule of the next day on OnBoard via the shared drive system. He then launches OnBoard in the morning at 6.00am.
	Early in the morning, nurses coordinate on the nurses' shift to know where and with whom they will be working today.

 	The surgical team is wondering about the status of the surgery in OR5. They go to visualize the schedule on OnBoard and check the OR5 state. They discuss with the board runner if it could be a possibility to move procedure X to another OR as OR5 will likely not be ready for a new surgery. The board runner negotiates and finds a solution.
	An anesthesiologist has a coworker that will not be able to come this day. He reorganizes the schedule of the anesthesiologists to compensate.
	A nurse notices on OnBoard that the wrong surgeon was entered in the system for patient X. He crosses the name on the strip and write the right name underneath instead.

	A new emergency case must receive care as soon as possible in the surgical suite. The board runner creates a strip and enters the new case in the flow. She partially fills the strip, with only the patient name and the fact that he is coming from the emergency room as she does not know all the details yet.
	A nurse must go to another surgical suite to see a patient. He pinch'n'drops on his phone the cases he is assigned to, to subscribe and be able to follow them from the other surgical suite.
 	The flow of patient is getting heavier as the surgical suite is accepting a lot of emergency cases today. The charge nurse goes to OnBoard to quickly reassign the nurses to be able to sustain the flow.

<table>
<tr>
<td>   </td>
<td>A nurse is subscribed to a case on her phone as she is assigned to it. She receives an update telling her that the start time of the procedure changed.</td>
</tr>
<tr>
<td>    </td>
<td>The board runner is informed by the EHR that a patient is allergic to latex. He drags’n’drops a “Latex allergy magnet” on the associated strip in OnBoard.

A C/ARM equipment will be needed for a case, as requested by the surgeon, the board runner write it on the associated strip in OnBoard.

A nurse wants to let the board runner know that patient X did not sign the consent form yet. He takes a picture of an empty consent form with the camera (see new features afterwards) and drops it on the associated strip in OnBoard.</td>
</tr>
<tr>
<td>
<table>
<tr><th>OR number</th><th>Start time</th><th>Status</th><th>Modified start time</th><th>Patient Na</th><th></th></tr>
<tr><td>1</td><td>7:30</td><td>Not Starte</td><td>0:00</td><td>E. Swan</td><td>Lapar</td></tr>
<tr><td>1</td><td>12:00</td><td>Not Starte</td><td>0:00</td><td>W. Turner</td><td>Appe</td></tr>
<tr><td>1</td><td>13:00</td><td>Not Starte</td><td>0:00</td><td>J. Sparrow</td><td>Lapar</td></tr>
<tr><td>3</td><td>7:30</td><td>Not Starte</td><td>0:00</td><td>D. Jones</td><td>Trans</td></tr>
<tr><td>5</td><td>7:30</td><td>patientEX</td><td>9:35</td><td>F. Chevalet</td><td>Appe</td></tr>
<tr><td>5</td><td>13:00</td><td>Not Starte</td><td>0:00</td><td>C. Beckett</td><td>Lapar</td></tr>
<tr><td>5</td><td>14:00</td><td>Not Starte</td><td>0:00</td><td>J. Norrington</td><td>Lapar</td></tr>
<tr><td>6</td><td>7:30</td><td>Not Starte</td><td>0:00</td><td>A. Teach</td><td>Place</td></tr>
</table>
</td>
<td>The manager realizes the day of surgery was very tedious and that there must have been many inefficiencies. She opens the logs of OnBoard to see if there were scheduling decisions that could have been improved for next time.</td>
</tr>
</table>

8.2. Towards seamless interactions

In this section, we present new types of features that were designed after the deployment, to push OnBoard flexibility and connectivity further. In particular, we wanted to better integrate all subsystems, design interactions that would facilitate the transitions between subsystems, and offer a kind of interaction continuum that would make the user forget he/she is working with computers [30].

8.2.1. Increased flexibility and usability of the writing feature

Writing on paper still feels different from writing on a touch screen, even with the current best technologies. Technologies are improving, and this might not be an obstacle soon. We think that the feedback quality of writing on OnBoard is key to usability and deployment in the surgical suite. With the prototype that was deployed in our experiment at FondrenOR, writing on the electronic board was still not as satisfying as writing on a traditional whiteboard.

The literature on digital handwriting is surprisingly short on implementation details and subtleties that would lead to fast and nice rendering. In particular, we suspected that implementing nice handwriting rendering with JavaFX is challenging due to the library truncating the floating part of the event coordinates (even though the type of the event coordinates is “double”). We had to resort to another input technology: we adapted an existing java library for direct windows Real-Time Synchronous pen events [199] to make the coordinates more accurate by using the full resolution of the input. Indeed, the accuracy of some large display input is higher than the accuracy of the display output. Combined with a library we wrote to build dynamic, pressure-variable Bezier curves, we obtained much better result as the coordinate of the Bezier curves did not stick anymore to pixels: jags are removed, and anti-aliasing is much better. This result is another example why differentiating between input and output is beneficial [57].

However, because JavaFX and WinPointer technologies cannot cohabitate, we had to provide the better input mechanism with a 5x5cm translucent overlay window on top of the main application (see Figure 99). The handwriting interaction necessitates now a semi-temporal and spatial mode. To handwrite, the user needs to click on a strip first. This makes the overlay appear centered on the position of the click for a couple of seconds before fading away. The user must write within the overlay before its fades away. The overlay follows the user’s writing position while writing,

allowing her to write in a discontinuous manner (multi-shape letters, multiple words). We chose to make the size of the overlay large enough that the user is unlikely to cross the borders inadvertently while writing, and as small as possible to allow multiple users to write on the board at the same time.

Though adding a mode seems cumbersome for the user, it brings two benefits. First, we observed that users would leave unwanted traces when failing to properly press on the "grainy zone" to move a strip and unexpectedly starting a handwriting interaction. The newly introduced mode helps prevent such artefacts. Second, we benefited from this overlay window by moving writing parameters (stroke size, color) from the top bar to the overlay, thus making them closer to the writing context. The mode could be more implicitly started provided that the display is capable of differentiating between touch and pen interaction. As the deployed screen was not capable, we kept this interaction.

Another aspect that improved the writing/erasing feature in OnBoard is the use of a high-refresh display such as the Microsoft Surface (120Hz instead of 60Hz). This lowers the latency between input and graphical output. Combining the Microsoft Surface Hub with the interaction proposed above provides a more usable writing/erasing feature, closer to a traditional whiteboard.

We suspect that slow and ugly handwriting may refrain users from updating the board. The new technique improved latency and the quality of the graphical rendering. Though we did not gather enough supporting data that it helped improve users' satisfaction and incentive to using it, we at least eliminated a potential barrier to its use.

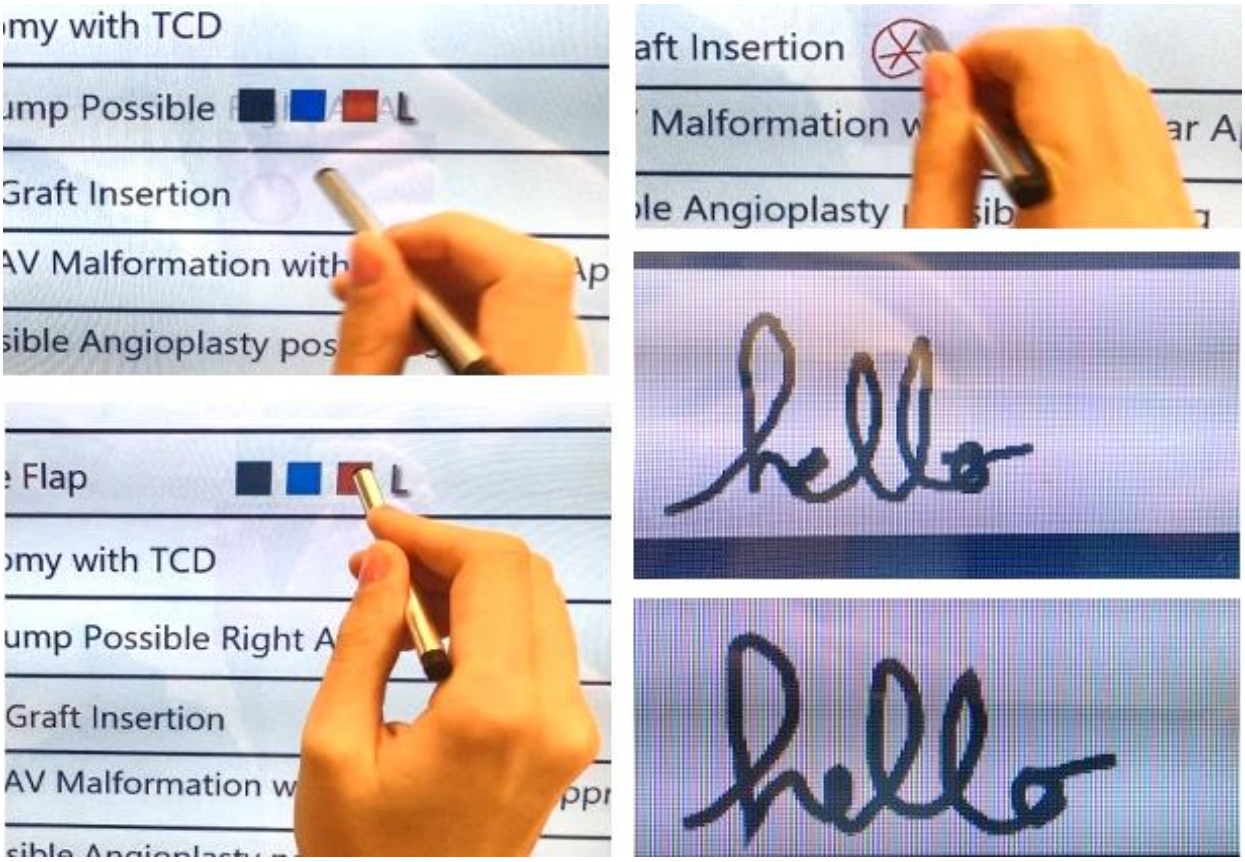


Figure 99. A new writing feature based on an overlay capture more accurate inputs from the touch screen than the main window. We can appreciate the difference between the former writings (middle-right picture) and the new writings allowed by the new technic (bottom-right picture).

8.2.2. Inputs from the external world in different formats

Following the idea of blurring the boundaries between the external and the digital world of managing tools for the surgical suite, we thought about a feature/tool that could bring increased flexibility in the type of inputs that could be made on OnBoard.

We installed an IPEVO P2V webcam (see Figure 100) wired by USB to the computer (IF25. Camera inputs). When OnBoard is launched, it launches a C# application from which we retrieve in the Java code the pictures taken by the webcam.

The webcam can take pictures from up-close, thanks to an auto-focus or a focus button that can be pressed by the user before taking the picture (see Figure 101). When the user takes a picture, the

picture appears on OnBoard interface as a magnet (a "picture-magnet"). It can be dragged on the scene, and if released on a strip it is attached to the strip. The picture-magnet can be deleted like the other magnets with a quick swipe-away movement. One can add written note on the picture-magnet, zoom in, zoom out and rotate it.

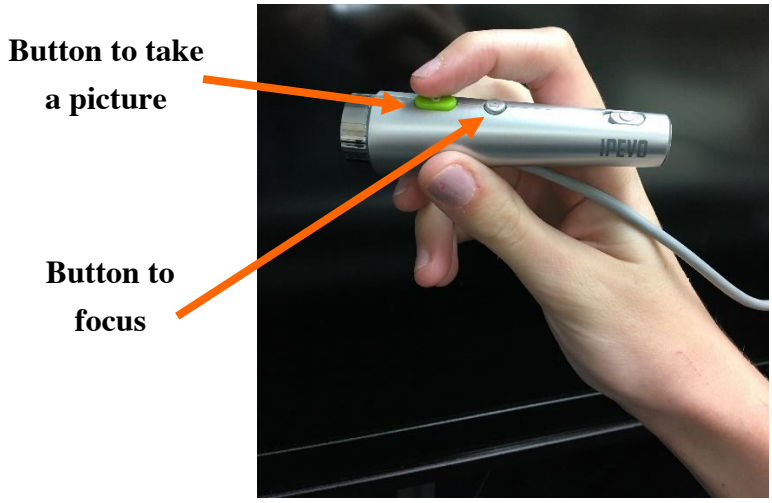


Figure 100. Webcam IPEVO P2V.

We designed this feature to be versatile. The envisioned scenarios are as follow:

- A nurse takes a picture of a part of a surgeon's schedule that he printed from the EHR, and drag'n'drops the picture-magnet on the patient's strip. Later, the nurse and other nurses working with this surgeon will check the schedule.
- The board runner writes on paper two possibilities of re-scheduling, takes a picture, and drag'n'drop it somewhere on OnBoard dashboard.
- The anesthesiologist takes a picture of himself/herself and drag'n'drop it on the patients he/she is responsible for.

Other possibilities can be envisioned as the camera allows a flexible type of inputs. This feature has interesting properties. First, the direct manipulation of the camera makes it easy and ready-to-use (*P2. Reify, P3. Partial, TP1. Flexibility/open-ended/co-adaptive*). Second, it can allow to palliate connections' difficulties with the hospital system (*TP3. Real World, TP1. Flexibility/open-ended/co-adaptive*). A picture can be taken of the schedule or any information from the EHR one

would like to put on the board.). Third, users can draw the attention of others via another type of graphics. Finally, the camera input/output might be highly appropriable, and users might be able to invent new usages that we did not foresee.

One could propose to connect the smartphone app with the board to take the pictures from the phone app instead of from the IPEVO connected webcam. We argue that it is preferred by the hospital that patient-related information does not commute on the phones of the personnel to guarantee patient privacy and data security. A user could also take a picture of a patient lab result or CT-scan and drop it on the patient's strip. However, we do not believe this would be an appropriate use due to the semi-public location of OnBoard and the fact that not all medical staff are authorized to access this type of patient information.

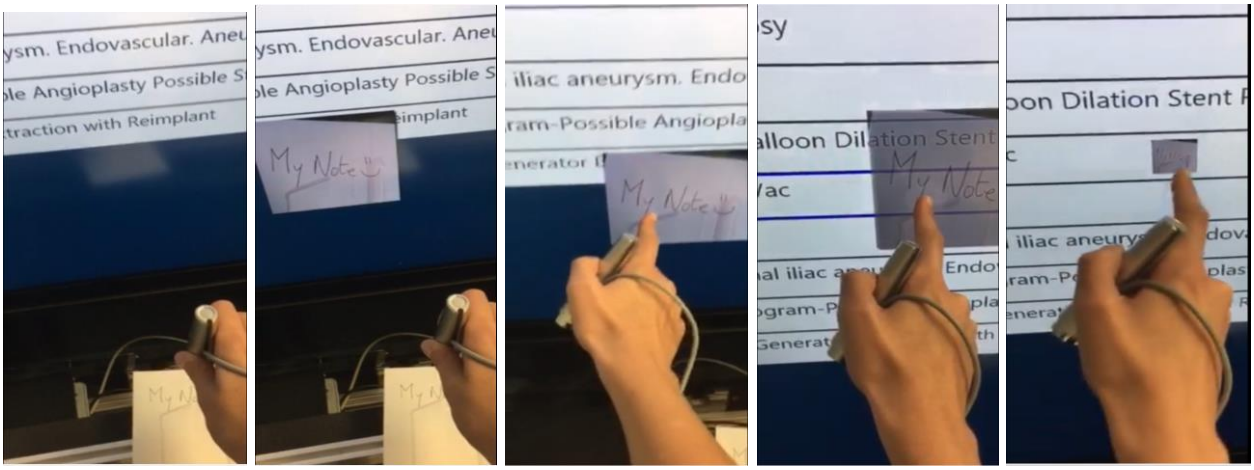


Figure 101. Use of a micro webcam to take pictures and create a magnet object in OnBoard of the picture that was taken. A magnet can be associated to a strip.

8.2.3. IoT – Bluetooth connection of OnBoard to an external embedded microcontroller

Connecting the OnBoard platform to embedded microcontrollers opens numerous possibilities of inputs/outputs/awareness tools. As an example, we designed a pen (one of the dry-erase pens for whiteboard without ink) in which we can fit a small microcontroller (see Figure 102).

Figure 102. Pen enable to contain an embbeded microcontroller. The pen was a little too small so we had to make a little cut on the side.

The microcontroller used is an Arduino-compatible Adafruit Feather, with a Bluefruit chip enabling BLE connections (Bluetooth Low Energy) (see Figure 103).

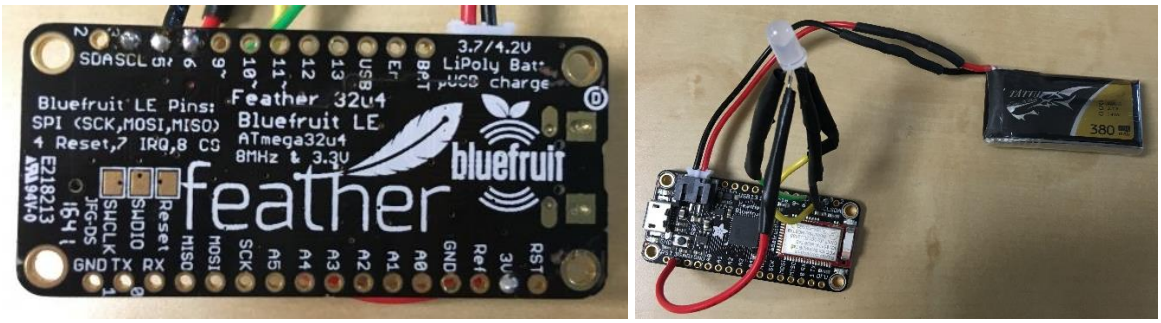


Figure 103. Left: Adafruit Feather, with a Bluefruit BLE chip. Right: Wired microcontroller with the RGB led and a battery.

We wired the microcontroller pins with an RGB led to change its color as we wish. We plugged a battery to the microcontroller that could fit in the pen (see Figure 103).

We coded the microcontroller to change the colors of the RGB led via Bluetooth communication.

On the Java code of OnBoard side, we used Bluetooth Low Energy BLED112 USB dongle via the RXTXcomm, bgib-gui.jar and bglib_protocol APIs.

When the user chooses a color in the toolbar of OnBoard (see Figure 104), the pen will turn into the chosen color. This allows the user to know which color he/she will write with, without having to look at the toolbar or writing and then having to erase because it was the wrong color.

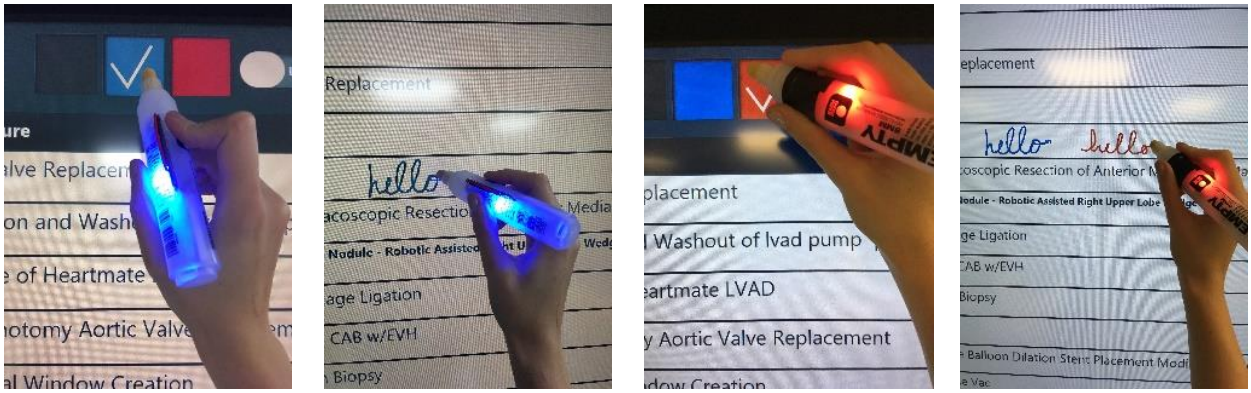


Figure 104. User choosing different colors to writ eon OnBoard a and writing with the special pen.

This simple example illustrates the potential of a platform like OnBoard connected to embedded objects. As the user picks and holds the colored pen, s/he might be more aware of the status of the handwriting interaction. In fact, the status of the interaction was an undesirable side-effect of using neutral, uncolored pens. Bringing the status into the artefact that is used to perform the interaction eliminates a potential usability difficulty, and makes the interaction "disappear into the fabric of the everyday world".

8.2.4. Minimal set of I/O features for electronic board

With hindsight from the OnBoard experiment, we propose a minimal set of I/O features for electronic boards to make them suitable as ubiquitous platforms and technology probes. The set of features might be interesting for researchers involved in future, similar projects.

The display should be physically located in the semi-public space and offer camera snapshots, free writings and a printing option (see Figure 105). The camera allows for a quick entry of any information based on an existing real-world object: a document, pictures of people, lab results etc. The writings allow a broad variety of other inputs: writing words, sentences, drawing symbols or other type of drawings, circling or framing existing inputs etc. The printing option would support the export on paper of any part of the display.

This minimum set of features can be developed in a simple and robust application Together, the inputs would make it easier for users to bring artefacts from the outside (with respect to the board) world and adapt the board to their practice or unexpected contingencies. On the other hand, the output would be the reverse asset: bringing electronic board artefacts into the real world. In

addition, designers would leverage on the transmission of information through these inputs and outputs to analyze them and provide better supporting tools for the revealed needs.

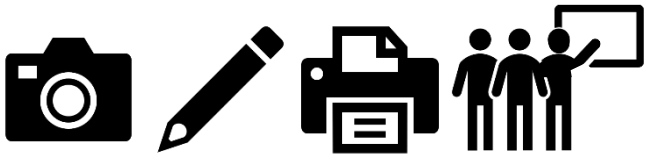


Figure 105. Minimum set of features for a technology probe for surgical staff collaboration.

8.3. Internet of humans in the surgical suite

In the surgical suite, numerous stakeholders work together. Communication plays an important role in the success of collaboration activities. Direct communication is not always possible, and interruptions are an issue to surgical staff performance and focus on the patient (see section 2.2.4 "Communication needs vs. interruptions problem"). Hence, connecting people via computers in a seamless way could have significant impacts for patient care.

As Weiser describes, computers should adapt to humans instead of humans needing to learn and adapt their workflow to computers. In this section, we look into using computers as medium [30] to improve communication between humans in the surgical suite.

8.3.1. Internet of things: humans' awareness of the system status

A cyber-physical system brings many sensors to acquire a system's status. In our case, sensors were developed (SmartOR sensors) to acquire the ORs' state. Other sensors such as patient location sensors or surgical equipment status and location can be added and provide a more comprehensive and finer grained system status information.

In Figure 106, we represent the internet of things for the surgical suite: in orange for the OR's state; in green for the equipment; in blue for the patient location in the surgical suite/hospital.

