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Participatory design to support power grid operators in control rooms

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Participatory design to support power grid operators in control rooms

*Conception participative pour aider les opérateurs de
réseaux électriques dans les salles de contrôle*

Thèse de doctorat de l'université Paris-Saclay

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communication (STIC)

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Mots clés: Salle de supervision du réseau électrique, Conception participative, Interaction instrumentale, Relève

Résumé: La technologie des salles de contrôle critiques pose de nombreux défis aux opérateurs, notamment en ce qui concerne l'augmentation de la charge de travail, la surcharge d'informations et le manque de conscience de la situation. Ma revue de la littérature de recherche sur la productivité des salles de contrôle montre que la technologie actuelle a été développée avec un engagement limité des opérateurs dans le processus de design, ce qui a conduit à des outils qui ciblent des problèmes spécifiques tout en négligeant le flux de travail global. Nous avons mené un projet de conception participative de deux ans avec les opérateurs de RTE (le réseau électrique français) afin de mieux comprendre les problèmes auxquels les opérateurs sont confrontés. Les principaux besoins concernent l'amélioration de vue générale d'information et le soutien aux tâches secondaires des opéra-

teurs, par exemple la traçabilité d'informations et la hiérarchisation des tâches. Nous avons utilisé une approche théorique générative pour concevoir StoryLines, un timeline interactif qui aide les opérateurs à collecter des informations à partir de divers outils pour créer une vue d'ensemble, créer des rappels et partager des informations pertinentes avec l'opérateur de l'équipe suivante. La combinaison de la conception participative et de la théorie générative nous a permis d'explorer les pratiques existantes des opérateurs en matière de prise de notes sur l'état du réseau et les événements futurs attendus, ce qui a permis d'informer le design des StoryLines. Nous avons mené deux études comparatives d'observation structurée afin d'évaluer les forces et les faiblesses de StoryLines et de suggérer des orientations pour la recherche future.

Title: Participatory design to support power grid operators in control rooms

Keywords: Power grid control room, Participatory design, Instrumental interaction, Handover

Abstract: Safety-critical control room technology poses multiple challenges for operators, especially with respect to increasing workload, information overload, and lack of situation awareness. My review of the research literature on control room productivity shows that today's technology was developed with limited operator involvement in the design process, which has led to tools that target specific problems while neglecting the overall workflow. We conducted a two-year participatory design project with RTE (the French power grid) operators to better understand the problems operators face. Key needs include improved information overviews and support for operators' secondary tasks, e.g., tracing information and prioritization. We used a generative theory approach to design StoryLines, an interactive timeline that helps operators collect information from diverse tools to create an overview, record reminders and share relevant information with the next shift's operator. The combination of participatory design and generative theory let us explore operators' existing note-taking practices about grid status and expected future events, which informed the design of StoryLines. We conducted two comparative structured observation studies to assess the strengths and weaknesses of StoryLines and to suggest directions for future research.

Résumé

La technologie des salles de contrôle critiques pose de nombreux défis aux opérateurs, tels que l'augmentation de la charge de travail, le manque de connaissances et d'expertise, la surcharge d'informations et la conception inappropriée de l'interface. La recherche tente de résoudre ces problèmes, en réduisant les informations non pertinentes, en améliorant la présentation des informations par une meilleure catégorisation et visualisation, et en réduisant la charge de travail des opérateurs par l'automatisation, la collaboration ou même à la surveillance des opérateurs afin de leur apporter une aide supplémentaire. J'ai découvert deux limites principales : le manque d'engagement des opérateurs dans le processus de conception des outils destinés à leur usage, et l'absence de prise en compte de l'intégration de ces outils dans le flux de travail et l'environnement des opérateurs.

Nous avons mené un projet de conception participative avec des opérateurs de RTE. Les résultats de ces ateliers avec les opérateurs font écho à certaines conclusions de la littérature notamment la surcharge d'informations, la conception inadéquate de l'interface et la surcharge croissante. Les résultats révèlent également de nouveaux problèmes spécifiques à la salle de contrôle de RTE, tels que la redondance entre les outils et les documents, la perte des informations transmises oralement, et le manque de soutien aux tâches secondaires des opérateurs, comme la traçabilité des informations et la priorisation des tâches. En outre, nos résultats fournissent des exemples spécifiques et détaillés des défis rencontrés par les opérateurs de leur point de vue. Cela permet d'offrir une opportunité clé pour concevoir pour ces défis spécifiques tout en tenant compte de la façon de travailler des opérateurs.