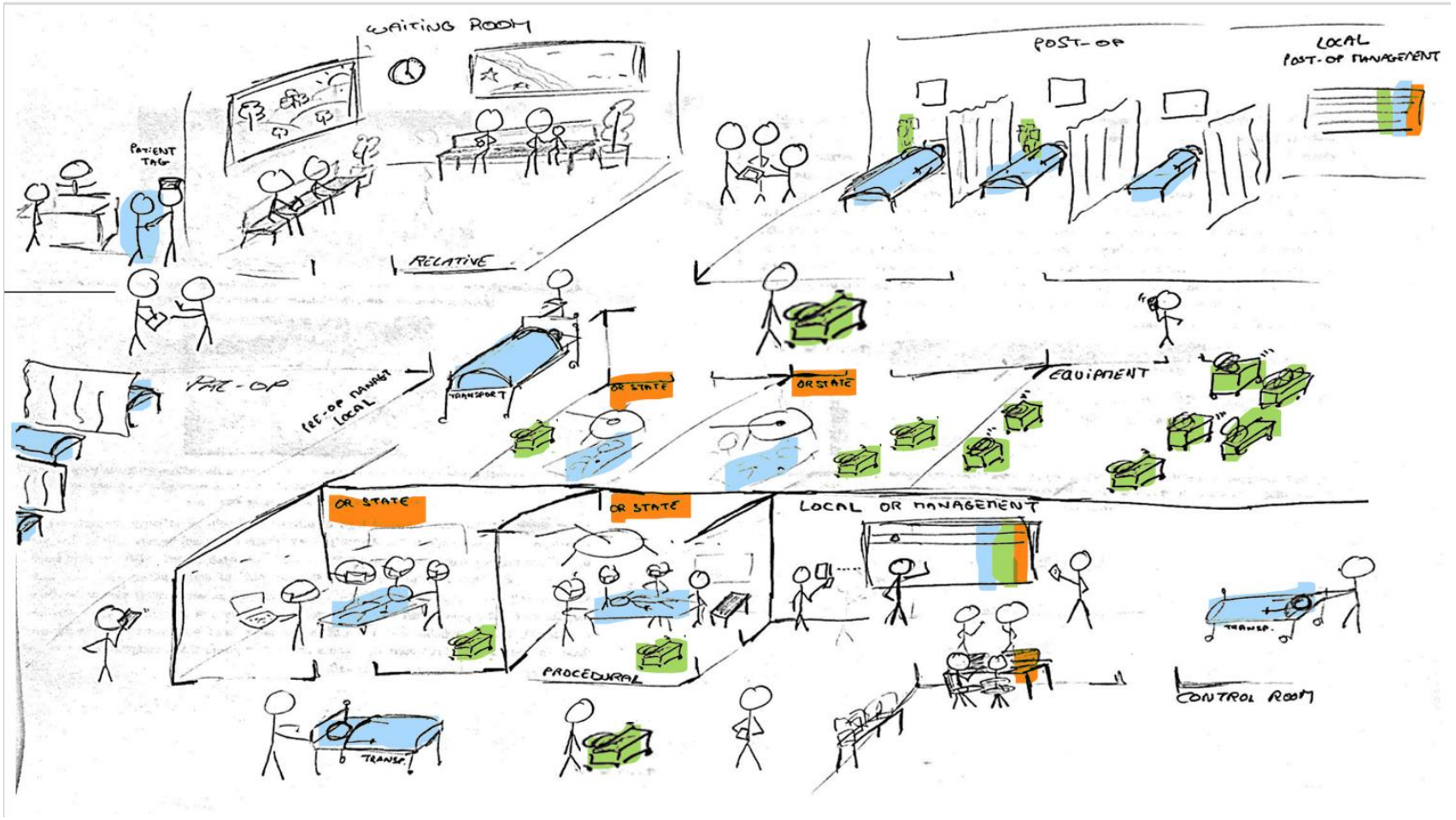


Figure 106. Ubiquitous surgical suite. In the same color: connected humans and objects. Yellow: Surgical suite coordination. Blue: Patient location information. Green: Equipment location and status information. Orange: OR state information.

The OR's state is acquired by the SmartOR sensors, and the information is distributed on different mediums such as OnBoard for the local and semi-public place, personal tablets/phones for mobile applications, and desktop station for management levels. For instance, the details of the OR state are irrelevant to the patient's family but is useful to the board runner to anticipate on the schedule of surgeries. Based on this acquisition, OnBoard combines the OR state with the schedule of surgeries, which gives a broader information on the surgical suite status. Figure 107 depicts the scenario where the board runner can anticipate a scheduling change based on the OR state information.

Figure 107. The board runner visualizes that the patient in OR1 just got intubated. It tells him that OR1 will not be ready for the next patient in time. He starts thinking about an alternative and look into re-scheduling the next patient for OR2.

The patient location acquisition can be acquired by equipping the patient with a localization bracelet when they enter the surgical suite. For instance, such bracelet could use the Bluetooth technology or RFID within a Real-Time Localization System (RTLS). In Figure 108, the board runner visualizes that the patient, scheduled for OR3 at 9:30, just arrived in Pre-Op. He can compare this information with the current status of the OR3. This tells him that if the patient stays scheduled for OR3, they surgical flow will see a delay. Hence, he can detect the issue and think about how to resolve the scheduling conflict.

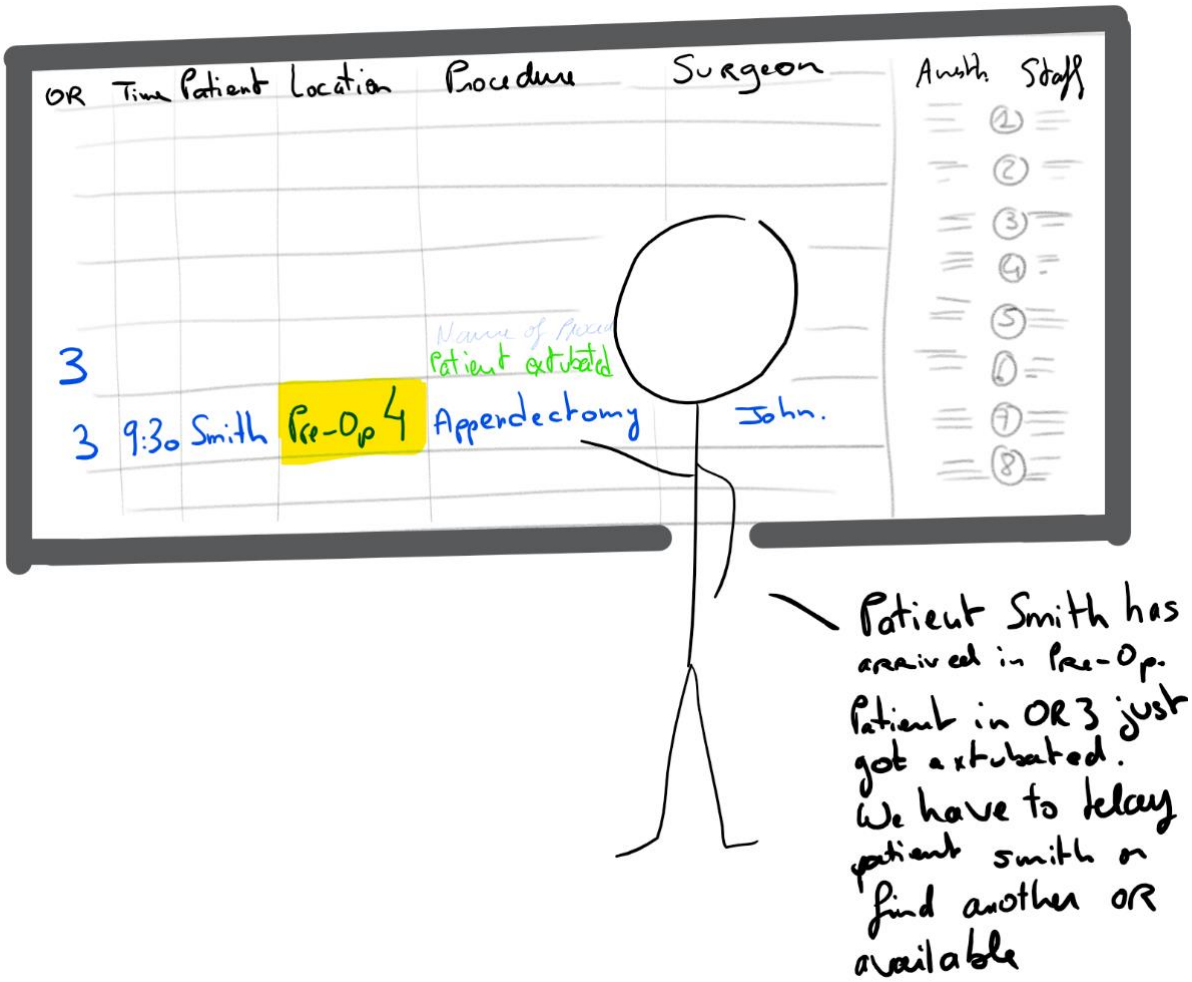


Figure 108. The board runner detects a scheduling conflicts in OR3 thanks to the CPS sending to OnBoard the OR state.

In most cultures, respecting privacy is necessary in a professional context. Hence, tracking the surgical staff is not acceptable. Besides, nothing proves that it would be beneficial. It might even be counter-productive because it would not be accepted by the surgical staff. Promoting the system to track events more than people – except for the patient who is in the hospital to be treated and not professionally judged, is a better guidance for future systems for surgical suite efficiency. We leverage here the notion of "internet of humans" [161], to encourage human interactions and preserve a culture of mutual respect between all stakeholders.

8.3.2. Internet of humans: humans' awareness of the other humans as human beings

Connecting humans in the hospital is key to the patient care, especially as the element being treated by the surgical staff is a person and not an object. The surgical staff works through difficult shifts, often more than 24 hours in a row. They spend a lot of time together and must deal with other staff shifts and quickly becoming efficient with working with someone on a new shift. Hence, using seamless computer systems fostering interactions between the surgical staff, their teammates, the patient and their relatives may have a positive impact.

In Figure 106, we represent the internet of humans for the surgical suite in purple for the connection between the surgical staff and the patients' relatives; in yellow for the connection between the surgical staff and teammates; in light blue the direct communication among the surgical staff or with the support of OnBoard, a mobile phone or a connected and flexible bracelet around the forearm.

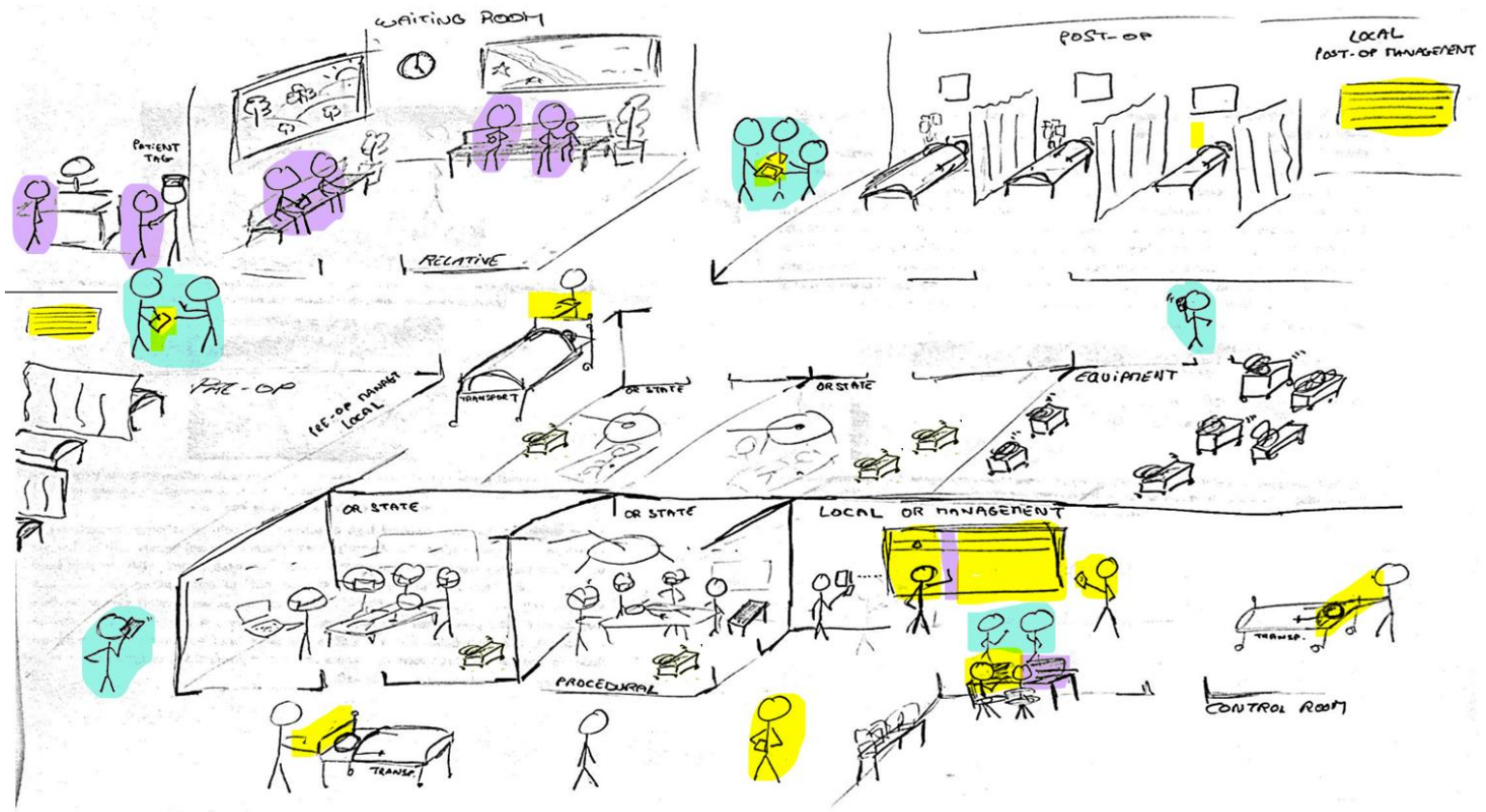


Figure 109. Ubiquitous surgical suite: Internet of Humans. In the same color: connected humans and objects. Yellow: Surgical suite coordination. Purple: Information to patient's relatives. Light blue: direct communication or with the support of OnBoard or a mobile phone.

Figure 110, Figure 111 and Figure 112 illustrates a storyboard about an example of human-human interactions via the storyboard describing the arrival of a patient and her spouse in the surgical suite. The surgical staff will provide them with means to communicate with the surgical team about the patient journey in the surgical suite. When the patient arrives, her spouse is offered to download an app on his mobile phone, through which he will be kept updated about his wife surgery before, during and after the procedure. The surgery happens to be delayed, which can be stressful for the spouse who is not aware of the reasons. The nurse can send in the app an update informing the husband that the delay is due to the fact the anesthesiologist did not see the patient yet and that everything is going fine.

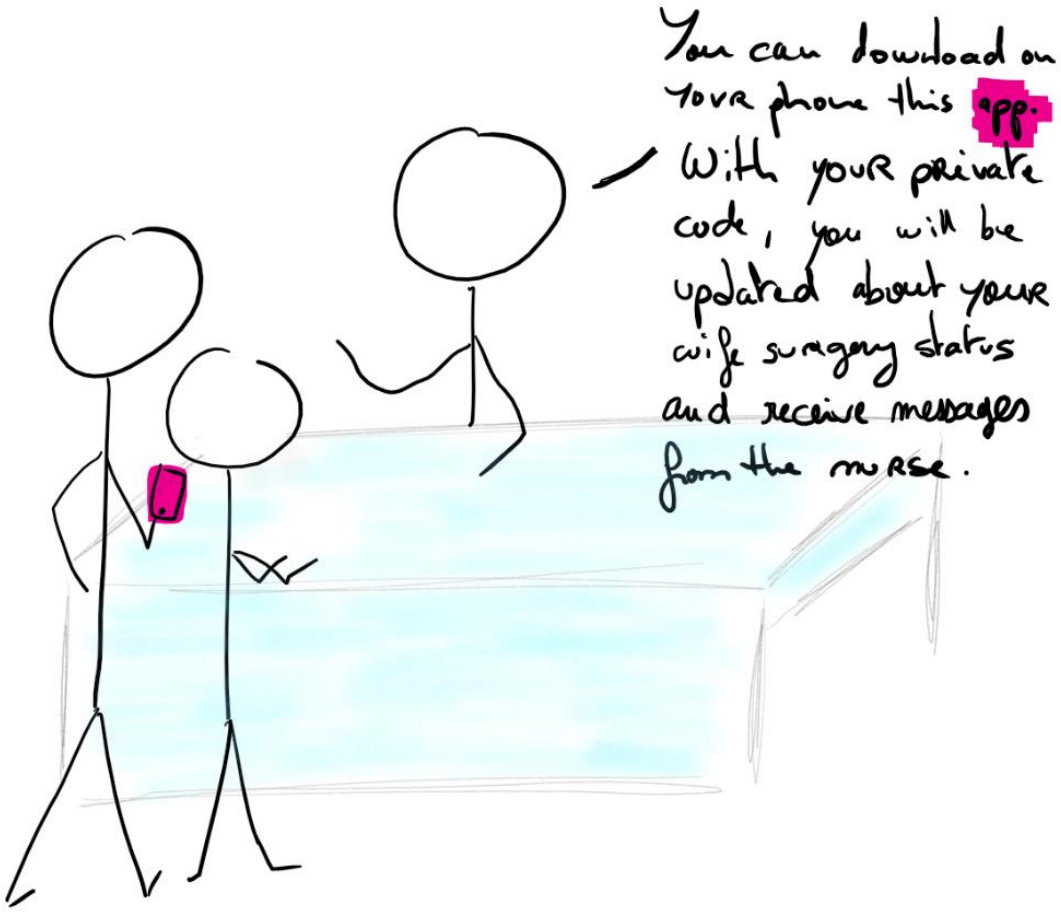


Figure 110. (1/3) The patient and her spouse arrive in the surgical suite. They can download an app so that the spouse can be updated about his wife journey in the surgical suite.

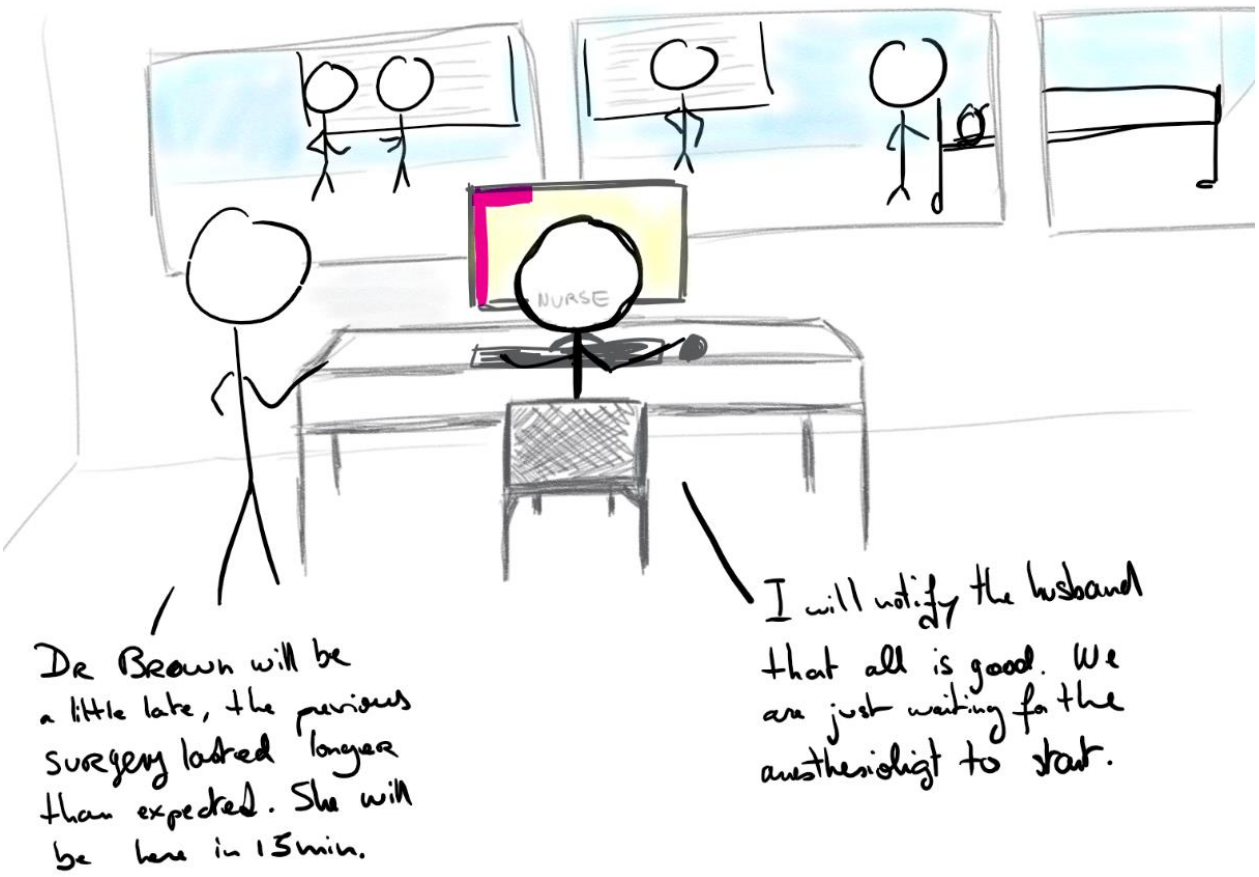


Figure 111. (2/3) The nurse sends in the app an update informing the husband that the delay is due to the fact the anesthesiologist did not see the patient yet and that everything is going fine.

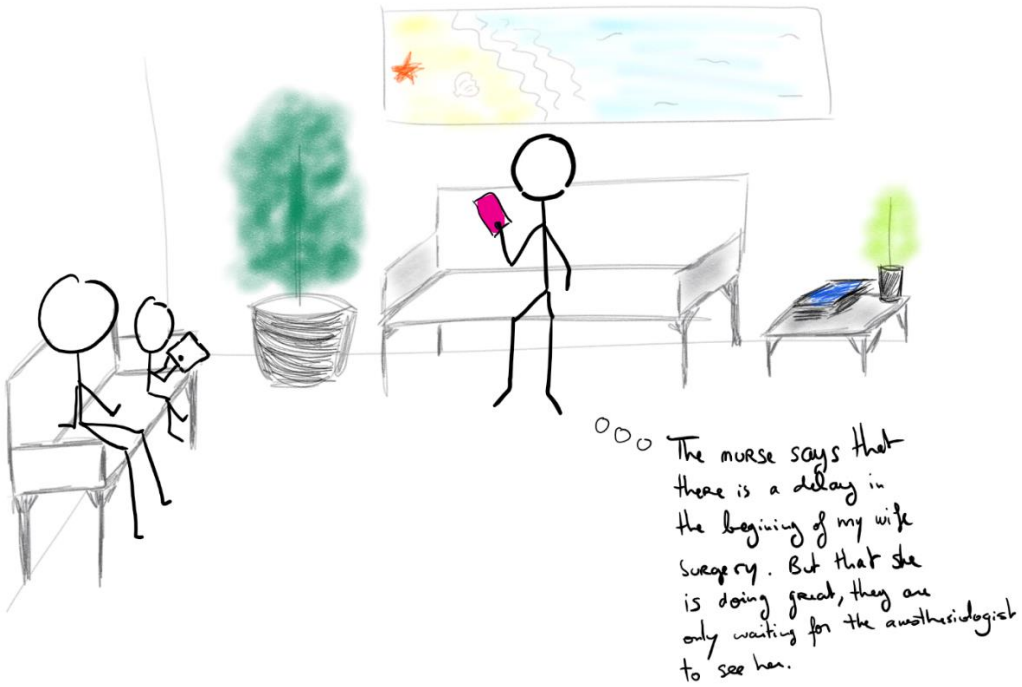


Figure 112. (3/3) Finally, the husband receives the information about his wife status and why the surgery did not start yet.

Figure 113 illustrates a human-human interaction storyboard fostered by the computer system and how the cyber-physical system helps the transporter to bring the patient to the right destination and with human interactions at the same time. The transporter is wearing a connected (but not localized) bracelet, with a flexible display allowing him/her to wear it seamlessly on his/her forearm. In this storyboard, the transporter gets an update to bring the patient to a first destination. He is also informed of the name of the patient. Hence, he can introduce himself, start a conversation and begin the transport of the patient. During the transport, he receives an update from the board runner, redirecting the transporter to another place with the patient. In this scenario, the transporter was able to change the destination of the patient without arriving first to the wrong place, realizing it is no more where the patient must be sent, and then redirecting to the new place.

Figure 114 depicts a utopic ubiquitous hospital that bring situation awareness about the different surgical suites to a higher-level of operations management to optimize the distribution of resources.

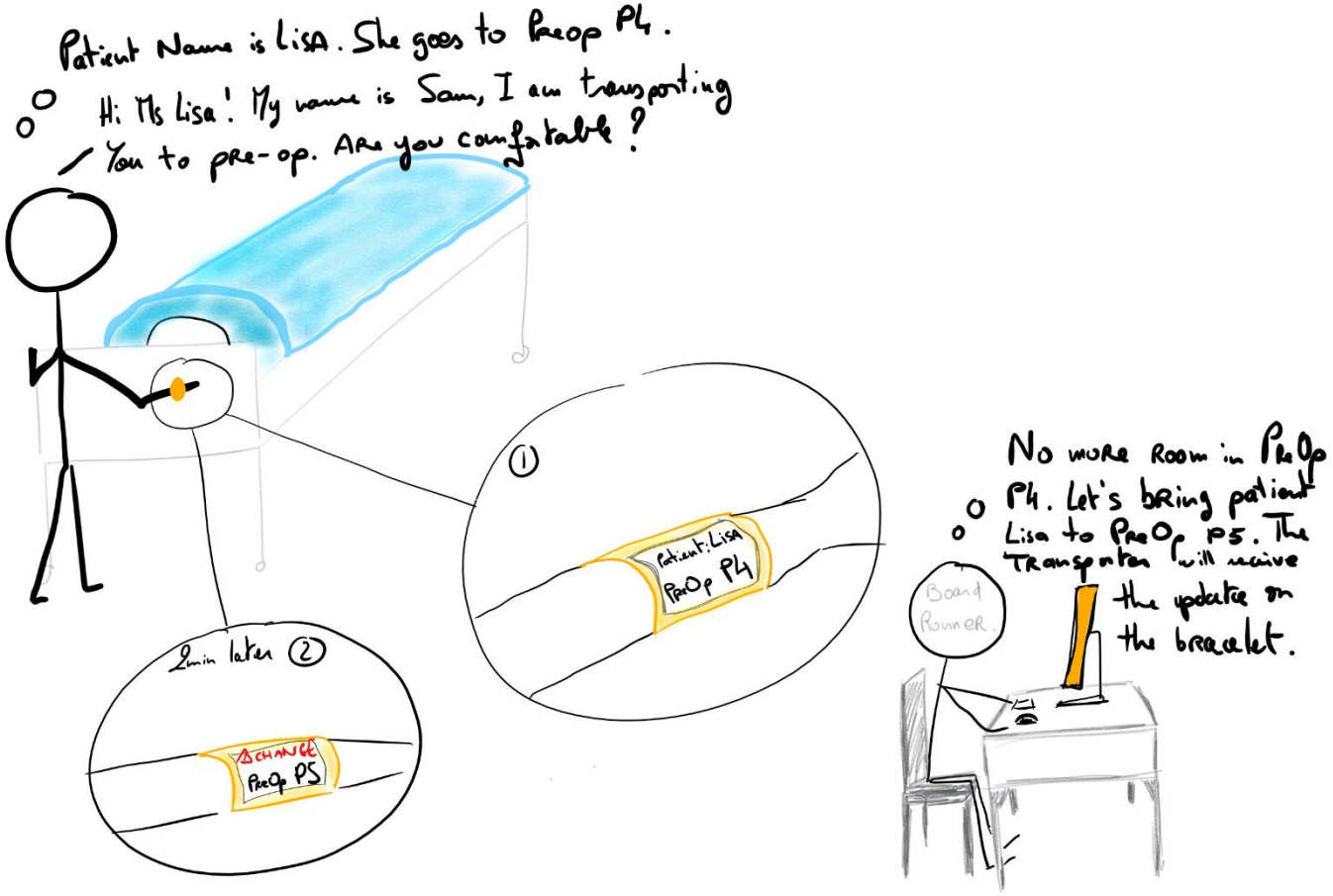


Figure 113. Transporter bringing the patient to the surgical suite. A connected tablet gives him the minimum information to take the patient to the right place, and the patient name to start a conversation and improve patient experience.

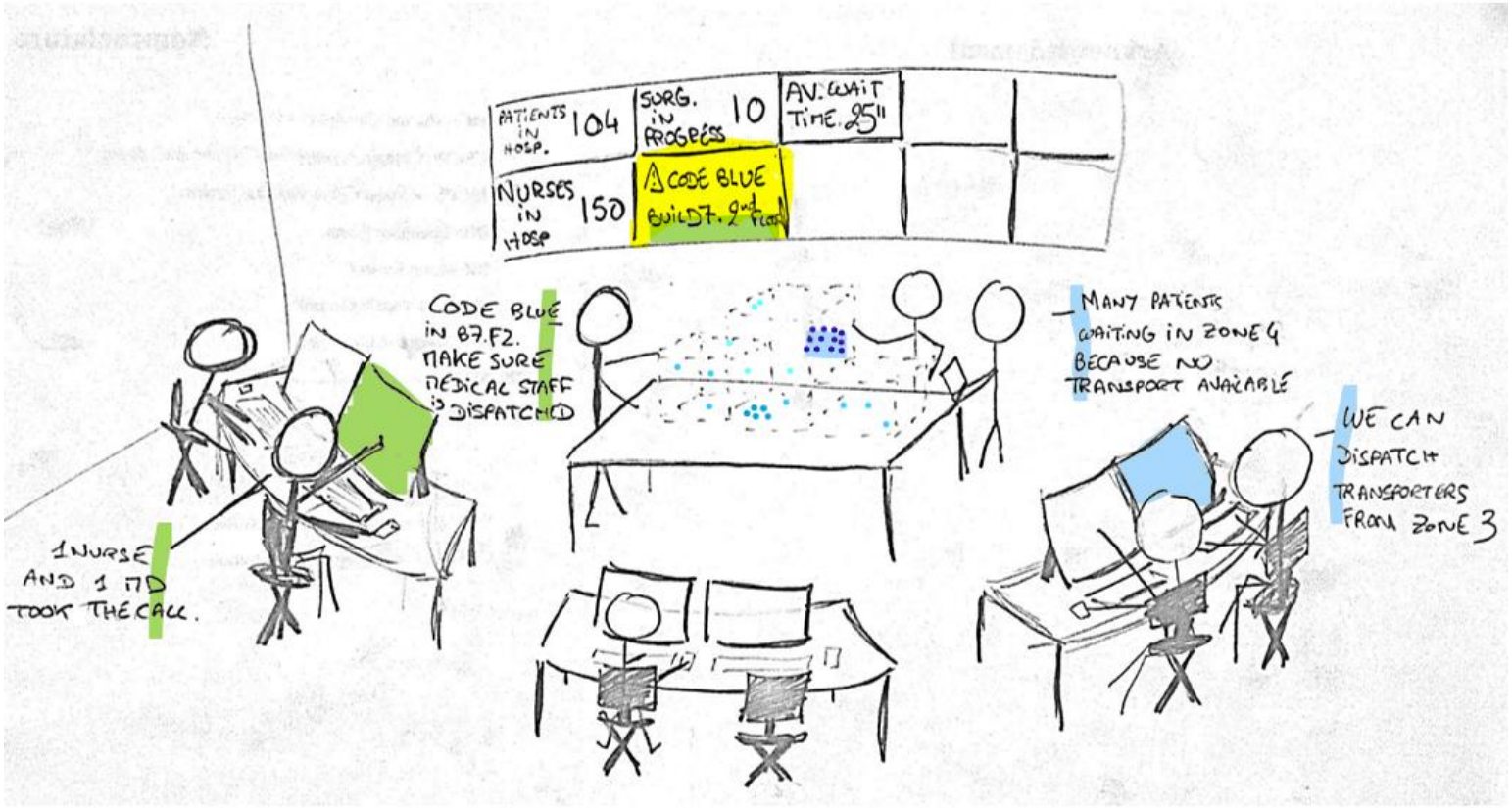


Figure 114. Utopic ubiquitous hospital. High level operational and surveillance management.

8.4. Summary

In this chapter, we detailed new use cases allowed by OnBoard within the Cyber-Physical System. We then designed and developed new features to support seamless interactions between the surgical staff and the computer system.

Especially in a context of healthcare, re-focusing the attention of the surgical staff on the patient, fostering communication with the patient and with the team is key to the patient care. We envisioned a ubiquitous computing system for the surgical suite that promote human interactions over interactions with the computer. We hope that these few examples will inspire future designers of surgical suite system to build applications that are centered on the team and on the patient for a seamless, respectful and safer delivery of care.

9

CONCLUSION

Our hypothesis was that interactions between the surgical staff and the patient flow management tools are key to foster flexibility, collaboration and awareness required by their activity. We have studied in this thesis how we could efficiently computerize the surgical staff activity based on this hypothesis. To this end, we designed and developed OnBoard, an application for large displays for the management of Operating Rooms in a Surgical Suite, a mobile phone application to remotely communicate on the status of running procedure, and a visualization of an algorithm that models the workflow in the surgical suite. We also discussed how to expand this work to a ubiquitous computing system for the surgical suite, fostering seamless human-human interactions.

The objective of OnBoard is to propose a computerized environment for surgical flow management that supports both the hospital management in cost performance and the medical staff in patient care. OnBoard is a large multitouch, multiusers, interactive surface that offers interactions following design principles that favor appropriation. It is part of a Cyber-Physical System detecting key events in the surgical suite. OnBoard is a practical example of a prototype for ubiquitous computing for the surgical suite environment. Figure 115 shows the timeline of the thesis and the different steps.

In this chapter, we summarize the contributions of this dissertation and how they were achieved.

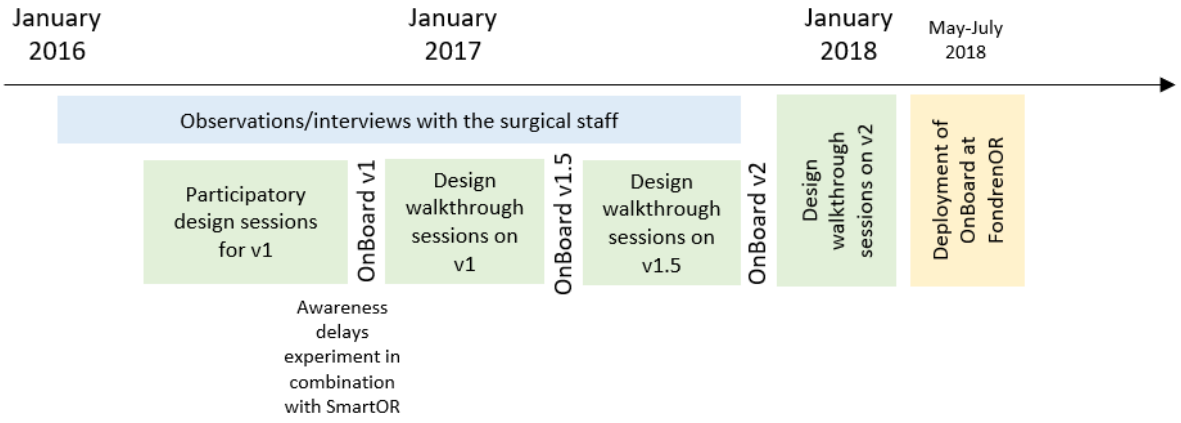


Figure 115. Timeline of the thesis.

9.1. Contributions

In chapter 2, we provided a review of literature on the difficulties of computerization of hospital workflow, with focus on the collaboration aspects. We then reviewed computerization challenges in other fields and explored how large surfaces have contributed so far to support computerization of collaborative activities. The related work encouraged us to cross what we learnt between the needs from traditional surgical whiteboards to electronic whiteboards, and what can be offered by multitouch interactions, to design a more usable support for the surgical suite staff.

In chapter 3, we summarized the context of the design of OnBoard. OnBoard is meant to be the central collaborative tool of a cyber-physical system detecting key events in the surgical suite and displaying them on OnBoard. I participated in the construction of a mathematical model of the surgical workflow [68,69]and the design of a visualization of the mathematical model. We finally led an experimentation in combination with the SmartOR [94,96] in the surgical suite to identify bottlenecks of workflow inefficiencies and delays. The experiment showed an average of 14 min delays with more than 20min standard deviation between events in the operating rooms and the associated update on the whiteboard. The whiteboard being a central tool for communication and coordination these delays have a negative impact on collaboration.

In chapter 4, we presented the methods used to conduct our research work. Initially, the whole thesis was supposed to be based on a technology probes approach. However, the critical context of the surgical suite prevented us to have an easy access and install prototypes often and quickly. We therefore used more classical User-Centered Design methods and borrowed principles from the technology probe approach. We performed participatory design sessions with 9 surgical staff and 13 design walkthrough sessions on 3 different versions of these prototypes with a total of 12 surgical staff. We used participatory design and continuous improvement from users' observations and feedback in a real setting.

In chapter 5, we detailed an accurate analysis of the activity of the surgical team, based on 13 interviews, 12 contextual inquiries with 20 surgical staff and a campaign of photography of the surgical whiteboards [135]. We visited and observed 6 of the 8 surgical suites of the Houston Methodist Hospital. 22 System Usability Scale questionnaires about the use of the surgical whiteboard, were answered by the surgical staff. These analyses allowed us to understand the surgical staff and their needs. We understood that the surgical whiteboard plays a central role in the surgical suite collaboration and offers properties that no electronic whiteboard could offer so far. We then developed an analogy between air traffic control and the surgical suite. These steps allowed us to identify 6 high-level requirements necessary to the development, integration and acceptance of a tool to support surgical workflow activities [136]: *R1. Enriched surgical flow*, *R2. Multi-users and multi-roles*, *R3. Teammates' activity*, *R4. Communication and Coordination*, *R5. Dynamic change*, and *R6. Work adaptation*. We provided an analysis of the activity of the surgical team, based on interviews, observations, questionnaires and an analogy with civil aviation.

In chapter 6, we first identified 5 design principles necessary to the development, integration and appropriation of a tool to support surgical workflow activities [136]: *P1. Multi-touch*, *P2. Reify*, *P3. Partial*, *P4. Feedthrough*, and *P5. Robust*. We then borrowed 3 technology probes principles: *TP1. Flexibility, Open-ended and co-adaptive*, *TP2. Real-world*, and *TP3. Instrumented*. Finally, we borrowed 3 graphical design techniques from Digistrip: *DG1. Texture or color gradation to code information*, *DG2. Different fonts to convey information*, and *DG3. Animation to facilitate transitions*. From these principles, we designed multi-users interactions on a large surface. The resulting system is a large shared surface, OnBoard, that displays the surgical cases associated with highly interactive features. We verified the quality of implementation or implemented the missing interactions of 4 error prevention features and 6 error recovery features. We contributed

with the design of innovative multi-users interactions on a large surface and a prototype of electronic whiteboard for the surgical suite which demonstrates the integration of the specifications and technical challenges.

In chapter 7, we reported on the design evaluations and the deployment of OnBoard in a real surgical suite for 2 months [136]. We performed design walkthrough sessions on 4 different versions of the prototype with a total of 12 surgical staff, with 13 separate sessions. We finally deployed the system in a 12 ORs surgical suite, FondrenOR, for 2 months. The system ran through a total of 300 procedures. We contributed with the deployment of the prototype in the surgical suite and its evaluation by the surgical staff.

In chapter 8, we reinterpreted the thesis work towards ubiquitous computing for the surgical suite. We describe the new use cases of OnBoard in the surgical suite. We then proposed 3 new features to promote seamless interactions with the computer and determined a minimal set of features for a technology probe for the surgical staff. Finally, we projected the OnBoard platform onto a ubiquitous system considering the importance of human-human interactions in the surgical suite.

We overall received a substantial amount of participation from the surgical teams of Houston Methodist Hospital. Participation was voluntary and much appreciated by the staff and by the design team. Such participation played a key in the success of the design of the interactions and their appropriation.

9.2. Research Questions' answers

9.2.1. RQ1: How to computerize users' activity without jeopardizing their collaboration nor the flexibility needed for OR management?

We followed methods that include the users at every step of the design (User-Centered Design) (see Figure 115). Interviews and observations were effective to understand the mechanism of collaboration within the surgical suite and the different roles. It allowed us to identify the tools used to manage the surgical flow. The related work about these tools and challenges of design for surgical workflow management led us to isolate the strengths of the surgical whiteboard.

We were able to extract requirements for a digital surgical flow management combining the strengths of traditional whiteboards and computers. We determined design principles to be followed during the design of interactive features of OnBoard. The design principles are the result of a study of related work about design for interactive systems for air traffic control and technology probes:

P1. *Multi-touch*: Large multitouch surfaces offer extensive means to favor direct collaboration and direct manipulation. We used traditional drag n drop-based features on objects manipulation and more advanced multitouch interactions such as the erasing feature and the pinch n drop.

P2. *Reify:* We reified cases into mobile strips on the large surface. We reified the action to add an emergency case into a droppable magnet. The staff and physical magnets were reified into digital magnets. We finally reified the action of changing procedure start times with the manipulation of an interactive clock.

P3. *Partial:* We allowed the addition of an emergency case and a new staff without filling all their information.

P4. *Feedthrough:* By keeping the OnBoard system physically similar to the whiteboard, we preserved the feedthrough provided by traditional whiteboards and promote mutual awareness and synchronous and asynchronous communication improvements. Indeed, by being large and located in a central place of interactions between the surgical staff, OnBoard allows other users to see that someone is interacting with it and what he/she is doing. Furthermore, allowing manual writing/erasing almost everywhere allow users to see that humans (and not an automatic system) made inputs. Similarly, when a modification of OR number or start time is made, the computer font turns into a handwriting font.

P5. *Robust:* The interactions were designed to work efficiently in a high-pressure environment, respecting usability and simplicity. Furthermore, each interaction went through usability inspections.

Borrowing technology probes principles aligned OnBoard features with the flexibility targeted for an effective deployment in the surgical suite:

TP1. *Flexibility, Open-ended and co-adaptive*: The free writing/erasing features offers a flexibility that guarantee the users that the system can adapt and allow unplanned inputs. Implementing this

principle was key to the deployment and to the collaboration between the design team and the surgical staff.

TP2. *Real-world*: The prototype following this principle is designed to be quickly implemented in real context to receive feedback and learn about the activity. OnBoard was deployed in the surgical suite to be tested be also to favor collaboration between the design team and the surgical staff.

TP3. *Instrumented*: OnBoard archives its states and the interactions performed as logs. The excel files offer the possibility to interface the EHR with OnBoard for loading of the initial schedule and surgical team.

Finally, we borrowed graphical design techniques from Digistrip:

DG1. *Texture or color gradation to code information*: Color coding of manual writings was preserved to distinguish planned schedule from emergency modifications, from anesthesia-related information. We also implemented a color coding to distinguish the staff (represented by names/role on magnets): doctor anesthesiologists in darker blue than their residents, and

DG2. *Different fonts to convey information*: it is possible to distinguish system-computed data and user input data through the font (computer vs handwritten).

DG3. *Animation to facilitate transitions*: as much as graphical design helps display information in better ways, animations in interfaces are useful to help understand state changes.

This knowledge and participatory design sessions allowed us to design a prototype with the surgical staff that fulfills their needs to manage the surgical flow. Testing the interactive feature via design walkthrough sessions allowed us to refine the prototype. Finally, succeeding to deploy the system in real conditions was a cornerstone and brought us more feedback from the users and the ability to validate or invalidate some features.

During design walkthrough sessions and during the deployment, the prototype served as a collaborative tool between the designer team and the surgical staff. Being able to manipulate the prototype and make quick changes in the interface promoted exchanges and improvements of OnBoard.

One of the most important design considerations is that team work requires direct communication between the different staff to take decisions: face-to-face discussions, supported by a global overview, are invaluable in the process of assessing patient conditions and priorities. We must

avoid providing interfaces that keep staff away from interacting with patients or talking directly to his/her colleagues with an extensive use of phone app communications.

Large touch surface products on the market reached a high level of quality and are entering the everyday life of people as Weiser predicted, along with tablets. With the OnBoard experiment, we conclude that to reach an effective ubiquitous computing for the surgical suite without jeopardizing the existing collaboration and usability levels, UCDs methods should be implemented along with design principles fostering flexibility.

9.2.2. RQ2. How to reach an effective deployment of a computerized system in a critical environment?

For a critical environment, satisfying RQ1 alone is not enough. To reach deployment, the system needs to "earn" the trust of the users, which legitimately depends on: usability, reliability, privacy and security of the new system.

We first offered a system that is very similar in terms of use and layout to what the users are used to have to guarantee similar effectiveness and efficiency. In addition, it can be a safety measure. Indeed, the traditional whiteboard does support the workflow today, and it is probable that we do not know all the reasons why it works so well. In critical environments, radically changing a system is a risk which can have fatal consequences. It is the difference with a non-critical environment, where radically changing a system can be accepted because adaptation, learning and errors might be tolerable.

Second, the quality of the hardware plays a significant role. A "small" surface implied a shortage of space to write the surgery description. Lower resolution had for consequence to lower the usability of the writing/erasing feature from the traditional whiteboard. We noticed that a delay in the writing/erasing feedback due to the low screen resolution is detrimental to users' satisfaction. We replaced our first infrared 70" touch screen (30Hz, HD resolution) by a large 84" display, InGlass technology, 60Hz, 4K resolution. The quality of the interaction and display was much improved and better satisfied our users to the point that it made the board a credible replacement of the actual whiteboard.

Third, the reliability of the system is key to "earn" users' trust. Inaccuracies in interactions and slow-downs of the system harms its usability. For instance, hand writing recognition is still a

delicate matter for deployment in a critical environment. Our users are intolerant to mistakes and it is difficult to get a bullet-proof hand-writing recognition even for entering simple information such as an OR room number. Therefore, we oriented the design of interactions to satisfy *TP1*. *Flexibility, Open-ended and co-adaptive*, such as free writings, drag'n'drop of objects, mobile OR state timelines and free organization of strips. Technology probes principles had a positive impact on the results during the deployment along these lines: these features allowed the surgical staff to effectively manage the surgical flow with possibility to correct errors coming from the system (c.f. wrong patient associated to an OR, wrong surgeon associated to a patient). Implementing optimizations such as QuadTrees helped improving the speed of user feedback while interacting with OnBoard. Finally, the user can compensate for necessary information that is not captured yet by the sensors, e.g. inaccuracies in the automation. Indeed, the operating room state is captured by the sensors, but the sensors cannot tell which patient is in the room. The board runner can compensate the system's lack of information and move the operating room state timelines from one case to another as he/she is aware of this information.

Privacy of the surgical staff is respected with the current OnBoard and the Cyber-Physical System implemented. The surgical staff location is not tracked via RFID tags or Bluetooth tags. Tracking professionals, in westerns countries institutions, is not welcomed and is perceived as an invasion of personal privacy. Tracking the surgical staff could be a real brake to the deployment of a cyber-physical system in the surgical suite.

Security is an aspect that was not explored with OnBoard, to allow maximum flexibility. We discuss the challenge in the limitations in the section 9.3.

The whole Cyber-Physical System, comprising OnBoard, is a technology probe that informs about what impairs the efficiency of a surgical suite. With OnBoard by itself, we were confronted to a dilemma between the simple functionality of technology probes, and still bring new value to the users. The first version of OnBoard was a simple electronic whiteboard, with a surgical board layout. In other words, it was bringing nothing more and even worst: it degraded the usability of the writing/erasing feature. Hence, a probe must be simple enough to fit as a real word application but must be slightly complex to enhance usability of the system and provides value to the users.

9.2.3. RQ3. Can we generalize our work and promote an effective computerization beyond a particular example?

We first answer this question with the fact that OnBoard was designed with a different team, from a different surgical suite than the team and surgical suite where it was tested. The surgical staff of the surgical suite where OnBoard was deployed agreed with the proposed layout and concepts of OnBoard to manage the patient flow. With minor customizations, OnBoard was ready to be installed in a different surgical suite.

The design principles we determined were inspired and extended from previous design principles from air traffic control research projects. Our design principles can be applied to build and deploy future applications designed to foster teamwork in an intense workflow environment.

The interaction techniques designed during the thesis can inspire future projects to promote flexibility of the computer support.

9.3. Limitations

Allowing flexibility of interactive systems can be a tradeoff with connectivity capacity and security at first. For instance, as it became easier to move cases on the board (no need to erase a whole line, or re-writing everything after a modification), the question of unauthorized modification that would have no witness was raised. Even if unauthorized modifications are possible with the regular whiteboard, they are limited to the information on the whiteboard. The easier modifications interactions brought by the electronic board, and that were desired by the users to cope with unplanned events, also brings this side effect that must be solved in future work.

9.4. Future work towards ubiquitous computing for the surgical suite

Future research could start by addressing the limitations mentioned above. A first step would probably be the connection of OnBoard to the hospital system and the development of more sensors to capture more accurately OR states and patients' locations, for instance with RFID or

Bluetooth indoor localization technologies (BLE-RTLS). Another step is the need to explore how to enhance mutual awareness beyond OnBoard surface. The continuity between the large shared surface and the private mobile phones is a promising way forward. Deploying OnBoard in other surgical suites that would be interconnected could be an addition to create a continuum of interfaces to support the surgical flow and create unity. Further research on user interactions with OnBoard as a single user or multiple user could lead to more flexibility and hence, have the computer systems adapt to the surgical staff activities needs and not the contrary.

On a larger scale, usability of information technologies must increase in the hospital field. A program of NIST (National Institute of Standards and Technologies) is in place to establish a framework that defines and assesses health IT usability to guide industry in usability engineering practices [5]. Initiatives are implemented to improve health IT usability, as the current systems did not focus as much on usability as other industries yet.

Patient and Family engagement is a transformative force in the health industry, and insurance policy in the US has now a component strictly dependent on patient satisfaction that will keep growing in importance soon [101]. Future work encompasses the expansion of the continuum of interactions to reach the patient and family members who need to manage anxiety and be prepared.