J'ai choisi de me concentrer sur le design d'un outil pour la relève pour cette salle de contrôle. J'ai utilisé la théorie générative d'interaction pour comprendre les lacunes d'utilisation de prise de notes pour tracer et organiser les informations. J'ai identifié certains des besoins de l'opérateur, tels que le fait d'avoir une vue d'ensemble et de minimiser la perte d'informations non persistante. Sur la base de ces besoins, j'ai conçu StoryLines, un outil interactif qui permet la collecte et la centralisation d'informations provenant de différents outils et d'organiser les informations, de créer des vues d'ensemble et des rappels pour les événements critiques futurs.

Nous avons mené 2 études comparatives d'observation structurée avec les opérateurs pour mieux comprendre comment intégrer les StoryLines dans l'environnement et soutenir les pratiques existantes des opérateurs. J'ai découvert que même si la prise de note comprend des informations incomplètes, elle aide à mieux organiser, distinguer et optimiser la quantité d'information, ce qui était un problème avec les StoryLines qui fournissaient trop d'informations. Il est nécessaire de séparer la prise de notes pour soi et pour les autres et d'inclure des fonctions plus interactives pour trouver l'information et faciliter l'organisation. J'ai utilisé toutes ces informations pour améliorer le design de StoryLines et l'adapter davantage à l'utilisation des opérateurs.

Mes conclusions suggèrent que bien que les opérateurs apprécient la capacité de capter et de centraliser les informations provenant de différents outils, le papier offre toujours une utilisation simple et intuitive, ce qui est plus difficile à obtenir avec les outils numériques. Mon travail montre que la conception participative est un moyen efficace d'impliquer les opérateurs de systèmes critiques dans

des activités de conception productives et que la combinaison de la conception participative et d'une approche théorique peut permettre une conception centrée sur l'utilisateur simple mais efficace.

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1 - Introduction

Safety-critical industries such as nuclear power, aviation, rail, and energy rely on control rooms to ensure their safe and efficient operation. Each control room serves as an information center for expert operators who monitor and manage a highly complex system.

Such systems are not static: rapidly changing technology, operational complexities, increasing demand for services and constantly evolving threats, e.g. cybersecurity attacks, make them extremely difficult to maintain. Even “minor” errors can lead to serious financial and other consequences, including disrupting traffic flows, generating safety hazards, and causing fatal accidents. Some of the big incidents in control rooms include Italy blackout in 2003 [42], and Texas Power Grid Failure in 2021 [55].

Control rooms are complex environments driven by a unique blend of advanced technology and highly trained operators, creating a dynamic and collaborative relationship, since they rely on centralizing massive volumes of real-time data from various sources such as sensors, and communication systems, to provide an overview of the system status and performance, which operators use to make rational, informed, and timely decisions. It is natural to assume that the main challenge for control rooms is the massive amount and diversity of information and the inefficiency of decision-making partly caused by human limitations and errors. For that reason, there is a need to include advanced technological tools to improve handling the massive amount of data and improve the decision-making process. This is why the evolution of control rooms mainly focused on including advanced technology to improve real-time monitoring, control, and decision-making, which might lead to a neglect of the well-being and capabilities of human operators, despite the critical role they play in the control room as they are the final decision-makers. Control room operators are important assets, as they are trained to learn how to employ computer-based tools to gather data and interpret the state of the system. They must constantly make trade-offs between ensuring safety and meeting operational goals. To do it, they create sophisticated mental models that let them discover underlying patterns and make decisions under rapidly changing situations or crises [116].