REFERENCES

1. Bonnie A. Nardi and Steve Whittaker. 2001. The Place of Face-to-Face Communication in Distributed Work. *Distributed Work*.
2. Assistant Secretary for Public Affairs. 2013. System Usability Scale (SUS). Retrieved September 13, 2018 from /how-to-and-tools/methods/system-usability-scale.html
3. Cécilia Aguero and Philippe Chopin. 2012. Le ContrÔLe AÉRien Militaire Au Bout Des Doigts: Une Conception Multi-touch CentrÉe Utilisateur. In *Proceedings of the 2012 Conference on Ergonomie Et Interaction Homme-machine* (Ergo'IHM '12), 209:209–209:212. https://doi.org/10.1145/2652574.2653440
4. Imeh Akpan, Paul Marshall, Jon Bird, and Daniel Harrison. 2013. Exploring the Effects of Space and Place on Engagement with an Interactive Installation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13), 2213–2222. https://doi.org/10.1145/2470654.2481306
5. Thelma A. Allen. 2017. Health IT Usability. *NIST*. Retrieved October 30, 2018 from https://www.nist.gov/programs-projects/health-it-usability
6. R. R. Amalberti. 1999. AUTOMATION IN AVIATION: A HUMAN FACTORS PERSPECTIVE. IN: HANDBOOK OF AVIATION HUMAN FACTORS. *Publication of: Lawrence Erlbaum Associates, Incorporated*. Retrieved October 30, 2018 from https://trid.trb.org/view.aspx?id=507922
7. Paola Amaldi and Anthony Smoker. 2012. The Problem with Automation is Not Over-automation but Lack of Automation Policy. In *Proceedings of the 2Nd International Conference on Application and Theory of Automation in Command and Control Systems* (ATACCS '12), 176–181. Retrieved October 30, 2018 from http://dl.acm.org/citation.cfm?id=2325676.2325700
8. E. Ammenwerth, A. Buchauer, B. Bludau, and R. Haux. 2000. Mobile information and communication tools in the hospital. *International Journal of Medical Informatics* 57, 1: 21–40.
9. Christopher Andrews, Alex Endert, Beth Yost, and Chris North. 2011. Information visualization on large, high-resolution displays: Issues, challenges, and opportunities. *Information Visualization* 10, 4: 341–355. https://doi.org/10.1177/1473871611415997
10. Caroline Appert and Michel Beaudouin-Lafon. 2006. SwingStates: Adding State Machines to the Swing Toolkit. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology* (UIST '06), 319–322. https://doi.org/10.1145/1166253.1166302
11. Caroline Appert, Emmanuel Pietriga, Éléonore Bartenlian, and Rafael Morales González. 2018. Custom-made Tangible Interfaces with Touchtokens. In *Proceedings of the 2018 International Conference on Advanced Visual Interfaces* (AVI '18), 15:1–15:9. https://doi.org/10.1145/3206505.3206509

12. Joshua L. Argo, Catherine C. Vick, Laura A. Graham, Kamal M. F. Itani, Michael J. Bishop, and Mary T. Hawn. 2009. Elective surgical case cancellation in the Veterans Health Administration system: identifying areas for improvement. *American Journal of Surgery* 198, 5: 600–606. https://doi.org/10.1016/j.amjsurg.2009.07.005
13. Dominik Aronsky, Ian Jones, Kevin Lanaghan, and Corey M. Slovis. 2008. Supporting Patient Care in the Emergency Department with a Computerized Whiteboard System. *Journal of the American Medical Informatics Association : JAMIA* 15, 2: 184–194. https://doi.org/10.1197/jamia.M2489
14. Joan S. Ash, Marc Berg, and Enrico Coiera. 2004. Some Unintended Consequences of Information Technology in Health Care: The Nature of Patient Care Information System-related Errors. *Journal of the American Medical Informatics Association* 11, 2: 104–112. https://doi.org/10.1197/jamia.M1471
15. A. F. Attaallah, O. M. Elzamzamy, A. L. Phelps, P. Ranganthan, and M. C. Vallejo. 2016. Increasing operating room efficiency through electronic medical record analysis. *Journal of Perioperative Practice* 26, 5: 106–113. https://doi.org/10.1177/175045891602600503
16. Prasad Balkundi and David A. Harrison. 2006. Ties, Leaders, and Time in Teams: Strong Inference about Network Structure's Effects on Team Viability and Performance. *The Academy of Management Journal* 49, 1: 49–68. https://doi.org/10.2307/20159745
17. Robert Ball, Chris North, and Doug A. Bowman. 2007. Move to improve: promoting physical navigation to increase user performance with large displays. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, 191–200.
18. Jakob E. Bardram. 2009. Activity-based Computing for Medical Work in Hospitals. *ACM Trans. Comput.-Hum. Interact.* 16, 2: 10:1–10:36. https://doi.org/10.1145/1534903.1534907
19. Jakob E. Bardram and Claus Bossen. 2005. A Web of Coordinative Artifacts: Collaborative Work at a Hospital Ward. In *Proceedings of the 2005 International ACM SIGGROUP Conference on Supporting Group Work* (GROUP '05), 168–176. https://doi.org/10.1145/1099203.1099235
20. Jakob E. Bardram and Claus Bossen. 2005. Mobility Work: The Spatial Dimension of Collaboration at a Hospital. *Computer Supported Cooperative Work (CSCW)* 14, 2: 131–160. https://doi.org/10.1007/s10606-005-0989-y
21. Jakob E. Bardram, Thomas R. Hansen, and Mads Soegaard. 2006. AwareMedia: A Shared Interactive Display Supporting Social, Temporal, and Spatial Awareness in Surgery. In *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work* (CSCW '06), 109–118. https://doi.org/10.1145/1180875.1180892
22. Jakob E. Bardram and Steven Houben. 2018. Collaborative Affordances of Medical Records. *Computer Supported Cooperative Work (CSCW)* 27, 1: 1–36. https://doi.org/10.1007/s10606-017-9298-5
23. Jakob E. Bardram and Niels Nørskov. 2008. A Context-aware Patient Safety System for the Operating Room. In *Proceedings of the 10th International Conference on Ubiquitous Computing* (UbiComp '08), 272–281. https://doi.org/10.1145/1409635.1409672

24. Sakine Batun, Brian T. Denton, Todd R. Huschka, and Andrew J. Schaefer. 2010. Operating Room Pooling and Parallel Surgery Processing Under Uncertainty. *INFORMS Journal on Computing* 23, 2: 220–237. https://doi.org/10.1287/ijoc.1100.0396
25. Johannes Beller, Matthias Heesen, and Mark Vollrath. 2013. Improving the Driver–Automation Interaction: An Approach Using Automation Uncertainty. *Human Factors* 55, 6: 1130–1141. https://doi.org/10.1177/0018720813482327
26. Hugh Beyer and Karen Holtzblatt. 1997. *Contextual Design : A Customer-Centered Approach to Systems Designs (Morgan Kaufmann Series in Interactive Technologies)*. {Morgan Kaufmann}. Retrieved October 15, 2018 from http://www.amazon.fr/exec/obidos/ASIN/1558604111/citeulike04-21
27. Xiaojun Bi, Yuanchun Shi, and Xiaojie Chen. 2006. uPen: a smart pen-liked device for facilitating interaction on large displays. In *First IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP '06)*, 7 pp.-. https://doi.org/10.1109/TABLETOP.2006.35
28. Charles E. Billings. 2018. *Aviation Automation: The Search for A Human-centered Approach*. CRC Press.
29. Ashly D. Black, Josip Car, Claudia Pagliari, Chantelle Anandan, Kathrin Cresswell, Tomislav Bokun, Brian McKinstry, Rob Procter, Azeem Majeed, and Aziz Sheikh. 2011. The Impact of eHealth on the Quality and Safety of Health Care: A Systematic Overview. *PLOS Medicine* 8, 1: e1000387. https://doi.org/10.1371/journal.pmed.1000387
30. Susanne Bødker. 1989. A Human Activity Approach to User Interfaces. *Hum.-Comput. Interact.* 4, 3: 171–195. https://doi.org/10.1207/s15327051hci0403_1
31. Claus Bossen. 2018. Next Generation Healthcare Infrastructures: Firing, Hiring and Reskilling staff. Retrieved from https://di.ku.dk/begivenhedsmappe/begivenheder-2018/workshop-next-generation-of-electronic-health-records/Bossen.pdf
32. Claus Bossen and Erik Grönvall. 2015. Collaboration In-between: The Care Hotel and Designing for Flexible Use. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing* (CSCW '15), 1289–1301. https://doi.org/10.1145/2675133.2675243
33. Claus Bossen and Lotte Groth Jensen. 2014. How Physicians "Achieve Overview": A Case-based Study in a Hospital Ward. In *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing* (CSCW '14), 257–268. https://doi.org/10.1145/2531602.2531620
34. David Bouget, Max Allan, Danail Stoyanov, and Pierre Jannin. 2017. Vision-based and marker-less surgical tool detection and tracking: a review of the literature. *Medical Image Analysis* 35: 633–654. https://doi.org/10.1016/j.media.2016.09.003
35. Fabienne C. Bourgeois, Daniel J. Nigrin, and Marvin B. Harper. 2015. Preserving Patient Privacy and Confidentiality in the Era of Personal Health Records. *Pediatrics* 135, 5: e1125–e1127. https://doi.org/10.1542/peds.2014-3754
36. Stacy Branham, Gene Golovchinsky, Scott Carter, and Jacob T. Biehl. 2010. Let's Go from the Whiteboard: Supporting Transitions in Work Through Whiteboard Capture and Reuse. In

Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10), 75–84. https://doi.org/10.1145/1753326.1753338

37. Marie-Christine Bressolle, Bernard Pavard, and Marcel Leroux. 1998. The role of multimodal communication in cooperation: The cases of air traffic control. In *Multimodal Human-Computer Communication* (Lecture Notes in Computer Science), 326–343.
38. Marcellin Buisson, Alexandre Bustico, Stéphane Chatty, Francois-Régis Colin, Yannick Jestin, Sébastien Maury, Christophe Mertz, and Philippe Truillet. 2002. Ivy: Un Bus Logiciel Au Service Du DéVeloppement De Prototypes De SystèMes Interactifs. In *Proceedings of the 14th Conference on L'Interaction Homme-Machine* (IHM '02), 223–226. https://doi.org/10.1145/777005.777040
39. Emily M. Campbell, Dean F. Sittig, Joan S. Ash, Kenneth P. Guappone, and Richard H. Dykstra. 2006. Types of Unintended Consequences Related to Computerized Provider Order Entry. *Journal of the American Medical Informatics Association : JAMIA* 13, 5: 547–556. https://doi.org/10.1197/jamia.M2042
40. Stephen V. Cantrill. 2010. Computers in patient care: the promise and the challenge. *Communications of the ACM* 53, 9: 42. https://doi.org/10.1145/1810891.1810907
41. John M. Carroll (ed.). 1995. *Scenario-based Design: Envisioning Work and Technology in System Development*. John Wiley & Sons, Inc., New York, NY, USA.
42. Stéphane Chatty and Patrick Lecoanet. 1996. Pen Computing for Air Traffic Control. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '96), 87–94. https://doi.org/10.1145/238386.238436
43. Patrick Y. K. Chau. 1996. An empirical investigation on factors affecting the acceptance of CASE by systems developers. *Information & Management* 30, 6: 269–280. https://doi.org/10.1016/S0378-7206(96)01074-9
44. Patrick Y. K. Chau and Paul Jen-Hwa Hu. 2002. Investigating healthcare professionals' decisions to accept telemedicine technology: an empirical test of competing theories. *Information & Management* 39, 4: 297–311. https://doi.org/10.1016/S0378-7206(01)00098-2
45. Apoorve Chokshi, Teddy Seyed, Francisco Marinho Rodrigues, and Frank Maurer. 2014. ePlan Multi-Surface: A Multi-Surface Environment for Emergency Response Planning Exercises. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces* (ITS '14), 219–228. https://doi.org/10.1145/2669485.2669520
46. Jean Ho Chu, Paul Clifton, Daniel Harley, Jordanne Pavao, and Ali Mazalek. 2015. Mapping Place: Supporting Cultural Learning through a Lukasa-inspired Tangible Tabletop Museum Exhibit. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '14*, 261–268. https://doi.org/10.1145/2677199.2680559
47. Andrew Clayphan, Anthony Collins, Judy Kay, Nathan Slawitschka, and Jenny Horder. 2018. Comparing a Single-Touch Whiteboard and a Multi-Touch Tabletop for Collaboration in School Museum Visits. *IMWUT* 2: 6–6. https://doi.org/10.1145/3191738
48. Andrew Clayphan, Roberto Martinez-Maldonado, Martin Tomitsch, Susan Atkinson, and Judy Kay. 2016. An In-the-Wild Study of Learning to Brainstorm: Comparing Cards,

Tabletops and Wall Displays in the Classroom. *Interacting with Computers* 28, 6: 788–810. https://doi.org/10.1093/iwc/iww001
49. Larry L. Constantine and Lucy A. D. Lockwood. 1999. *Software for Use: A Practical Guide to the Models and Methods of Usage-Centered Design*. Pearson Education.
50. Stéphane Conversy, Hélène Gaspard-Boulinc, Stéphane Chatty, Stéphane Valès, Carole Dupré, and Claire Ollagnon. 2011. Supporting Air Traffic Control Collaboration with a TableTop System. In *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work* (CSCW '11), 425–434. https://doi.org/10.1145/1958824.1958891
51. Alfred Cuschieri. 2006. Nature of human error: implications for surgical practice. *Annals of Surgery* 244, 5: 642–648. https://doi.org/10.1097/01.sla.0000243601.36582.18
52. James W. Danaher. 1980. Human Error in ATC System Operations. *Human Factors* 22, 5: 535–545. https://doi.org/10.1177/001872088002200503
53. Deborah S. Debono, David Greenfield, Joanne F. Travaglia, Janet C. Long, Deborah Black, Julie Johnson, and Jeffrey Braithwaite. 2013. Nurses' workarounds in acute healthcare settings: a scoping review. *BMC Health Services Research* 13, 1: 175. https://doi.org/10.1186/1472-6963-13-175
54. Frederic Dehais, Vsevolod Peysakhovich, Sébastien Scannella, Jennifer Fongue, and Thibault Gateau. 2015. "Automation Surprise" in Aviation: Real-Time Solutions. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15), 2525–2534. https://doi.org/10.1145/2702123.2702521
55. W. Edwards Deming. 1986. *Out of the crisis*. Massachusetts Institute of Technology, Center for Advanced Engineering Study, Cambridge, Mass.
56. Brian T. Denton, Andrew J. Miller, Hari J. Balasubramanian, and Todd R. Huschka. 2010. Optimal Allocation of Surgery Blocks to Operating Rooms Under Uncertainty. *Operations Research* 58, 4-part-1: 802–816. https://doi.org/10.1287/opre.1090.0791
57. Elisabeth U. Dexter, Franklin Dexter, Danielle Masursky, Michael P. Garver, and Nancy A. Nussmeier. 2009. Both bias and lack of knowledge influence organizational focus on first case of the day starts. *Anesthesia and Analgesia* 108, 4: 1257–1261. https://doi.org/10.1213/ane.0b013e31819a6dd4
58. Nilanjan Dey, Amira S. Ashour, Fuqian Shi, Simon James Fong, and João Manuel R. S. Tavares. 2018. Medical cyber-physical systems: A survey. *Journal of Medical Systems* 42, 4: 74. https://doi.org/10.1007/s10916-018-0921-x
59. C. Diaz-Arrastia, C. Jurnalov, G. Gomez, and C. Townsend. 2002. Laparoscopic hysterectomy using a computer-enhanced surgical robot. *Surgical Endoscopy And Other Interventional Techniques* 16, 9: 1271–1273. https://doi.org/10.1007/s00464-002-8523-5
60. James Paul Dourish. 1996. Open implementation and flexibility in CSCW toolkits. University of London.
61. Paul Dourish. 2006. Re-space-ing Place: "Place" and "Space" Ten Years on. In *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work* (CSCW '06), 299–308. https://doi.org/10.1145/1180875.1180921

62. EMC and IDC. 2014. The Digital Universe Driving Data Growth in Healthcare. Retrieved from https://www.emc.com/analyst-report/digital-universe-healthcare-vertical-report-ar.pdf
63. S. Ayca Erdogan and Brian T. Denton. 2011. Surgery Planning and Scheduling. In *Wiley Encyclopedia of Operations Research and Management Science*. American Cancer Society. https://doi.org/10.1002/9780470400531.eorms0861
64. Abigail C Evans, Jacob O Wobbrock, and Katie Davis. 2016. Modeling Collaboration Patterns on an Interactive Tabletop in a Classroom Setting. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing - CSCW '16*, 858–869. https://doi.org/10.1145/2818048.2819972
65. Rollin J. Fairbanks, Theresa K. Guarrera, Keith S. Karn, Stanley H. Caplan, Manish N. Shah, and Robert L. Wears. 2008. Interface Design Characteristics of a Popular Emergency Department Information System. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 52, 12: 778–782. https://doi.org/10.1177/154193120805201203
66. Geraldine Fitzpatrick and Gunnar Ellingsen. 2013. A Review of 25 Years of CSCW Research in Healthcare: Contributions, Challenges and Future Agendas. *Computer Supported Cooperative Work (CSCW)* 22, 4: 609–665. https://doi.org/10.1007/s10606-012-9168-0
67. Marc Garbey, Guillaume Joerger, Albert Huang, Remi Salmon, Jinsu Kim, Vadim Sherman, Brian Dunkin, and Barbara Bass. 2015. An intelligent hospital operating room to improve patient health care. *Journal of Computational Surgery* 2, 1: 3. https://doi.org/10.1186/s40244-015-0016-7
68. Marc Garbey, Guillaume Joerger, Juliette Rambourg, Brian Dunkin, and Barbara Bass. 2017. Multiscale Modeling of Surgical Flow in a Large Operating Room Suite: Understanding the Mechanism of Accumulation of Delays in Clinical Practice. *Procedia Computer Science* 108: 1863–1872. https://doi.org/10.1016/j.procs.2017.05.228
69. Marc Garbey, Juliette Rambourg, Guillaume Joerger, Brian J. Dunkin, and Barbara L. Bass. 2017. Multiscale Modeling of Surgical Flow Explains Lognormal Distribution of Surgical Time and Occurrence of Large Delays. *Journal of the American College of Surgeons* 225, 4, Supplement 2: e22. https://doi.org/10.1016/j.jamcollsurg.2017.07.580
70. H. Gaspard-Boulinc and S. Conversy. 2017. Usability Insights for Requirements Engineering Tools: A User Study with Practitioners in Aeronautics. In *2017 IEEE 25th International Requirements Engineering Conference (RE)*, 223–232. https://doi.org/10.1109/RE.2017.20
71. Trisha Greenhalgh, Libby Morris, Jeremy C. Wyatt, Gwyn Thomas, and Katey Gunning. 2013. Introducing a nationally shared electronic patient record: Case study comparison of Scotland, England, Wales and Northern Ireland. *International Journal of Medical Informatics* 82, 5: e125–e138. https://doi.org/10.1016/j.ijmedinf.2013.01.002
72. Trisha Greenhalgh, Henry W. W. Potts, Geoff Wong, Pippa Bark, and Deborah Swinglehurst. 2009. Tensions and paradoxes in electronic patient record research: a systematic literature review using the meta-narrative method. *The Milbank Quarterly* 87, 4: 729–788. https://doi.org/10.1111/j.1468-0009.2009.00578.x

73. Gido Albert Hakvoort. 2016. Multi-touch and mobile technologies for galleries, libraries, archives and museums. University of Birmingham. Retrieved September 14, 2018 from http://etheses.bham.ac.uk/6901/
74. Shah Ahsanul Haque, Syed Mahfuzul Aziz, and Mustafizur Rahman. 2014. Review of Cyber-Physical System in Healthcare. *International Journal of Distributed Sensor Networks* 10, 4: 217415. https://doi.org/10.1155/2014/217415
75. Jed Harris and Austin Henderson. 1999. A Better Mythology for System Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '99), 88–95. https://doi.org/10.1145/302979.303003
76. Steve Harrison and Paul Dourish. 1996. Re-place-ing space: the roles of place and space in collaborative systems. In *Proceedings of the 1996 ACM conference on Computer supported cooperative work - CSCW '96*, 67–76. https://doi.org/10.1145/240080.240193
77. Robert L. Helmreich. 2000. On error management: lessons from aviation. *BMJ* 320, 7237: 781–785. https://doi.org/10.1136/bmj.320.7237.781
78. Morten Hertzum. 2017. The Cost of Improved Overview: An Analysis of the Use of Electronic Whiteboards in Emergency Departments. In *Human-Computer Interaction - INTERACT 2017* (Lecture Notes in Computer Science), 402–410.
79. Morten Hertzum and Jesper Simonsen. 2015. Visual overview, oral detail: The use of an emergency-department whiteboard. *International Journal of Human-Computer Studies* 82: 21–30. https://doi.org/10.1016/j.ijhcs.2015.04.004
80. Richard Hillestad, James Bigelow, Anthony Bower, Federico Girosi, Robin Meili, Richard Scoville, and Roger Taylor. 2005. Can electronic medical record systems transform health care? Potential health benefits, savings, and costs. *Health Affairs (Project Hope)* 24, 5: 1103–1117. https://doi.org/10.1377/hlthaff.24.5.1103
81. David U. Himmelstein, Adam Wright, and Steffie Woolhandler. 2010. Hospital computing and the costs and quality of care: a national study. *The American Journal of Medicine* 123, 1: 40–46. https://doi.org/10.1016/j.amjmed.2009.09.004
82. Chih-Yuan Ho, Mark I. Nikolic, Molly J. Waters, and Nadine B. Sarter. 2004. Not Now! Supporting interruption management by indicating the modality and urgency of pending tasks. *Human Factors* 46, 3: 399–409. https://doi.org/10.1518/hfes.46.3.399.50397
83. David Hoyt and Clifford Ko. 2017. *Optimal Resources for Surgical Quality and Safety*. ACS.
84. Pi-Jung Hsieh. 2015. Healthcare professionals' use of health clouds: Integrating technology acceptance and status quo bias perspectives. *International Journal of Medical Informatics* 84, 7: 512–523. https://doi.org/10.1016/j.ijmedinf.2015.03.004
85. D. Hu, Y. Gong, B. Hannaford, and E. J. Seibel. 2015. Semi-autonomous simulated brain tumor ablation with RAVENII Surgical Robot using behavior tree. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 3868–3875. https://doi.org/10.1109/ICRA.2015.7139738
86. Albert Y. Huang, Guillaume Joerger, Vid Fikfak, Remi Salmon, Brian J. Dunkin, Barbara L. Bass, and Marc Garbey. 2017. The SmartOR: a distributed sensor network to improve

operating room efficiency. *Surgical Endoscopy* 31, 9: 3590–3595. https://doi.org/10.1007/s00464-016-5390-z

87. Albert Y. Huang, Guillaume Joerger, Remi Salmon, Brian Dunkin, Vadim Sherman, Barbara L. Bass, and Marc Garbey. 2016. A robust and non-obtrusive automatic event tracking system for operating room management to improve patient care. *Surgical Endoscopy* 30, 8: 3638–3645. https://doi.org/10.1007/s00464-015-4610-2
88. Christophe Hurter, Rémi Lesbordes, Catherine Letondal, Jean-Luc Vinot, and Stéphane Conversy. 2012. Strip'TIC: Exploring Augmented Paper Strips for Air Traffic Controllers. In *Proceedings of the International Working Conference on Advanced Visual Interfaces* (AVI '12), 225–232. https://doi.org/10.1145/2254556.2254598
89. Edwin L. Hutchins, James D. Hollan, and Donald A. Norman. 1985. Direct Manipulation Interfaces. *Hum.-Comput. Interact.* 1, 4: 311–338. https://doi.org/10.1207/s15327051hci0104_2
90. Hilary Hutchinson, Wendy Mackay, Bo Westerlund, Benjamin B. Bederson, Allison Druin, Catherine Plaisant, Michel Beaudouin-Lafon, Stéphane Conversy, Helen Evans, Heiko Hansen, Nicolas Roussel, and Björn Eiderbäck. 2003. Technology Probes: Inspiring Design for and with Families. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '03), 17–24. https://doi.org/10.1145/642611.642616
91. P. Isenberg, D. Fisher, S. A. Paul, M. R. Morris, K. Inkpen, and M. Czerwinski. 2012. Co-Located Collaborative Visual Analytics around a Tabletop Display. *IEEE Transactions on Visualization and Computer Graphics* 18, 5: 689–702. https://doi.org/10.1109/TVCG.2011.287
92. Mikkel R. Jakobsen and Kasper HornbÆk. 2014. Up Close and Personal: Collaborative Work on a High-resolution Multitouch Wall Display. *ACM Trans. Comput.-Hum. Interact.* 21, 2: 11:1–11:34. https://doi.org/10.1145/2576099
93. Marina Jirotka, Rob Procter, Mark Hartswood, Roger Slack, Andrew Simpson, Catelijne Coopmans, Chris Hinds, and Alex Voss. 2005. Collaboration and Trust in Healthcare Innovation: The eDiaMoND Case Study. *Computer Supported Cooperative Work* 14: 369–398. https://doi.org/10.1007/s10606-005-9001-0
94. G. Joerger, J. Rambourg, M. Garbey, S. Conversy, and H. Gaspard-Boulinc. 2017. Re-engineer operating room data acquisition and transmission for improving surgical suite awareness and management. In *2017 IEEE EMBS International Conference on Biomedical Health Informatics (BHI)*, 205–208. https://doi.org/10.1109/BHI.2017.7897241
95. Guillaume Joerger. 2017. Multiscale modeling and event tracking wireless technologies to improve efficiency and safety of the surgical flow in an OR suite.
96. Guillaume Joerger, Juliette Rambourg, Helene Gaspard-Boulinc, Stephane Conversy, Barbara L. Bass, Brian J. Dunkin, and Marc Garbey. 2018. A Cyber-Physical System to Improve the Management of a Large Suite of Operating Rooms. *ACM Trans. Cyber-Phys. Syst.* 2, 4: 34:1–34:24. https://doi.org/10.1145/3140234
97. Patrick W. Jordan, B. Thomas, Ian Lyall McClelland, and Bernard Weerdmeester. 1996. *Usability Evaluation In Industry*. CRC Press.