However, operators face all kinds of challenges as a result of these technocentric approaches and their own limitations. These limitations include fatigue or stress in crises. They must handle “information overload” when they cannot process the available data and manage the confusion that arises when their mental models do not match the information displayed [61]. Operators must also communicate effectively with other operators, adjusting informa-

tion exchanges according to their perception of each other's skills, knowledge, and emotional state. Finally, they must learn to adapt to the ongoing introduction of new tools, even if they are inconsistent with existing tools and interfere with their existing work practices [104]. The effective functioning of control rooms relies not only on advanced technology and tools but also on the seamless interaction between operators and their tools and environment.

Therefore there is a need to balance this focus on improving control room efficiency, which was mainly centered around technological advances, by addressing the challenges faced by operators and designing (operator-centric) tools around operators' different practices such as the handover, in order to increase their efficiency.

I am interested in the role human operators play in these complex systems and seek to create tools that help them make better-informed and more effective decisions. To that end, the thesis goal is to: (1) understand the needs and challenges of power grid control room operators and (2) present tools that are operator-centric rather than technology-centric.

Through this thesis, I aim to answer the following research questions :

- How do current tools support or interfere with operators' workflow?
- How do control room operators capture and exchange information about the system's state?
- Do operators' current tools support information capture and exchange? if not, how to improve it?

1.1 . Thesis statement

Control room operators' work is a complex and interconnected decision-making process, rather than a series of individual single decisions. This complex decision-making is a result of operators managing the information provided by tools and colleagues and adapting them to their mental models, which they constructed based on their knowledge and expertise. Control rooms are currently designed around technology rather than operators, which reduces rather than enhances the overall efficiency.

I believe we need to shift the focus from designing around technological needs to designing around operators' workflow, mental models, and existing practices. In this thesis, I had the chance to work closely with power grid operators who are difficult-to-access users. I identified these operators' need for tools to support tracing and managing information in their control room, by using bottom-up participatory design methods, and I design and evaluate a handover tool that supports operators in capturing information and creating overviews.

1.2 . Contributions

This thesis includes *empirical, design, and theoretical* contributions [6, 73].

1.2.1 . Empirical contribution

I present the key findings from our participatory design workshops and comparative structured observation studies.

Power grid operators issues and needs

The main issue in the control room technology is their predominant focus on the technical needs while neglecting the operator's workflow. While operators are provided with all the needed technical information, they are also obliged to do several tasks to adapt them to their actual needs and workflow.

- Operators struggle to centralize information that is scattered across many tools, that do not communicate among themselves.
- Operators use memory and note-taking to compensate for the lack of support in their secondary tasks (organizing tasks and overviews, tracking information for future constraints, and planning actions).
- Operators need to take notes on paper to keep track of non-persistent information (information communicated orally, information in tools that disappear).
- Operators have poor access to some historical information, due to poor interface and interaction design.
- Operators lose information between shifts due to not sharing personal notes during the handover, and hardships in retrieving information.

Centralizing information for the handover

- Operators build their overviews around key events along with some historical information to provide context.
- Operators group and use personal and shared information in different ways. Personal information is viewed as an overview they keep augmenting, while shared stories are viewed as to-do lists, which are disregarded once they are finished.
- Operators need tracking digital tools to be as intuitive and simple to use as paper, allowing easy organization, distinguish-ability of information and expressivity.
- Operators need a shared control for capturing information and organizing overviews, where operators guide the system to the key points and the system provides the collected information on them.

1.2.2 . Design contribution

StoryLines is a prototype tool for handover. *StoryLines* allows the automatic and manual collection of the different events happening during the shift from different tools. It transforms the different information into persistent objects called "elements" while conserving the link to their provenance. Using these different elements operators can create overviews, by grouping relevant elements together in stories, creating reminders, and sharing these stories. These overviews minimize the loss of information between shifts, and allow to augment the notes rather than redo them.

1.2.3 . Theoretical contribution

I demonstrate the use of *generative theory of interaction* [6], specifically *Instrumental interaction* [4, 7] principles on a specific use case with control room operators.

1.3 . Context

This thesis is part of the project CAB [114] which focuses on developing a virtual assistant prototype that will help operators manage complex situations in telecom, railway, and power grid control rooms and an aircraft cockpit. Being part of this project allowed me to collaborate with RTE (the French Power Grid) and have access to their control room operators.

1.4 . Research approach

I used inductive (bottom-up) [14] participatory design methods to identify and analyze the challenges operators currently have, specifically in their interaction with their environment. then explore solutions to these challenges. While there are different methods to identify operators' challenges such as hierarchical or cognitive task analysis, my focus was on capturing nuanced and specific detailed needs that are harder to capture with these abstract methods which focus on exhaustive overviews of operators' tasks and goals. I am more interested in the operator's perspective of their challenge and needs without stripping them from their context, complications, and imperfections. Bottom-up approaches also empower the operators as they give them the active role of choosing the issues to work on, and the ability to guide and shape the design process. The use of specific contexts in this approach ensures that solutions designed are adapted to real-world complexities and imperfections, which allows quick filtering of inadequate design ideas.

I started with very specific and detailed stories about these challenges, which were the basis for exploring the design space. I also used the *generative*

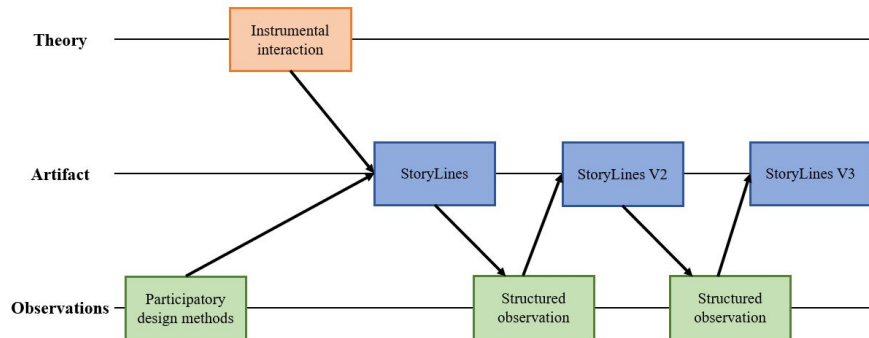


Figure 1.1. **Research approach based on Mackay and Fayard [73] research model**

theory of interaction [6], and *Instrumental interaction* [4, 7] to guide and ground our design space exploration and produce a prototype which was evaluated with the operators to get grounded feedback and improve it. (Figure 1.1)

I started this thesis in the middle of the COVID-19 pandemic, which pushed me to adjust the participatory design activities. In addition, our users are control room operators who are difficult-to-access users with very limited availability and a very sensitive environment.

This section describes the different participatory methods I used to identify the challenges (Story Interviews) illustrate and represent them (Interaction snippets, paper prototype) situate and contextualize them (Persona, current scenario), explore potential solutions (paper and video prototype, future scenario) and evaluate them (Generative walk-through, comparative structured observation).

1.4.1 . Story Interviews

I used semi-structured interviews called *Story interviews* [72] to uncover the different issues operators currently have in their environment, by asking for detailed step-by-step stories about operators' recent and noteworthy experiences, especially breakdowns. This method also helped us to anchor the operators in a methodology focused on details of specific incidents rather than generalities about how their operations are supposed to work since these generalities do not help us understand operators' issues, how or why they occur. *Story interviews* method [72] is inspired by Flanagan's *critical incident technique* [35] which takes advantage of human memory of notable events. We chose this method because we were in the discovery phase and we wanted to work on issues operators chose rather than imposing on them to work on an issue we chose. This type of interview allows us to easily get access to these issues which would have taken longer if we started with observations or general interviews about operators' job.

1.4.2 . Interaction snippets

I used interaction snippets [72] to better illustrate operators' issues. These issues identified in the previous activities were mainly described orally, which abstracted several parts and made it harder to understand especially since they are very context-specific and the context is a very complex control room environment. Interaction snippets [72] help transform the breakdowns into a series of simple interactions between the user and system (actions and reactions) represented by sketches and text descriptions. This method lets users and researchers develop a shared representation of the details of the users' current and future interaction with the system. Operators' expertise and high understanding of their environment allow them to skip or abstract parts that seem obvious to them but are harder for outsiders to understand, thus, describing each breakdown in the level of interaction pushes operators to explain these abstract parts.