98. Clare-Marie Karat. 1994. Cost-justifying Usability. In Randolph G. Bias and Deborah J. Mayhew (eds.). Academic Press, Inc., Orlando, FL, USA, 45–70. Retrieved October 2, 2018 from http://dl.acm.org/citation.cfm?id=186524.186609
99. Joakim Klemets and Pieter Toussaint. 2015. Availability Communication: Requirements for an Awareness System to Support Nurses' Handling of Nurse Calls. *Studies in Health Technology and Informatics* 216: 103–107.
100. Ross Koppel and Christoph U. Lehmann. 2015. Implications of an emerging EHR monoculture for hospitals and healthcare systems. *Journal of the American Medical Informatics Association: JAMIA* 22, 2: 465–471. https://doi.org/10.1136/amiajnl-2014-003023
101. Katharina Kovacs Burns, Mandy Bellows, Carol Eigenseher, and Jennifer Gallivan. 2014. "Practical" resources to support patient and family engagement in healthcare decisions: a scoping review. *BMC health services research* 14: 175. https://doi.org/10.1186/1472-6963-14-175
102. Leah Kulp, Aleksandra Sarcevic, Richard Farneth, Omar Ahmed, Dung Mai, Ivan Marsic, and Randall S. Burd. 2017. Exploring Design Opportunities for a Context-Adaptive Medical Checklist Through Technology Probe Approach. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (DIS '17), 57–68. https://doi.org/10.1145/3064663.3064715
103. Diana Kusunoki, Aleksandra Sarcevic, Zhan Zhang, and Maria Yala. 2015. Sketching Awareness: A Participatory Study to Elicit Designs for Supporting Ad Hoc Emergency Medical Teamwork. *Computer supported cooperative work : CSCW : an international journal* 24, 1: 1–38. https://doi.org/10.1007/s10606-014-9210-5
104. C. E. Lasome and Y. Xiao. 2001. Large public display boards: a case study of an OR board and design implications. *Proceedings of the AMIA Symposium*: 349–353.
105. I. Lee, O. Sokolsky, S. Chen, J. Hatcliff, E. Jee, B. Kim, A. King, M. Mullen-Fortino, S. Park, A. Roederer, and K. K. Venkatasubramanian. 2012. Challenges and Research Directions in Medical Cyber–Physical Systems. *Proceedings of the IEEE* 100, 1: 75–90. https://doi.org/10.1109/JPROC.2011.2165270
106. Jakob Leitner, James Powell, Peter Brandl, Thomas Seifried, Michael Haller, Bernard Dorray, and Paul To. 2009. Flux: A Tilting Multi-touch and Pen Based Surface. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '09), 3211–3216. https://doi.org/10.1145/1520340.1520459
107. Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, and Eric Lecolinet. 2016. Shared Interaction on a Wall-Sized Display in a Data Manipulation Task. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16), 2075–2086. https://doi.org/10.1145/2858036.2858039
108. Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, Éric Lecolinet, and Wendy E. Mackay. 2014. Effects of Display Size and Navigation Type on a Classification Task. 10 pages. Retrieved October 16, 2018 from https://hal.archives-ouvertes.fr/hal-00957269/document
109. Anna Loparev, Lauren Westendorf, Margaret Flemings, Jennifer Cho, Romie Littrell, Anja Scholze, and Orit Shaer. 2017. BacPack: Exploring the Role of Tangibles in a Museum

Exhibit for Bio-Design. In *Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '17*, 111–120. https://doi.org/10.1145/3024969.3025000
110. Daniel Thom Lopes, Renato Balancieri, Heloise Manica Paris Teixeira, and Maria Madalena Dias. 2014. Electronic Whiteboard in Hospitals: a systematic review. *Journal of Health Informatics* 6, 4. Retrieved September 17, 2018 from http://www.jhi-sbis.saude.ws/ojs-jhi/index.php/jhi-sbis/article/view/324
111. M. J. H. Lum, J. Rosen, M. N. Sinanan, and B. Hannaford. 2006. Optimization of a spherical mechanism for a minimally invasive surgical robot: theoretical and experimental approaches. *IEEE Transactions on Biomedical Engineering* 53, 7: 1440–1445. https://doi.org/10.1109/TBME.2006.875716
112. Wendy E. MacKay. 1999. Is Paper Safer? The Role of Paper Flight Strips in Air Traffic Control. *ACM Trans. Comput.-Hum. Interact.* 6, 4: 311–340. https://doi.org/10.1145/331490.331491
113. Fabrice Matulic, Daniel Vogel, and Raimund Dachselt. 2017. Hand Contact Shape Recognition for Posture-Based Tabletop Widgets and Interaction. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (ISS '17), 3–11. https://doi.org/10.1145/3132272.3134126
114. Emma M. Mercier, Steven E. Higgins, and Andrew Joyce-Gibbons. 2016. The effects of room design on computer-supported collaborative learning in a multi-touch classroom. *Interactive Learning Environments* 24, 3: 504–522. https://doi.org/10.1080/10494820.2014.881392
115. Christophe Mertz, Stéphane Chatty, and Jean-Luc Vinot. 2000. The influence of design techniques on user interfaces: the DigiStrips experiment for air traffic control.
116. Christophe P. Mertz, Stéphane Chatty, and Jean-Luc Vinot. 2000. Pushing the limits of ATC user interface design beyond S & M interaction : the DigiStrips experience. In *3rd USA/Europe Air Traffic Management R&D Seminar Napoli*.
117. André Mewes, Bennet Hensen, Frank Wacker, and Christian Hansen. 2017. Touchless interaction with software in interventional radiology and surgery: a systematic literature review. *International Journal of Computer Assisted Radiology and Surgery* 12, 2: 291–305. https://doi.org/10.1007/s11548-016-1480-6
118. Rafael Morales González. 2017. Rich multi-touch input with passive tokens. Paris Saclay. Retrieved September 17, 2018 from http://www.theses.fr/2017SACLS309
119. Rafael Morales Gonzalez, Caroline Appert, Gilles Bailly, and Emmanuel Pietriga. 2016. TouchTokens: Guiding Touch Patterns with Passive Tokens. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16), 4189–4202. https://doi.org/10.1145/2858036.2858041
120. Rafael Morales González, Caroline Appert, Gilles Bailly, and Emmanuel Pietriga. 2017. Passive Yet Expressive TouchTokens. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17), 3741–3745. https://doi.org/10.1145/3025453.3025894

121. Pamela J. Morgan, Lisa Cunningham, Sohini Mitra, Natalie Wong, Wei Wu, Victoria Noguera, Mary Li, and John Semple. 2013. Surgical safety checklist: implementation in an ambulatory surgical facility. *Canadian Journal of Anaesthesia = Journal Canadien D'anesthesie* 60, 6: 528–538. https://doi.org/10.1007/s12630-013-9916-8
122. Jacqueline Moss, Yan Xiao, and Siti Zubaidah. 2002. The Operating Room Charge Nurse: Coordinator and Communicator. *Journal of the American Medical Informatics Association : JAMIA* 9, 6 Suppl 1: s70–s74. https://doi.org/10.1197/jamia.M1231
123. Jakob Nielsen. 1993. *Usability Engineering*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.
124. Jakob Nielsen. 1994. Usability Inspection Methods. In *Conference Companion on Human Factors in Computing Systems* (CHI '94), 413–414. https://doi.org/10.1145/259963.260531
125. Don Norman. 2013. *The Design of Everyday Things: Revised and Expanded Edition*. Basic Books.
126. Halla Olafsdottir and Caroline Appert. 2014. Multi-touch Gestures for Discrete and Continuous Control. In *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces* (AVI '14), 177–184. https://doi.org/10.1145/2598153.2598169
127. Esben Warming Pedersen and Kasper Hornbæk. 2012. An experimental comparison of touch interaction on vertical and horizontal surfaces. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction Making Sense Through Design - NordiCHI '12*, 370. https://doi.org/10.1145/2399016.2399074
128. Ken Pfeuffer, Jason Alexander, and Hans Gellersen. 2016. GazeArchers: playing with individual and shared attention in a two-player look&shoot tabletop game. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia - MUM '16*, 213–216. https://doi.org/10.1145/3012709.3012717
129. David Pinelle and Carl Gutwin. 2002. Groupware Walkthrough: Adding Context to Groupware Usability Evaluation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '02), 455–462. https://doi.org/10.1145/503376.503458
130. Raquel Pinto, Palmyre Pierroux, Nelson Zagalo, and Lia Raquel Oliveira. 2015. Developing an interactive tabletop application for 'Creative Interpretation' in art museums. In *11th International Conference on Computer Supported Collaborative Learning*. Retrieved September 14, 2018 from http://repositorium.sdum.uminho.pt/handle/1822/42134
131. Peter G. Polson, Clayton Lewis, John Rieman, and Cathleen Wharton. 1992. Cognitive walkthroughs: a method for theory-based evaluation of user interfaces. *International Journal of man-machine studies* 36, 5: 741–773.
132. Ilinca Popovici, Plinio P. Morita, Diane Doran, Stephen Lapinsky, Dante Morra, Ashleigh Shier, Robert Wu, and Joseph A. Cafazzo. 2015. Technological aspects of hospital communication challenges: an observational study. *International Journal for Quality in Health Care: Journal of the International Society for Quality in Health Care* 27, 3: 183–188. https://doi.org/10.1093/intqhc/mzv016
133. Varuna Prakash, Christine Koczmara, Pamela Savage, Katherine Trip, Janice Stewart, Tara McCurdie, Joseph A. Cafazzo, and Patricia Trbovich. 2014. Mitigating errors caused by

interruptions during medication verification and administration: interventions in a simulated ambulatory chemotherapy setting. *BMJ Qual Saf*: bmjqs-2013-002484. https://doi.org/10.1136/bmjqs-2013-002484

134. Arnaud Prouzeau, Anastasia Bezerianos, and Olivier Chapuis. 2016. Towards Road Traffic Management with Forecasting on Wall Displays. In *Proceedings of the 2016 International Conference on Interactive Surfaces and Spaces* (ISS '16), 119–128. https://doi.org/10.1145/2992154.2992158
135. Juliette Rambourg, Stéphane Conversy, Hélène Gaspard-Boulinc, and Marc Garbey. 2016. Collaboration Within the Surgical Suite: BoardProbe Design for and with the Surgical Team. In *Actes De La 28ieme Conference Francophone Sur L'Interaction Homme-Machine* (IHM '16), 271–277. https://doi.org/10.1145/3004107.3004138
136. Juliette Rambourg, Hélène Gaspard-Boulinc, Stéphane Conversy, and Marc Garbey. 2018. Welcome OnBoard: An Interactive Large Surface Designed for Teamwork and Flexibility in Surgical Flow Management. In *ACM - Interactive Surface and Space (ISS'18)*. https://doi.org/10.1145/3279778.3279805
137. R Rasmussen, B Fleron, Morten Hertzum, and Jesper Simonsen. 2010. Balancing Tradition and Transcendence in the Implementation of Emergency-Department Electronic Whiteboads. *Selected Papers of the Information Systems Research Seminar in Scandinavia 2010*.
138. Rasmus Rasmussen. 2012. Electronic Whiteboards in Emergency Medicine: A Systematic Review. In *Proceedings of the 2Nd ACM SIGHIT International Health Informatics Symposium* (IHI '12), 483–492. https://doi.org/10.1145/2110363.2110418
139. Rasmus Rasmussen and Morten Hertzum. 2013. Visualizing the application of filters: A comparison of blocking, blurring, and colour-coding whiteboard information. *International Journal of Human-Computer Studies* 71, 10: 946–957. https://doi.org/10.1016/j.ijhcs.2013.06.002
140. Khairi Reda, Andrew E. Johnson, Michael E. Papka, and Jason Leigh. 2015. Effects of Display Size and Resolution on User Behavior and Insight Acquisition in Visual Exploration. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15), 2759–2768. https://doi.org/10.1145/2702123.2702406
141. Madhu C. Reddy, Paul Dourish, and Wanda Pratt. 2001. Coordinating Heterogeneous Work: Information and Representation in Medical Care. In *ECSCW 2001: Proceedings of the Seventh European Conference on Computer Supported Cooperative Work 16–20 September 2001, Bonn, Germany*, Wolfgang Prinz, Matthias Jarke, Yvonne Rogers, Kjeld Schmidt and Volker Wulf (eds.). Springer Netherlands, Dordrecht, 239–258. https://doi.org/10.1007/0-306-48019-0_13
142. Jun Rekimoto. 1997. Pick-and-drop: A Direct Manipulation Technique for Multiple Computer Environments. In *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology* (UIST '97), 31–39. https://doi.org/10.1145/263407.263505
143. Alexander Rind, Taowei David Wang, Wolfgang Aigner, Silvia Miksch, Krist Wongsuphasawat, Catherine Plaisant, and Ben Shneiderman. 2013. Interactive Information

Visualization to Explore and Query Electronic Health Records. *Foundations and Trends® in Human–Computer Interaction* 5, 3: 207–298. https://doi.org/10.1561/1100000039
144. Markus Rittenbruch and Gregor McEwan. 2009. An Historical Reflection of Awareness in Collaboration. In *Awareness Systems: Advances in Theory, Methodology and Design*, Panos Markopoulos, Boris De Ruyter and Wendy Mackay (eds.). Springer London, London, 3–48. https://doi.org/10.1007/978-1-84882-477-5_1
145. LAURENCE Rognin, PASCAL Salembier, and MOUSTAPHA Zouinar. 2000. Cooperation, reliability of socio-technical systems and allocation of function. *International Journal of Human-Computer Studies* 52, 2: 357–379. https://doi.org/10.1006/ijhc.1999.0293
146. J. Rosen, L. N. Sekhar, D. Glozman, M. Miyasaka, J. Dosher, B. Dellon, K. S. Moe, A. Kim, L. J. Kim, T. Lendvay, Y. Li, and B. Hannaford. 2017. Roboscope: A flexible and bendable surgical robot for single portal Minimally Invasive Surgery. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*, 2364–2370. https://doi.org/10.1109/ICRA.2017.7989274
147. M. Rudisill. 1994. Flight crew experience with automation technologies on commercial transport flight decks. *Human performance in automated systems: Current research and trends*: 203–211.
148. Vít Rusnák, Caroline Appert, Olivier Chapuis, and Emmanuel Pietriga. 2018. Designing Coherent Gesture Sets for Multi-scale Navigation on Tabletops. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 1–12. https://doi.org/10.1145/3173574.3173716
149. M. Saffarian, J. C. F. de Winter, and R. Happee. 2012. Automated Driving: Human-Factors Issues and Design Solutions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 56, 1: 2296–2300. https://doi.org/10.1177/1071181312561483
150. Dan Saffer. 2013. *Microinteractions: Designing with Details*. O'Reilly Media, Inc.
151. Douglas Schuler and Aki Namioka. 1993. *Participatory Design: Principles and Practices*. CRC Press.
152. Stacey D. Scott, M. Sheelagh T. Carpendale, and Kori M. Inkpen. 2004. Territoriality in Collaborative Tabletop Workspaces. In *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work* (CSCW '04), 294–303. https://doi.org/10.1145/1031607.1031655
153. P. Scupelli, S. Fussell, Kiesler, Sara, Yuqing Ren, P. Scupelli, S. Fussell, Kiesler, Sara, and Yuqing Ren. 2007. Trajectories in Multiple Group Coordination: A Field Study of Hospital Operating Suites. In *2007 40th Annual Hawaii International Conference on System Sciences (HICSS'07)*, 138–138. https://doi.org/10.1109/HICSS.2007.578
154. Peter G. Scupelli, Yan Xiao, Susan R. Fussell, Sara Kiesler, and Mark D. Gross. 2010. Supporting Coordination in Surgical Suites: Physical Aspects of Common Information Spaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10), 1777–1786. https://doi.org/10.1145/1753326.1753593
155. Aviv Shachak and Shmuel Reis. 2009. The impact of electronic medical records on patient-doctor communication during consultation: a narrative literature review. *Journal of*

Evaluation in Clinical Practice 15, 4: 641–649. https://doi.org/10.1111/j.1365-2753.2008.01065.x
156. James S. Shaha, Mouhanad M. El-Othmani, Jamal K. Saleh, Kevin J. Bozic, James Wright, John M. Tokish, Steve H. Shaha, and Khaled J. Saleh. 2015. The Growing Gap in Electronic Medical Record Satisfaction Between Clinicians and Information Technology Professionals: Issues of Most Concern and Suggested Remediations. *JBJS* 97, 23: 1979. https://doi.org/10.2106/JBJS.N.01118
157. B. Shneiderman, C. Plaisant, and B. W. Hesse. 2013. Improving Healthcare with Interactive Visualization. *Computer* 46, 5: 58–66. https://doi.org/10.1109/MC.2013.38
158. Ben Shneiderman, Catherine Plaisant, Maxine Cohen, and Steven Jacobs. 2009. *Designing the User Interface: Strategies for Effective Human-Computer Interaction*. Addison-Wesley Publishing Company, USA.
159. Stéphane Sire. 2000. La collaboration directe d'un paradigme d'interaction pour le travail assisté par ordinateur. Toulouse 1. Retrieved October 29, 2018 from http://www.theses.fr/2000TOU10005
160. Stéphane Sire, Stéphane Chatty, Hélène Gaspard-Boulinc, and François-Régis Colin. 1999. How Can Groupware Preserve our Coordination Skills? Designing for Direct Collaboration. In *INTERACT*, 304–312.
161. Salvatore Sorce, Stefano Ruggieri, Vito Gentile, Antonio Gentile, and Alessio Malizia. 2017. Human-to-Human Interaction: The Killer Application of Ubiquitous Computing? In *Human-Computer Interaction. User Interface Design, Development and Multimodality* (Lecture Notes in Computer Science), 86–93.
162. Pieter S. Stepaniak and Franklin Dexter. 2016. Constraints on the scheduling of urgent and emergency surgical cases: Surgeon, equipment, and anesthesiologist availability. *Perioperative Care and Operating Room Management* 3: 6–11. https://doi.org/10.1016/j.pcorm.2016.02.001
163. Anthony Tang, Joel Lanir, Saul Greenberg, and Sidney Fels. 2009. Supporting Transitions in Work: Informing Large Display Application Design by Understanding Whiteboard Use. In *Proceedings of the ACM 2009 International Conference on Supporting Group Work* (GROUP '09), 149–158. https://doi.org/10.1145/1531674.1531697
164. Anthony Tang, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. 2006. Collaborative Coupling over Tabletop Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '06), 1181–1190. https://doi.org/10.1145/1124772.1124950
165. Charlotte Tang and Sheelagh Carpendale. 2008. Evaluating the Deployment of a Mobile Technology in a Hospital Ward. In *Proceedings of the 2008 ACM Conference on Computer Supported Cooperative Work* (CSCW '08), 205–214. https://doi.org/10.1145/1460563.1460596
166. Sara Tena, Ignacio Aedo, David Díez, and Paloma Díaz. 2014. TIPExtop: An exploratory design tool for emergency planning. *ISCRAM*. Retrieved September 11, 2018 from

/paper/TIPExtop%3A-An-exploratory-design-tool-for-emergency-Tena-Aedo/20cb52cb2ab54da4286f76cfe77769e056f4d8b9
167. Harold Thimbleby. 2013. Technology and the Future of Healthcare. *Journal of Public Health Research* 2, 3. https://doi.org/10.4081/jphr.2013.e28
168. N. J. Toff. 2010. Human factors in anaesthesia: lessons from aviation. *BJA: British Journal of Anaesthesia* 105, 1: 21–25. https://doi.org/10.1093/bja/aeq127
169. Lili Tong, Aurélien Tabard, Sébastien George, and Audrey Serna. 2017. Horizontal vs. Vertical: How the Orientation of a Large Interactive Surface Impacts Collaboration in Multi-surface Environments. In *Human-Computer Interaction – INTERACT 2017* (Lecture Notes in Computer Science), 202–222.
170. Thomas C. Tsai, E. John Orav, and Ashish K. Jha. 2015. Patient satisfaction and quality of surgical care in US hospitals. *Annals of Surgery* 261, 1: 2–8. https://doi.org/10.1097/SLA.0000000000000765
171. Stéphane Vales, Stéphane Chatty, Alexandre Lemort, and Stéphane Conversy. 2006. MAMMI Phase1-Collaborative workspaces for en-route air traffic controllers. In *INO 2006, 5th Eurocontrol Innovative Research Workshop & Exhibition*.
172. Stéphane Valès, Stéphane Chatty, Alexandre Lemort, and Stéphane Conversy. 2006. MAMMI Phase1- Collaborative workspaces for en-route air traffic controllers. pp 5-10. Retrieved September 13, 2018 from https://hal-enac.archives-ouvertes.fr/hal-01021772/document
173. Stéphane Vales, Stéphane Conversy, Jérome Lard, and Claire Ollagnon. 2007. MAMMI Phase2-Design and evaluation test bed for collaborative practices on en-route control positions. In *CARE-INO 2007, 6th Eurocontrol Innovative Research Workshop & Exhibition*.
174. Stéphane Valès, Stéphane Conversy, Jérome Lard, and Claire Ollagnon. 2007. MAMMI Phase2 - Design and evaluation test bed for collaborative practices on en-route control positions. pp 37-45. Retrieved September 13, 2018 from https://hal-enac.archives-ouvertes.fr/hal-01021978/document
175. Stéphane Valès, Carole Dupré, Hélène Gaspard-Boulinc, Stéphane Conversy, Claire Ollagnon, Vincent Peyruquéou, and Joel Viala. 2008. MAMMI Phase 3 - Exploring collaborative workspaces for air traffic controllers in the scope of SESAR. pp 15-24. Retrieved September 13, 2018 from https://hal-enac.archives-ouvertes.fr/hal-01022265/document
176. Taowei David Wang, Krist Wongsuphasawat, Catherine Plaisant, and Ben Shneiderman. 2011. Extracting insights from electronic health records: case studies, a visual analytics process model, and design recommendations. *Journal of medical systems* 35, 5: 1135–1152.
177. Mark Weiser. 1999. The computer for the 21st century. *Mobile Computing and Communications Review* 3, 3: 3–11.
178. Steve Whittaker, David Frohlich, and Owen Daly-Jones. 1994. Informal Workplace Communication: What is It Like and How Might We Support It? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '94), 131–137. https://doi.org/10.1145/191666.191726

179. Steve Whittaker and Heinrich Schwarz. 1999. Meetings of the Board: The Impact of Scheduling Medium on Long Term Group Coordination in Software Development. *Computer Supported Cooperative Work (CSCW)* 8, 3: 175–205. https://doi.org/10.1023/A:1008603001894
180. Earl L. Wiener. 1989. *Human factors of advanced technology (glass cockpit) transport aircraft*. Retrieved November 5, 2018 from https://ntrs.nasa.gov/search.jsp?R=19890016609
181. Hannah J. Wong, Michael Caesar, Salim Bandali, James Agnew, and Howard Abrams. 2009. Electronic inpatient whiteboards: Improving multidisciplinary communication and coordination of care. *International Journal of Medical Informatics* 78, 4: 239–247. https://doi.org/10.1016/j.ijmedinf.2008.07.012
182. Krist Wongsuphasawat, John Alexis Guerra Gomez, Catherine Plaisant, Taowei David Wang, Ben Shneiderman, and Meirav Taieb-Maimon. 2011. LifeFlow: visualizing an overview of event sequences. 10.
183. Yan Xiao, Caterina Lasome, Jacqueline Moss, Colin F. Mackenzie, and Samer Faraj. 2001. Cognitive Properties of a Whiteboard: A Case Study in a Trauma Centre. In *ECSCW 2001: Proceedings of the Seventh European Conference on Computer Supported Cooperative Work 16–20 September 2001, Bonn, Germany*, Wolfgang Prinz, Matthias Jarke, Yvonne Rogers, Kjeld Schmidt and Volker Wulf (eds.). Springer Netherlands, Dordrecht, 259–278. https://doi.org/10.1007/0-306-48019-0_14
184. Yan Xiao, Stephen Schenkel, Samer Faraj, Colin F. Mackenzie, and Jacqueline Moss. 2007. What Whiteboards in a Trauma Center Operating Suite Can Teach Us About Emergency Department Communication. *Annals of Emergency Medicine* 50, 4: 387–395. https://doi.org/10.1016/j.annemergmed.2007.03.027
185. Ulrich von Zadow, Daniel Bösel, Duc Dung Dam, Anke Lehmann, Patrick Reipschläger, and Raimund Dachselt. 2016. Miners: Communication and Awareness in Collaborative Gaming at an Interactive Display Wall. In *Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces* (ISS '16), 235–240. https://doi.org/10.1145/2992154.2992174
186. Shumin Zhai. 2012. Foundational Issues in Touch-Surface Stroke Gesture Design — An Integrative Review. *Foundations and Trends® in Human–Computer Interaction* 5, 2: 97–205. https://doi.org/10.1561/1100000012
187. Cheng Zhang, Pingbo Tang, Nancy Cooke, Verica Buchanan, Alper Yilmaz, Shawn W. St. Germain, Ronald Laurids Boring, Saliha Akca-Hobbins, and Ashish Gupta. 2017. Human-centered automation for resilient nuclear power plant outage control. *Automation in Construction* 82: 179–192. https://doi.org/10.1016/j.autcon.2017.05.001
188. HOME. *WearTheCost.org*. Retrieved October 2, 2018 from https://www.wearthecost.org/index.html
189. computerize Definition in the Cambridge English Dictionary. Retrieved August 30, 2018 from https://dictionary.cambridge.org/us/dictionary/english/computerize
190. 25 largest hospitals in America. Retrieved October 3, 2018 from https://www.beckershospitalreview.com/lists/25-largest-hospitals-in-americajan-18.html

191. About Us - NewYork-Presbyterian. Retrieved October 3, 2018 from https://www.nyp.org/about-us
192. ISO 9241-210:2010 - Ergonomics of human-system interaction -- Part 210: Human-centred design for interactive systems. Retrieved September 6, 2018 from https://www.iso.org/standard/52075.html
193. CRM Training Implementation. *EASA*. Retrieved October 2, 2018 from https://www.easa.europa.eu/document-library/general-publications/crm-training-implementation
194. Regulations. *EASA*. Retrieved October 2, 2018 from https://www.easa.europa.eu/document-library/regulations
195. Air Transport Policy and Regulation. Retrieved October 2, 2018 from https://www.icao.int/sustainability/pages/economic-policy.aspx
196. Accreditation Council for Continuing Medical Education | ACCME. Retrieved October 16, 2018 from https://www.accme.org/
197. A programme worth watching - Low-cost radar. Retrieved October 24, 2018 from https://www.economist.com/science-and-technology/2013/03/16/a-programme-worth-watching
198. ATOP Photos. Retrieved October 24, 2018 from https://www.faa.gov/air_traffic/technology/atop/atop_photos/
199. JWinPointer.jar: Java library for multitouch and stylus pen. Retrieved November 5, 2018 from http://www.michaelmcguffin.com/code/JWinPointer/

APPENDICE

APPENDIX 1: MATHEMATICAL MODEL DESCRIPTION

This mathematical model is more precisely detailed, validated and exploited in [68,69] *and the doctoral dissertation of Guillaume Joerger* [95].. *We simply recall here the basic description of the model*.

We propose a staff-specific Agent-Based Model (ABM) intended to retain the key features we observed in daily clinical practice.

An ABM is type of modeling where individuals (or entities performing a task), their interactions and their environment are represented as algorithms.

The proposed model specifically takes into account the contributions of each staff member in the team necessary to advance the task. Some staff, for example the anesthesiologist and the cleaning team, is assigned to several ORs and the model accounts for delays in awareness of events and time to circulate around the OR suite. The theoretical framework has been kept as general as possible to be able to apply it to any hospital system, and calibrate and adapt the modular structure to the detail of clinical data specific to the hospital. To summarize, the model computes the time evolution of two sets of unknowns:

- State of task k for agent i is denoted as vector T_k^i
- Trajectory and state of agent i denoted S_i

We start here with a simplified graph showing the macro steps such preparation for anesthesia, access, surgical procedure (open or minimally invasive), closing time, time to awake the patient and OR exit – see Figure 116.

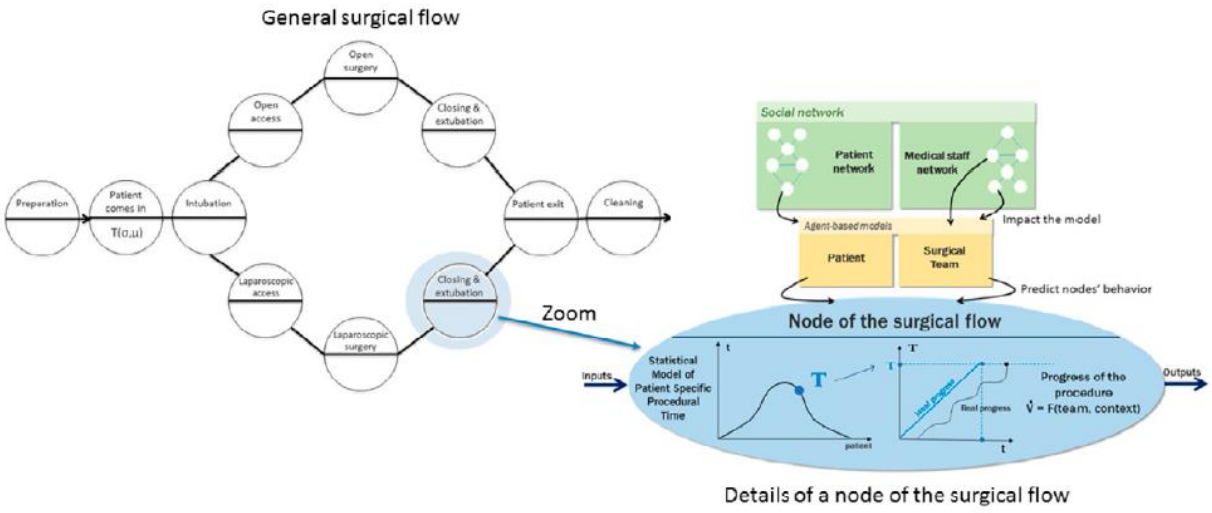


Figure 116. Illustration of our simplified flow chart on the left and its impact on the conceptual

The system was deployed in five pluri-disciplinary ORs and provides accurate measurements of the duration of each of these steps [87]. We use six main categories of agents:

- A for surgeons
- B for surgeons' assistants
- C for anesthesiologists
- R for Certified Registered Nurse Anesthesit (CRNA)
- D for scrub nurses
- E for cleaning crew

For simplicity, we assume that a surgical team, denoted S, in any given OR consists of one agent in each category. Most importantly each agent is associated with a level of technical skill and a level of communication skill. For example, a team of N surgeons noted $\{A(j,n)\}$ working in the ORs suite is represented by a $N \times 2$ matrix of performance level. The first index is the ID of the agent in the set $\{1 \dots N\}$, the second is for the performance type:

- $n = 1$ corresponds to the technical performance and is denoted by P_t^A
- $n = 1$ is for the communication performance index denoted P_c^A

Initially, we set up individual technical skills as a function of the number of years of experience in the current position, and communication skills as a function of the time spent working with the

current team, since frequency in team composition change is negatively correlated to information sharing [16].

We use an estimate of the duration for each macro step, such as patient intubation, access time, surgical procedure itself, patient extubation, or time to move the patients out of the OR – see Figure 116. This estimate is a statistical distribution that depends on the patient's medical conditions and reflects the ideal time that a perfect surgical team should achieve. As we will see later on, our model is stochastic and accounts for delays due team members lack of timely availability, poor coordination between tasks, or suboptimal performance of the surgical team. For any given OR only one task can be in process at any given time, as reflected on the flowchart - see Figure 116.

The progression $\tilde{T}$ of the task k for the agent i, noted T_k^i, from 0 to 1 is described by an ordinary differential equation with the right hand side depending on the team skills. $\tilde{T}$ is set to 0 if the task is not completed, i.e. $0 \leq T_k^i < 1$, and 1 otherwise. M is a sparse matrix that corresponds to the directed graph of Figure 116.

The master equation that provides the time evolution of the state of the graph of tasks $\{T_k^i\}$ handled by the team S_i that advances the task T_q at time step q is:

$$(1)\ T(t_{q+1}) = \left[M \times \left(\tilde{T}(t_q)\right)\right] \circ [(G(t_q - t_0))S_i \cdot E_k]$$

Here $\times$ denotes the sparse matrix vector product, and $\circ$ the vector product component-wise, and $\cdot$ the product of a vector by a scalar. This model has three components:

- $M \times \left(\tilde{T}(t_q)\right)$ where M is a sparse matrix that expresses the dependency on previous tasks.
- $\left(G(t_q - t_0)\right) S_i$ reflects the time-dependent progression of the individual task.
- $0 \leq E_k \leq 1$ is a positive factor representing a penalty for the environment conditions.

It may be the limitation resulting from shared equipment or specific overload of the hospital system due to epidemic or crisis. Conceptually we can represent the ABM computing kernel for each node of the flow graph as in Figure 116. The advancement of task provide by $G(t)$ is not linear in time, i.e. $\dot{G}(t) = constant$, but instead depends on team performance and coordination. We conveniently use an ordinary set of differential equations to integrate that progression in time:

$$(2)\ G = \beta F_k \dot{(S)} f + H_0$$

The initial condition is zero, and β is a normalizing constant such that G reaches 1 at completion of the task in the optimal configuration. Time integration starts only when all staff required for that specific task are present in the OR. More precisely, we define the optimum performance of a team as one that (i) has full awareness on the case, (ii) does not show any sign of fatigue or stress, and (iii) has best technical and communication skills. We represent mathematically each of these elements (i) to (iii) below. In equation (2), $1 \geq F_k(S) \geq 0$ stands for the team efficiency at the taskT_k.

The team performance component of the surgeon and his assistant for a specific task of the graph of nodes described at the high level is additive on technical skills, impacted by the worst skill in communication on the team, factored by a function $f(t)$ that takes into account fatigue, and efficiency as a correlation of repetition of the same surgery. Overall performance cannot go below a given threshold H_0 corresponding to a minimum processing rate, since the team has been granted surgical privileges. For simplicity we assume that the same surgical team operates in the same OR the entire day. Nurse shift is modeled as a time penalty for which the Ordinary Differential Equation (ODE) integration is on hold. We have applied these basic principles to the team performance description of each task in Figure 116 and used the following example in our simulations, with A for surgeons, B for surgeon's assistants, C for anesthesiologists, R for CRNA, D for scrub nurses and E for cleaning crews:

- Task T_1 placing the patient under anesthesia ($\propto_3^1 + \propto_4^1 = 1, 0 \leq \beta_1 \leq 1$):

$$(3)\ F_1(t) = \frac{1}{9}\beta_1[\propto_3^1 P_t^C + \propto_4^1 P_t^R] \min(P_c^C, P_c^R) + (1 - \beta_1)$$

- Task T_2 preparation for laparoscopy procedure to provide access ($\propto_2^2 + \propto_5^2 = 1, 0 \leq \beta_2 \leq 1$):

$$(4)\ F_2(t) = \frac{1}{9}\beta_2[\propto_2^2 P_t^B + \propto_5^2 P_t^D] \min(P_c^B, P_c^D) + (1 - \beta_2)$$

- Task T_3 preparation for open surgical procedure to provide access ($\propto_1^3 + \propto_2^3 + \propto_5^3 = 1, 0 \leq \beta_3 \leq 1$):

$$(5)\ F_3(t) = \frac{1}{9}\beta_3[\propto_1^3 P_t^A + \propto_2^3 P_t^B + \propto_5^3 P_t^D] \min(P_c^A, P_c^B, P_c^D) + (1 - \beta_3)$$

- Task T_4 laparoscopic procedure ($\propto_1^4 + \propto_2^4 = 1,\ 0 \leq \propto_3^4 \leq 1,\ 0 \leq \propto_5^4 \leq 1, 0 \leq \beta_4 \leq 1$):

$$(6)\ F_4(t) = \frac{1}{9}\beta_4[\propto_3^4 [\propto_5^4 [\propto_1^4 P_t^A + \propto_2^4 P_t^B] + (1 - \propto_5^4) P_t^D] + (1 - \propto_3^4) P_t^R] \min(P_c^A, P_c^B, P_c^R, P_c^D) + (1 - \beta_4)$$

- Task T_5 open surgery procedure ($\propto_1^5 + \propto_2^5 = 1,\ 0 \le \propto_3^5 \le 1,\ 0 \le \propto_5^5 \le 1, 0 \le \beta_5 \le 1$):

$$(7)\ F_5(t) = \frac{1}{9}\beta_5\left[\propto_3^5 [\propto_5^5 [\propto_1^5 P_t^A + \propto_2^5 P_t^B\right] + (1 - \propto_5^5) P_t^D] + (1 - \propto_3^5) P_t^R] \min(P_c^A, P_c^B, P_c^R, P_c^D) + (1 - \beta_5)$$

- Task T_6 closing laparoscopic procedure: similar to T_2.
- Task T_7 closing open surgery procedure: similar to the above.
- Task T_8 waking up procedure ($\propto_3^8 + \propto_4^8 = 1, 0 \le \beta_8 \le 1$):

$$(8)\ F_8(t) = \frac{1}{9}\beta_8[\propto_3^8 P_t^C + \propto_4^8 P_t^R] \min(P_c^A, P_c^C, P_c^R) + (1 - \beta_8)$$

- Task T_9 cleaning the OR ($0 \le \beta_9 \le 1$):

$$(9)\ F_9(t) = \frac{1}{9}\beta_9 P_t^E P_C^E + (1 - \beta_9)$$

Overall the team performance impact on task advancement are provided by the matrix $\propto$:

$$\begin{pmatrix} 0 & 0 & 0.6 & 0.4 & 0 \\ 0 & 0.5 & 0 & 0 & 0.5 \\ 0.5 & 0.3 & 0 & 0 & 0.2 \\ 0.6 & 0.4 & 0 & 0.8 & 0.8 \\ 0.8 & 0.2 & 0 & 0.8 & 0.8 \\ 0 & 0.6 & 0 & 0 & 0.4 \\ 0.3 & 0.5 & 0 & 0 & 0.2 \\ 0 & 0 & 0.6 & 0.4 & 0 \end{pmatrix}$$

and the vector:

$$\beta = [0.7 \quad 0.6 \quad 0.3 \quad 0.5 \quad 0.5 \quad 0.3 \quad 0.3 \quad 0.7]^t$$

This matrix is largely the result of a heuristic effort based on a priori knowledge.

See Results of this model in [68,69].

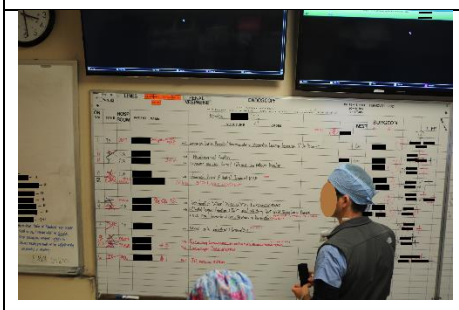
APPENDIX 2: SCENARIOS OF USE

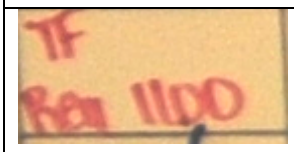
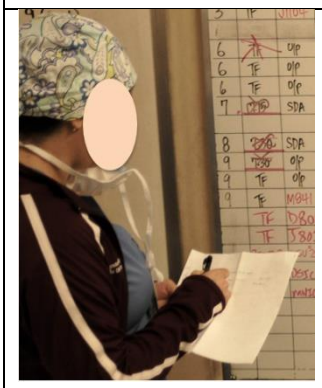
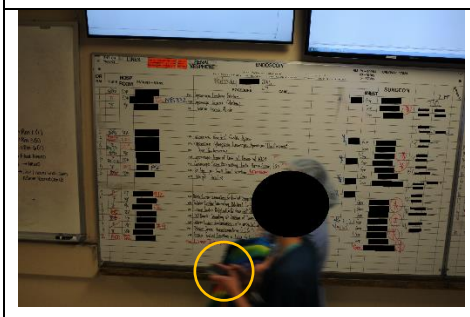
Scenarios of use of the whiteboard within the surgical suite. “wb” stands for “whiteboard” here.

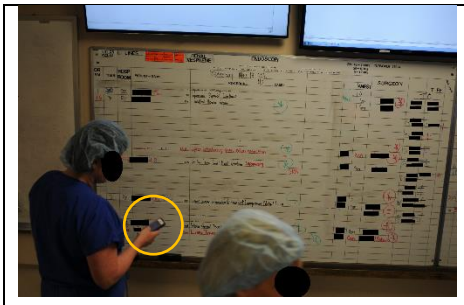
ID	Description
Sc1	The Nurse arrives at the beginning of his/her shift at Dunn OR
Sc2	The Surgeon arrives at the beginning of his/her shift at Dunn OR
Sc3	The Surgeon wants to squeeze an additional case in the schedule of the day (called “add-on”, or “emergency” even if it most of the time is not an emergency)
Sc4	The patient has arrived in PreOp
Sc5	The case started
Sc6	The current day is over, edition of the new whiteboard for the next day – “elective cases”
Sc7	The case is delayed, but will start as soon as the surgeon is ready for his/her next case
Sc8	Talk about a case with a colleague
Sc9	Create a “name alert” for two cases or add a latex allergy alert to a case
Sc10	Nurses break
Sc11	Display that the patient is in Neuro Intensive Care Unit (NICU) or SICU
Sc12	Not enough room on the board to manage all the cases (not often)
Sc13	A case is canceled
Sc14	The nurse go see the patient in PreOp.

Sc15	Surgeon or Nurse or Anesthesiologist or xx needs to have information that is on the whiteboards while being far away from it
Sc16	Board Runner or another staff making an input on the board needs concerned people to be aware of changes that have been made on cases that they work on
Sc17	A case is finished

ID	SC1
Description	The Nurse arrives at the beginning of his/her shift at Dunn OR
Aim	Get to know what he/she has to do
Actor	Nurse (RN)
Place	Information Hall, DUNN OR
System context	Whiteboard is edited and updated
User context	Just start his/her shift

Photo/Diagram	**Description**	**Drawbacks(-) Benefits(+)**
	Intention: Wants to know about his/her patients of the day Actions: Look at the board, find his/her name and determine who will be his/her patients for his/her shift, what are their procedures, where they currently are, when the procedures are scheduled (even though most of the	(-) wb clearness maybe not excellent – wb often packed with written information

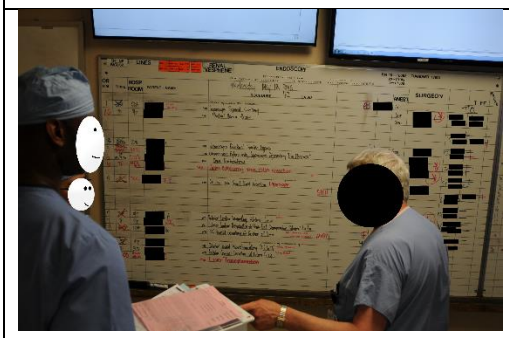
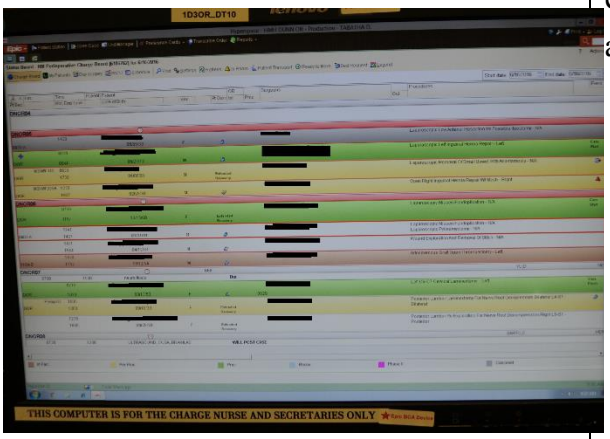
	time – except for 1st case of the day in the OR, the time is "as soon as the previous surgery is done and the OR is clean and the surgeon is ready"). He/She get to know where the surgeon for his/her next surgery is.	(+) wb contains most of the time all the information needed
	Intention: If there is a REQUEST, the time for the surgery is explicitly required Actions: Check requested times	
	Intention: Remember Actions: Can take notes to remember information on personal paper. OR NOT	(-) wb clearness maybe not be excellent – wb often packed with written information and quality of handwriting is variable. (+) very flexible, paper and pen, easy to carry, easy to edit.
	Intention: Get the information that is missing – like location of the surgeon or of techs Actions: Send a text message on the phones of the colleagues or make a call.	(-) Information should be spread by the hospital (?) (+) smartphone always in the pocket. Easy. Fast.

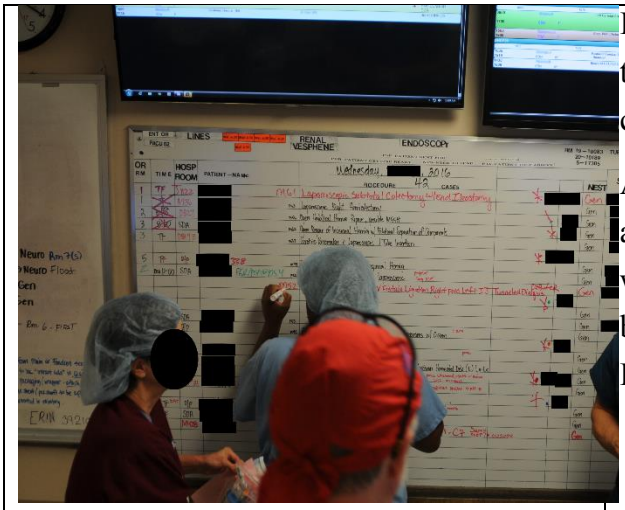
 		

ID	SC2
Description	The Surgeon arrives at the beginning of his/her day at Dunn OR
Aim	Check the schedule cases
Actor	Surgeon
Place	Information hall
System context	Wb edited and updated
User context	First entrance in the surgical suite of the day

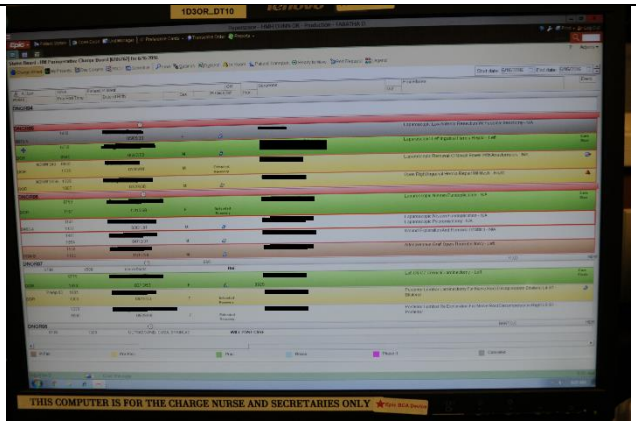
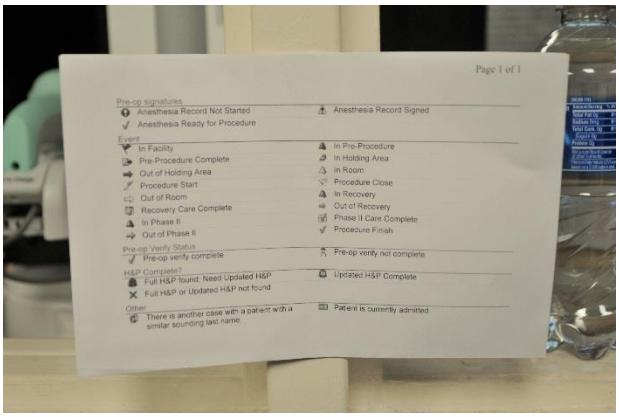
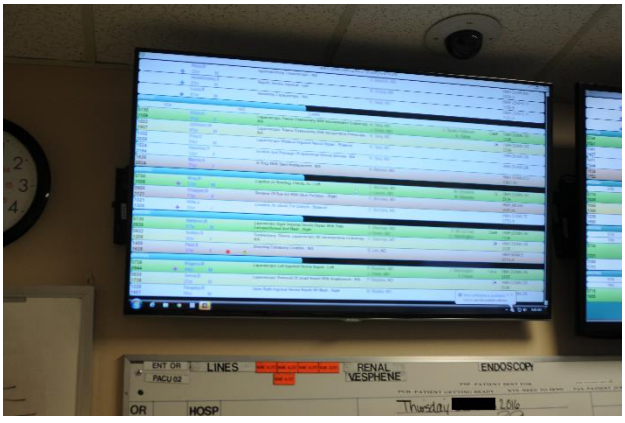
Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Verify his/her patients are correctly scheduled as he/she wanted. Actions: Look at the wb and read the information that concerns his/her cases.	(-) (+)

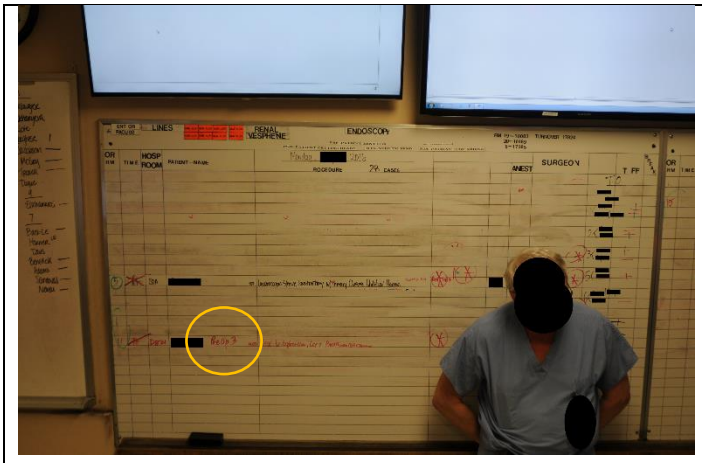
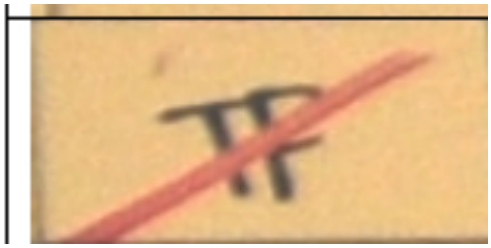
ID	SC3
Description	The Surgeon wants to squeeze an additional case in the schedule of the day (called “add-on”, or “emergency” even if it most of the time is not an emergency)
Aim	Add a case in the day
Actors	Surgeon + charge nurse + anesthesiologist
Place	Information hall
System context	Wb edited and updated
User context	/

Photo/Diagram	**Description**	**Drawbacks(-) Benefits(+)**
 	Intention: Determine when and where can be squeezed the additional case Actions: Discussions in front of the wb and in the control room in front of an EPIC computer to see the schedule and modify it.	(-) sometimes there is no room on the wb (+) The wb is a good support to the discussion and the interaction.

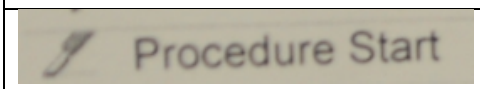
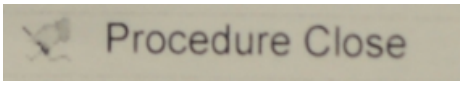
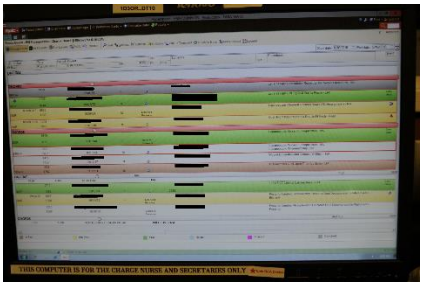
	Intention: inform the others that there will be an additional case. Actions: Nurse writes the additional case in red on the wb when the decision has been made. Case entered in EPIC system.	(-) (+) updated only when decision is made. Red shows the fact it is a new case.

ID	SC4
Description	Patient has arrived in PreOp
Aim	Awareness of the patient status
Actors	Surgical suite staff
Place	Information hall – Control room
System context	Wb edited and updated
User context	/

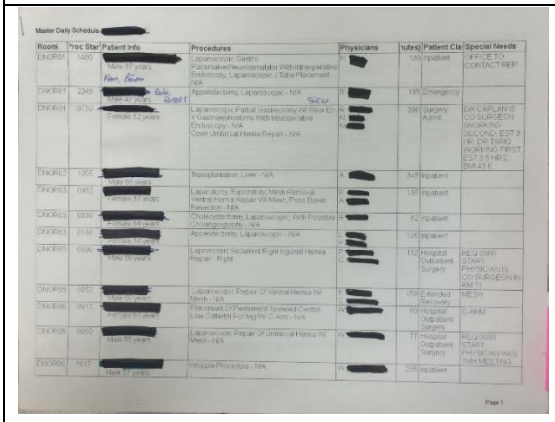
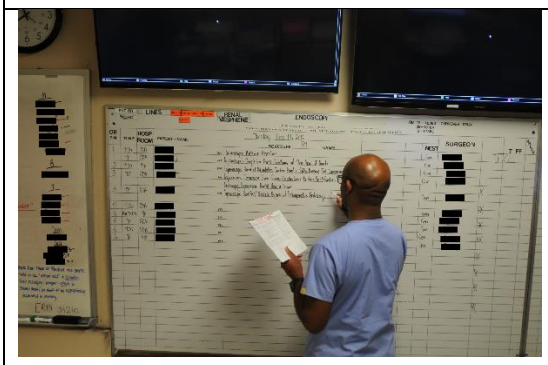
Photo/Diagram	Description	Drawbacks(-) Benefits(+)
  	Intention: Check where the patient X is. Actions: Look at EPIC screens in control room or information hall above the wb. The color indicated the steps the patient is going through (ex: yellow = pre procedure) The pictogram give more accurate information (ex: red bell = in preOp room)	(-) not always up to date (+)

 	Intention: Check where the patient X is BIS. Actions: The staff can see it written on the wb by another nurse. The “PreOp #” or the symbole /.	(-)not always up to date (+)

ID	SC5
Description	The case has started
Aim	Awareness of the patient status
Actor	Surgical suite staff
Place	Information hall / control room
System context	Wb is edited and updated
User context	

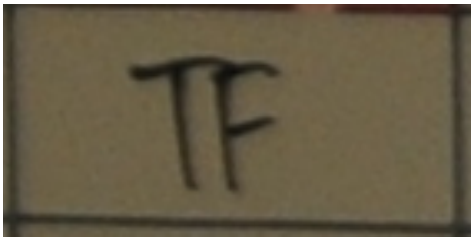
Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Inquire about the case status (WB) Actions: look at the wb, this symbols means the patient is in the OR.	(-) (+)
  	Intention: Inquire about the case status BIS () screens above the wb. Actions: look at the symbols on the top screens and the colors. Green means the patient is going through the surgery. The little symbols hereby indicates procedure status about start and end.	

ID	SC6
Description	The current day is over, edition of the new whiteboard for the next day – “elective cases”
Aim	Prepare the wb for the next next
Actor	Nurse/Charge nurse
Place	Information hall
System context	Wb is edited and updated
User context	End of the day, late in the afternoon

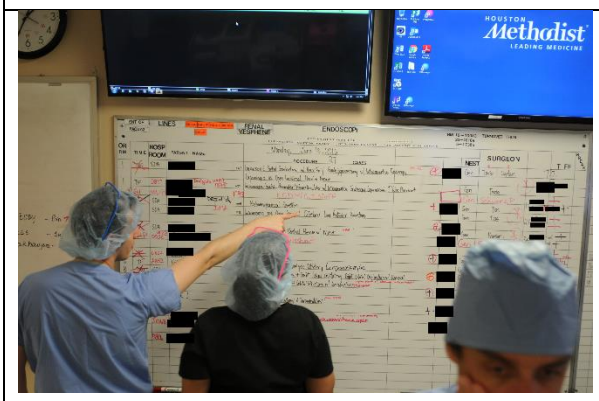
Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Bring the information, the schedule for the next day, to the wb Actions: Print the schedule from EPIC on paper.	(-) Staff must print it in control room and bring it to the wb
	Intention: Copy the schedule on the wb and organize the staff assignments Actions: take a pen and copy what is	(-) long and tiring (-)Hand writing must be very clear (-)Human mistake possible (+) Human check

	written on the paper, on the wb.	(+) Organize the staff

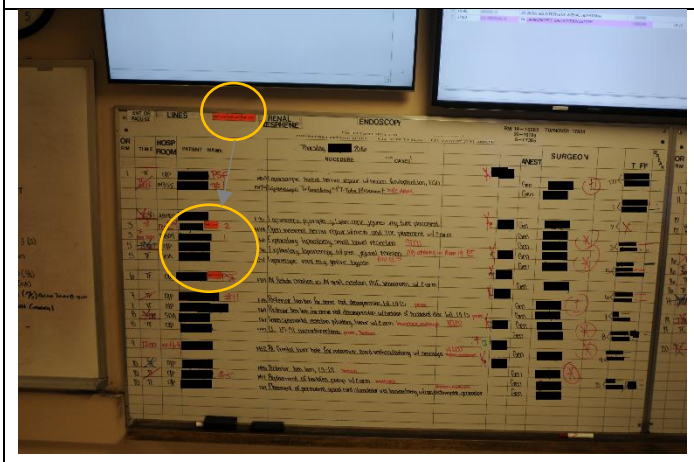
ID	SC7
Description	The case is delayed, but will start as soon as the surgeon is ready for his/her next case
Aim	Inform other staff that case is delayed
Actor	Nurse/charge nurse
Place	Information hall
System context	Wb is edited and updated
User context	

Photo/Diagram	**Description**	**Drawbacks(-) Benefits(+)**
 	Intention: Signify the case is going to be done as soon as the previous one in the same room is over and that the OR is clean. Actions: Write TF on the wb.	(-) not accurate

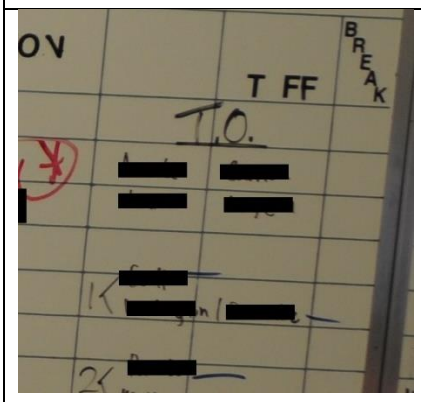
ID	SC8
Description	Talk about a case with a colleague
Aim	Exchange information about a case
Actor	Nurse/charge nurse/surgeon
Place	Information hall
System context	Wb is edited and updated
User context	

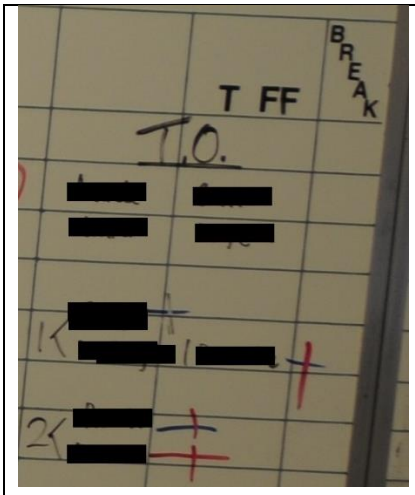
Photo/Diagram	**Description**	**Drawbacks(-) Benefits(+)**
 	Intention: Exchange unformal information about a case (delay, patient location, moving a case) Actions: The two protagonists walk to the wb. Show with the finger the case and exchange information.	(-) (+)

ID	SC9
Description	Create a “name alert” for two cases
Aim	Situation awareness of the whole staff for not mixing names and patients
Actor	Nurse/charge nurse/surgeon
Place	Information hall
System context	Wb is edited and updated
User context	

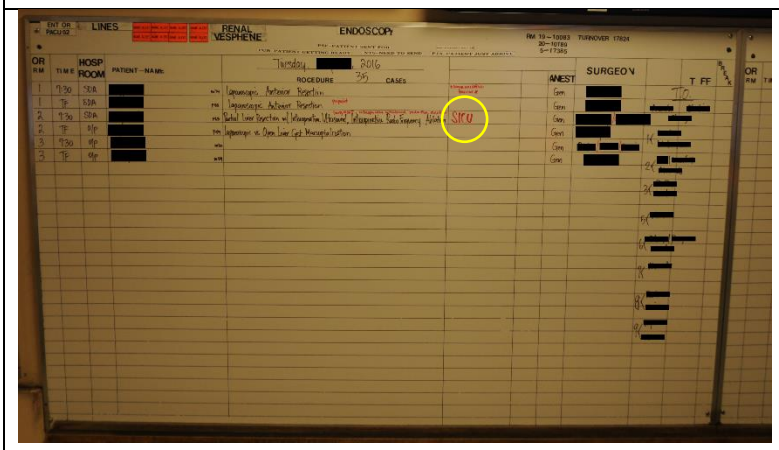
Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Prevent mistakes Actions: Take the orange “name alert” magnets at the top of the wb and place them on the cases where the mistake can be done.	(+) Efficient anticipation of problems.

ID	SC10
Description	Nurse break
Aim	Inform other staff that this nurse has taken his/her break already or not, if he/she is in break etc.
Actor	Nurse/charge nurse
Place	Information hall
System context	Wb is edited and updated
User context	Break time

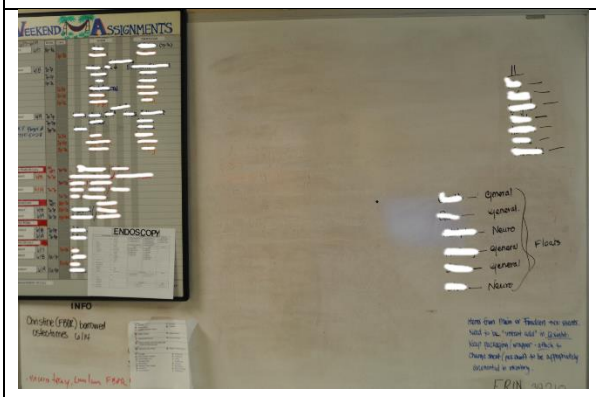
Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Show "no break" Actions: No symbol next to the name of the staff.	(-) (+)
	Intention: Show "in break" Actions: A horizontal line next to the staff name.	(-) (+) fast and easy

	Intention: Show “break has been taken and is over” Actions: Add of a vertical line next to the staff name, over the previous horizontal one.	(-) (+) fast and easy

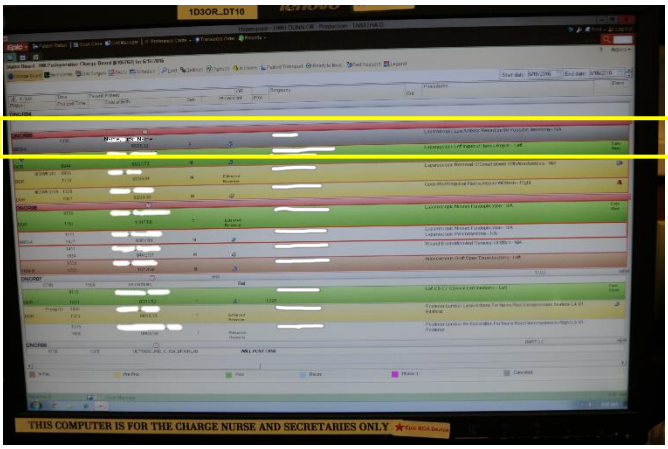
ID	SC11
Description	Display that the patient is in Neuro Intensive Care Unit (NICU) or SICU
Aim	Aware staff of special need for patients after surgery
Actor	Nurse/charge nurse
Place	Information hall
System context	Wb is being edited for the next day
User context	

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Inform the staff of the next day of special needs for the patient Actions: Take a red pen and write NICU or SICU	(-) (+)

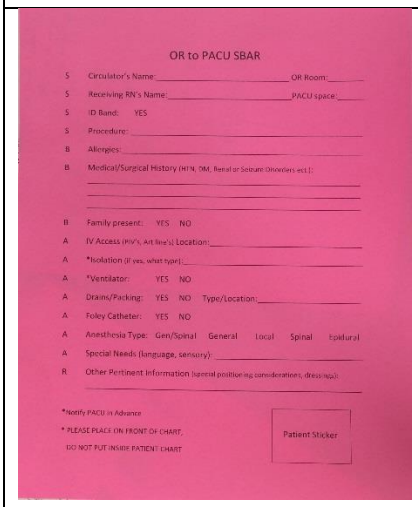
ID	SC12
Description	Not enough room on the board to manage all the cases (not often)
Aim	Find more space to keep displaying all the information
Actor	Charge nurse
Place	Information hall
System context	Wb is edited and updated
User context	

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Find more space Actions: Room is made on the left side extra wb, that usually deal with vacations, weekend assignments and other kind of notes.	(-) long and make some other information disappear (+) it worked well
	Intention: Write the information Actions: The additional cases are added on this wb	(-) not very clean and organized (+) it worked well

ID	SC13
Description	Case is canceled
Aim	Show to the staff that a case is canceled
Actor	Charge nurse
Place	Information hall / control room
System context	Wb is edited and updated
User context	

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Show to the staff that a case is canceled on the electronic screens. Actions:	(-) (+)

ID	SC14
Description	The nurse go see the patient just before the scheduled surgery
Aim	Check the patient and getting ready for the procedure
Actor	Nurse (RN)
Place	Information hall / control room
System context	Wb is edited and updated
User context	Is going to get his/her patient for the next procedure

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Must fill this sheet before going to see his/her patient in PreOp Actions: take a pen, look at the wb, look at the patient medical record and fill the sheet.	(-) (+) hospital procedure

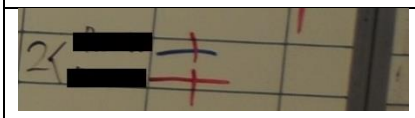
ID	SC15
Description	Surgeon or Nurse or Anesthesiologist or xx needs to have information that is on the whiteboards while being far away from it
Aim	Stay aware of latest updates
Actor	Surgeon or Nurse (RN) - staff
Place	Anywhere in the hospital
System context	Wb with its info
User context	Very various situations

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: Staff wants to be aware of whiteboard schedule modification or more information. Actions: take a phone, call the Board Runner or someone he/she knows is nearby the whiteboard	(-) a phone call/sms is very invasive. A phone call stops the action someone is doing (+) phone is very easy to use and quick

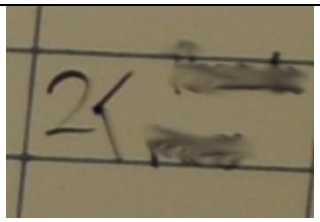
ID	SC16
Description	Board Runner or another staff making an input on the board needs concerned people to be aware of changes that have been made on cases that they work on
Aim	Make sure concerned staff is aware of the latest updates
Actor	Board Runner / Anesthesiologist
Place	Information hall
System context	Wb with its info and updates
User context	User is updating the board

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: User wants to make sure concerned staff is aware of the latest updates Actions: take a phone, call the concerned staff	(-) a phone call/sms is very invasive. A phone call stops the action someone is doing (+) phone is very easy to use and quick

ID	SC17
Description	A case is finished
Aim	Make sure the staff is aware of the latest updates
Actor	Board Runner
Place	Information hall
System context	Wb with its info and updates
User context	User is updating the board

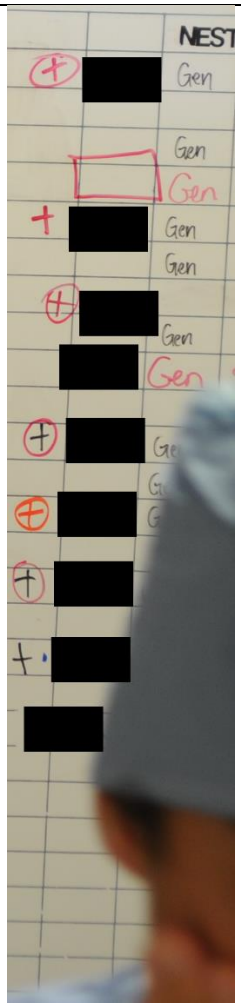
Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: User wants to make sure concerned staff is aware of the latest updates Actions: take and eraser and erase the case on the board	(-) if it was an error, the case has been totally erased and must be re-written, with potential errors. (+) easy

ID	SC18
Description	Assignments of nurses per ORs
Aim	Make sure the nurses are aware of their assignments
Actor	Board runner
Place	Information hall
System context	Wb with its info and updates
User context	User is updating the board

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**
	Intention: User wants to make sure the anesthesia staff is aware of their assignments Actions: take a pen and write nurses assignments on the wb.	(-) static and needs to be erased and rewritten every time (+) easy

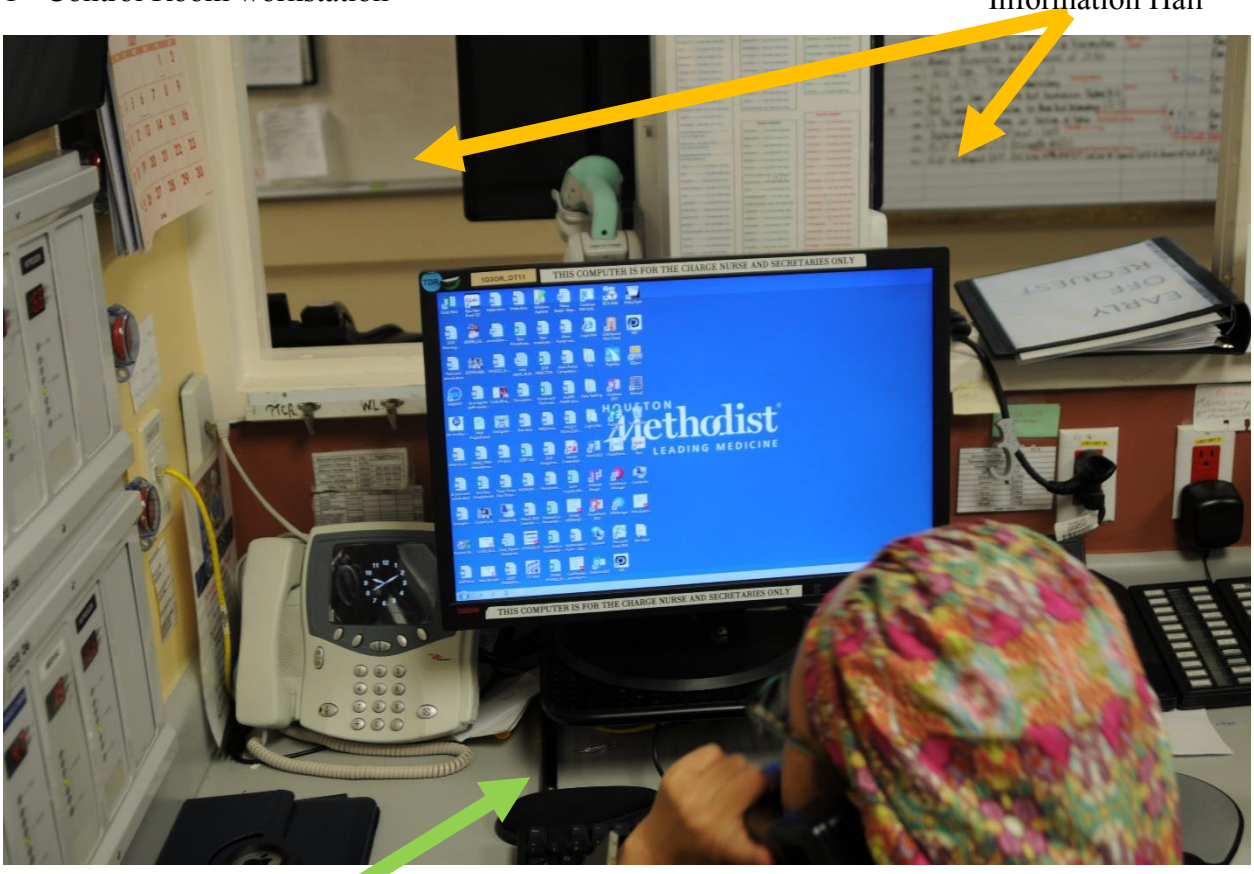
ID	SC19
Description	Assignments of anesthesia staff per ORs
Aim	Make sure the anesthesia staff is aware of their assignments
Actor	Anesthesiologist in charge
Place	Information hall
System context	Wb with its info and updates
User context	User is updating the board

Photo/Diagram	**Description**	**Drawbacks(-)** **Benefits(+)**

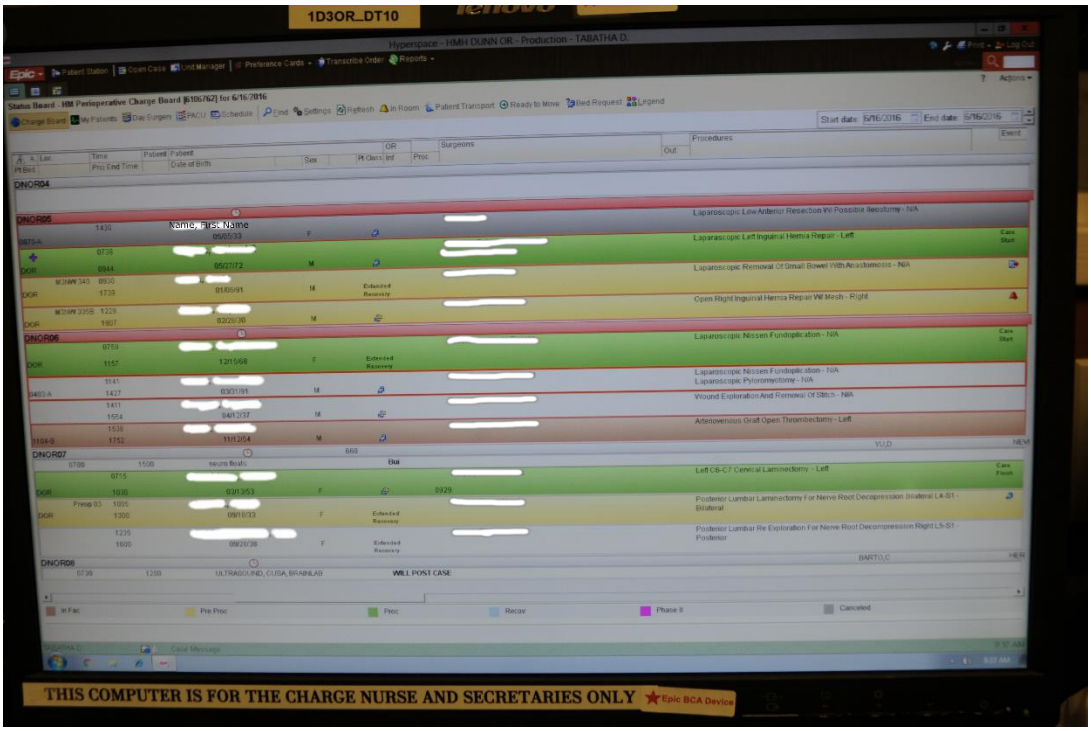
	Intention: User wants to make sure the anesthesia staff is aware of their assignments Actions: take a pen and write anesthesia assignments on the cases lines.	(-) static and needs to be erased and rewritten every time (+) easy

APPENDIX 3: Side activities around the whiteboard

1 - Control Room workstation



2- Control Room Screen EPIC case scheduling UI:



(NB: schedule for the next day, late in the evening, is printed from this interface/computer, and then the sheet schedule is taken and manually input on the whiteboard. It is important to let the user enter manually the date, because it can be confusing most of all on weekend, but assistance can be good)

Color code:

Green = In Room

Yellow = In PreOp

Brown = In Facility (in hospital)

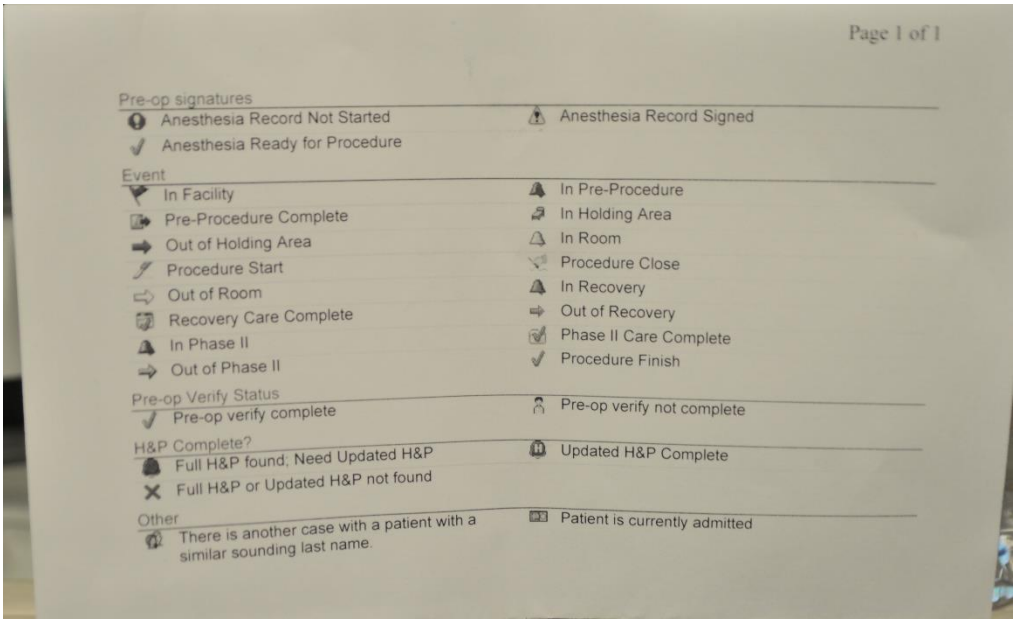
Blue = In Recovery

Gray = Canceled

Information Hall Screens

Pictograms:

These pictograms are visible on the screens of the Information Hall, on the lines that represent a case.



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Pre-op signatures

- Anesthesia Record Not Started
- Anesthesia Ready for Procedure
- Anesthesia Record Signed

Event

In Facility	In Pre-Procedure
Pre-Procedure Complete	In Holding Area
Out of Holding Area	In Room
Procedure Start	Procedure Close
Out of Room	In Recovery
Recovery Care Complete	Out of Recovery
In Phase II	Phase II Care Complete
Out of Phase II	Procedure Finish

Pre-op Verify Status

- Pre-op verify complete
- Pre-op verify not complete

H&P Complete?

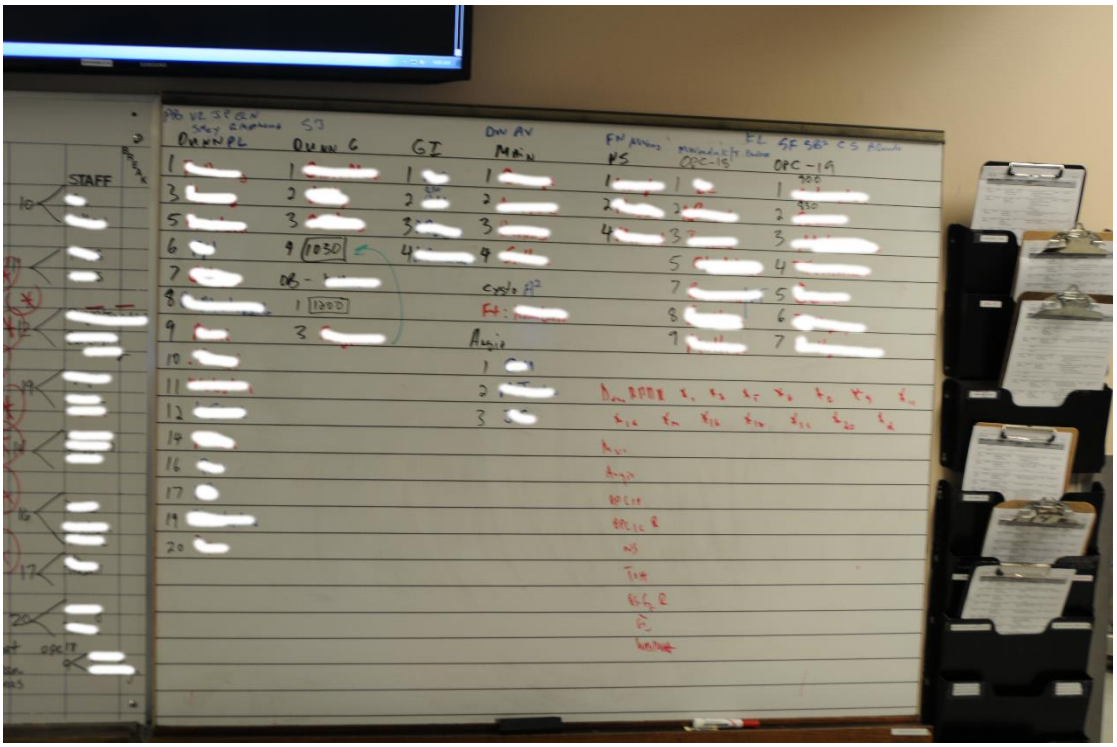
- Full H&P found, Need Updated H&P
- Full H&P or Updated H&P not found
- Updated H&P Complete

Other

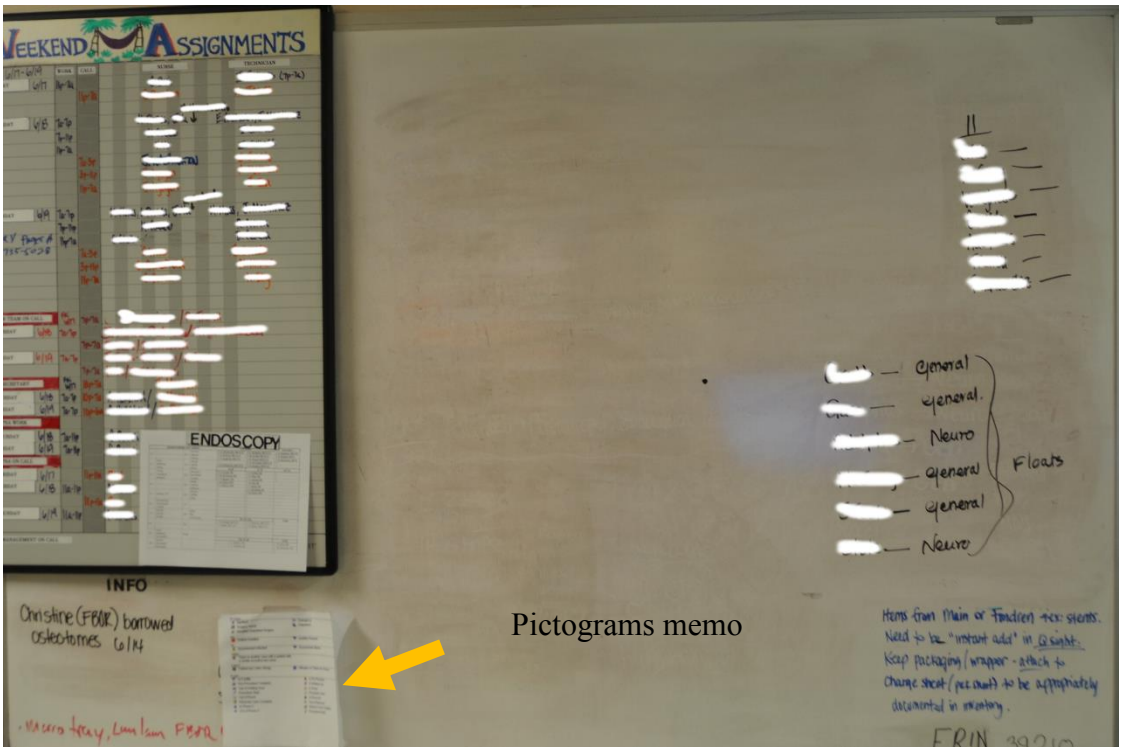
- There is another case with a patient with a similar sounding last name.
- Patient is currently admitted

Paper printed displayed next to workstations in control room.

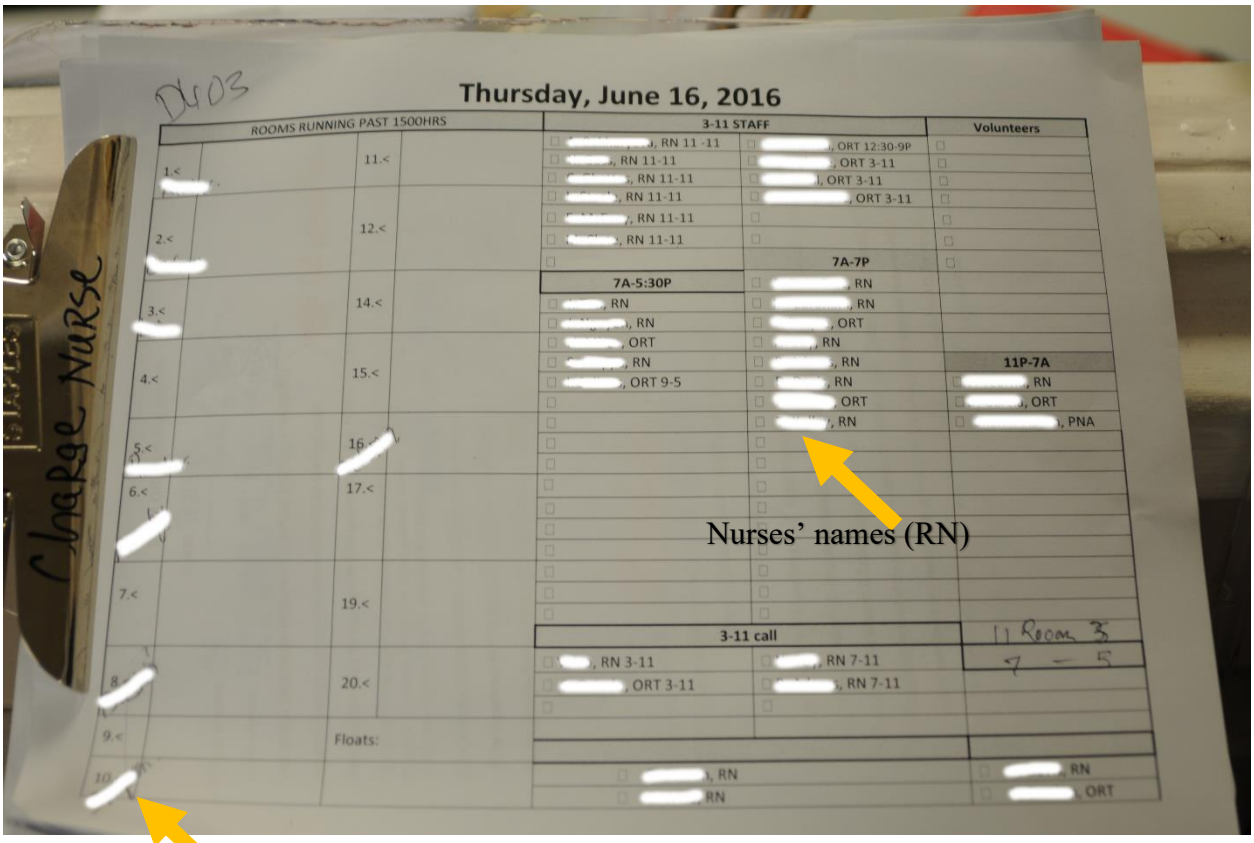
3 - Right Side Whiteboard – Anesthesiologist assignments to surgical suites



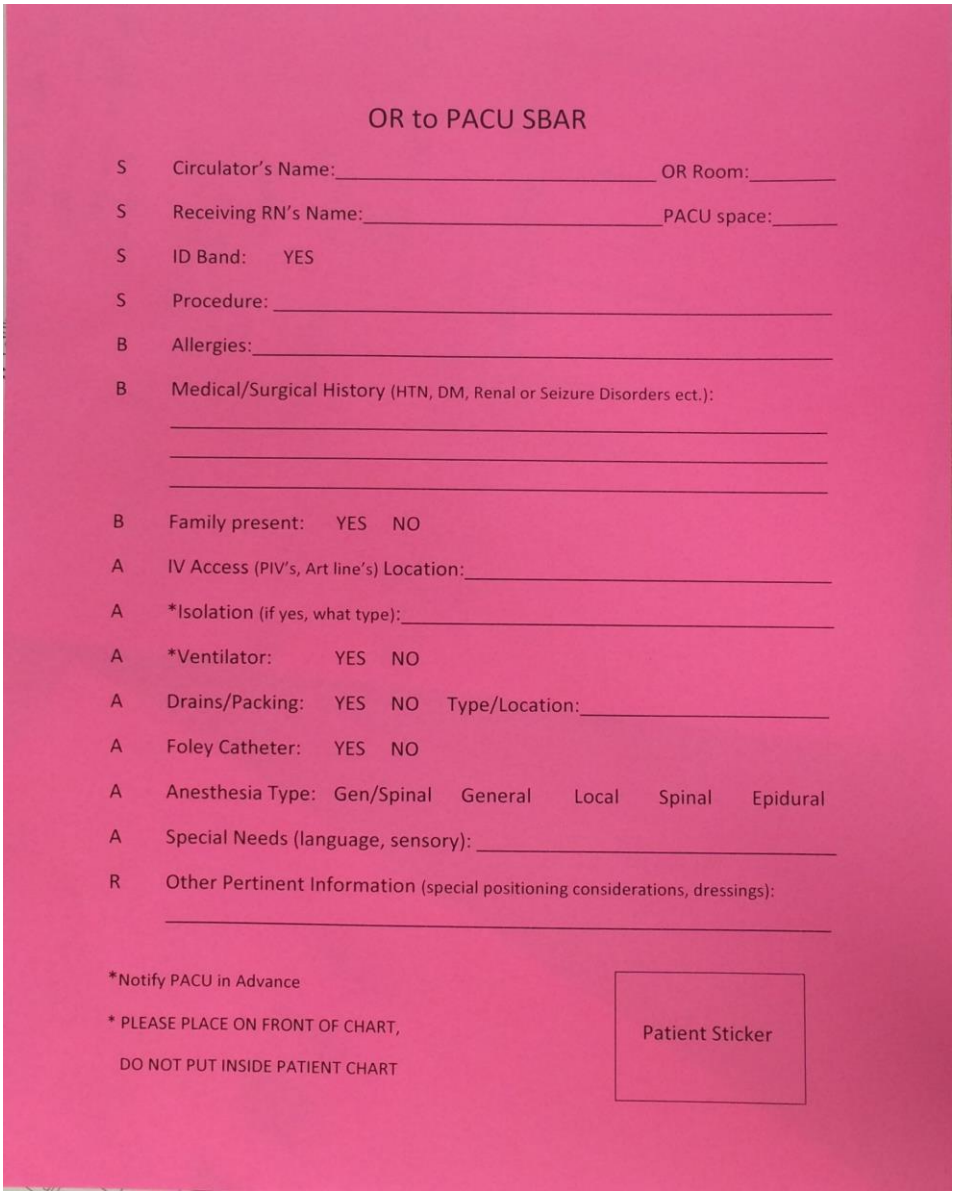
4 - Left Side Whiteboard – weekend assignments – Memo about pictograms…



5- Paper filled after 3pm by a nurse (RN) while watching the whiteboard, purpose is to prepare the afternoon after 3pm.



6 - Nurse paper note that he/she fills just before going to see a patient.



OR to PACU SBAR

S Circulator's Name:_____ OR Room:_____

S Receiving RN's Name:_____PACU space:_____

S ID Band: YES

S Procedure: _____

B Allergies:_____

B Medical/Surgical History (HTN, DM, Renal or Seizure Disorders ect.):

_____

_____

_____

B Family present: YES NO

A IV Access (PIV's, Art line's) Location:_____

A *Isolation (if yes, what type):_____

A *Ventilator: YES NO

A Drains/Packing: YES NO Type/Location:_____

A Foley Catheter: YES NO

A Anesthesia Type: Gen/Spinal General Local Spinal Epidural

A Special Needs (language, sensory): _____

R Other Pertinent Information (special positioning considerations, dressings):

_____

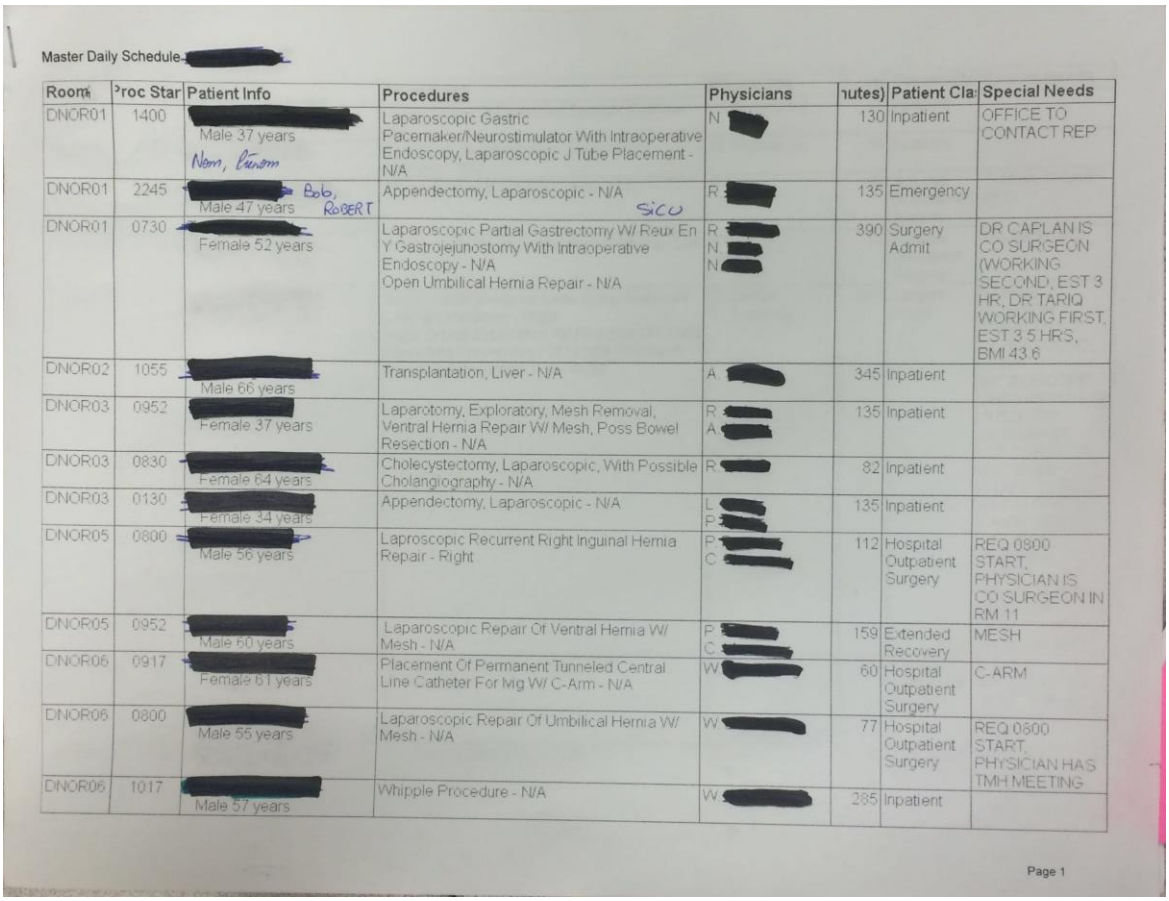
*Notify PACU in Advance

* PLEASE PLACE ON FRONT OF CHART,

DO NOT PUT INSIDE PATIENT CHART

Patient Sticker

7 - Late evening schedule for the day after. A nurse print this pages from EPIC (Hospital System), and go to copy it on the whiteboards. His/her writing clarity is very important otherwise the others complain while using the board the day after.



Master Daily Schedule [redacted]

Room	Proc Star	Patient Info	Procedures	Physicians	nutes)	Patient Cla	Special Needs
DNOR01	1400	[redacted] Male 37 years Nam, Binam	Laparoscopic Gastric Pacemaker/Neurostimulator With Intraoperative Endoscopy, Laparoscopic J Tube Placement - N/A	N [redacted]	130	Inpatient	OFFICE TO CONTACT REP
DNOR01	2245	[redacted] Male 47 years Bob, ROBERT	Appendectomy, Laparoscopic - N/A SICU	R [redacted]	135	Emergency	
DNOR01	0730	[redacted] Female 52 years	Laparoscopic Partial Gastrectomy W/ Reux En Y Gastrojejunostomy With Intraoperative Endoscopy - N/A Open Umbilical Hernia Repair - N/A	R [redacted] N [redacted] N [redacted]	390	Surgery Admit	DR CAPLAN IS CO SURGEON (WORKING SECOND, EST 3 HR, DR TARIQ WORKING FIRST, EST 3.5 HRS, BMI 43.6
DNOR02	1055	[redacted] Male 66 years	Transplantation, Liver - N/A	A [redacted]	345	Inpatient	
DNOR03	0952	[redacted] Female 37 years	Laparotomy, Exploratory, Mesh Removal, Ventral Hernia Repair W/ Mesh, Poss Bowel Resection - N/A	R [redacted] A [redacted]	135	Inpatient	
DNOR03	0830	[redacted] Female 64 years	Cholecystectomy, Laparoscopic, With Possible Cholangiography - N/A	R [redacted]	82	Inpatient	
DNOR03	0130	[redacted] Female 34 years	Appendectomy, Laparoscopic - N/A	L [redacted] P [redacted]	135	Inpatient	
DNOR05	0800	[redacted] Male 56 years	Laproscopic Recurrent Right Inguinal Hernia Repair - Right	P [redacted] C [redacted]	112	Hospital Outpatient Surgery	REQ 0800 START, PHYSICIAN IS CO SURGEON IN RM 11
DNOR05	0952	[redacted] Male 60 years	Laparoscopic Repair Of Ventral Hernia W/ Mesh - N/A	P [redacted] C [redacted]	159	Extended Recovery	MESH
DNOR06	0917	[redacted] Female 61 years	Placement Of Permanent Tunneled Central Line Catheter For Mg W/ C-Arm - N/A	W [redacted]	60	Hospital Outpatient Surgery	C-ARM
DNOR06	0800	[redacted] Male 55 years	Laparoscopic Repair Of Umbilical Hernia W/ Mesh - N/A	W [redacted]	77	Hospital Outpatient Surgery	REQ 0800 START, PHYSICIAN HAS TMH MEETING
DNOR06	1017	[redacted] Male 57 years	Whipple Procedure - N/A	W [redacted]	285	Inpatient	

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