1.4.3 . Paper & video prototype

I used paper and video prototype [72] to improve the representation level of the breakdowns and solutions. It helped us design and demonstrate how new solutions will be implemented and how the user interacts with the new solutions (design). Paper and video prototyping help push the designers to consider the different details of the interaction and the environment, which allows the viewers to better understand the design idea.

1.4.4 . Persona

Persona are fictional characters created based on the characteristics of the end-users identified in the previous studies. This method allows us to keep in mind the main aspects of end-users including their motivations, frustrations, and everything that prevents them from working efficiently. As expertise is a defining aspect of operators and how they manage their work, I chose to include personas with different levels of expertise which allows us to investigate different issues that arise with the level of expertise and improve our design to adapt to them.

1.4.5 . Current & future scenario

The current scenario (method of representing data) allows us to situate the breakdowns (events that illustrate key challenges) in a realistic and coherent context. the current scenario allows us to describe how the personas react and manage the breakdowns along with their short and long-term impacts in real-world situations. This current scenario provides an in-depth understanding of the breakdowns as they are not treated as isolated issues in a perfect context with perfect conditions. Based on the understanding of the current scenario, we can push our design ideas further to accommodate the imperfections of the realistic setting. The future scenario describes the same

events as the current scenario but with the introduction of a new system or solution. It illustrates how the new system integrates the environment and how operators use it.

1.4.6 . Generative walk-through

Generative walk-throughs [63] is an evaluation method, used to evaluate design ideas, by reviewing the design solution, critiquing them, and suggesting improvements. Generative walk-through consisted of going through each idea to examine it from the perspective of five socio-technical principles: situated action, rhythms and routines, co-adaptive systems, peripheral awareness, and distributed cognition [63], then brainstorming around those principles to generate new alternatives.

Generative walk-through is a simple mid-design evaluation method, which allows to elevate and improve the design. We can use the five socio-technical principles proposed by Lottridge and Mackay [63] or choose other principles that are important for the design. Then we review the design, preferably through a realistic scenario, in the perspective of these principles, for instance, does our design allow peripheral awareness? If it does, how to potentially improve it? if it does not, then how can we include it? This method allows us to have a fast mid-design evaluation since it does not need much time to prepare such as user testing, it does not need a functional prototype, and it helps guide the evaluation to ensure that the design fits its objectives.

1.4.7 . Comparative structured observation

I used comparative structured observation [37] to provide in-depth grounded feedback on the use, design, interactions, and function of the prototype. Comparative structured observation is a qualitative method, where participants experience different design alternatives through different tasks, which allows participants to reflect on the use of these design alternatives and give grounded feedback, and suggestions.

1.5 . Thesis overview

Chapter 2 presents the research on improving control room productivity from an operator's perspective. In this chapter I follow the information flow in the control room to identify the different issues that arise, I also provide guidelines for the different technologies and tools used to improve the control room and critique their lack of operators involvement in the design process of these tools.

Chapter 3 describes RTE (the French Power grid) control room, it explains the operator's job and description of their environment and the series of workshops we conducted with control room operators which allowed us to under-

stand their job better and highlight the different issues they are dealing with.

Chapter 4 focuses on the handover issue in the control room, and our use of the workshop results along with *the generative theory of interaction* [6] to design *StoryLines* as a tool for the handover.

Chapter 5 presents the comparative structured observation studies that compare the use of *StoryLines* for the handover and real-time, which I used to improve our design idea.

Chapter 6 describes the discussion reflecting on the implications of this thesis.

Chapter 7 concludes with the contribution of this thesis and the direction for the future.

2 - Literature review

2.1 . Introduction

Human operators are the center of information flow within the control room. Their role is not only central but also critical as they are constantly making important decisions to maintain the functioning and health of the system they monitor. I am interested in better understanding the role human operators play in these complex systems and how to improve their decision-making process and efficiency. This chapter explores the research literature related to different control room operations including power grid, nuclear power plant and air traffic control, especially challenges in information flow within the control room, and the tools proposed for increasing situation awareness (SA), reducing information overload, identifying and resolving information bottlenecks, and reducing errors. I conclude with a discussion and critique of current practices.

2.2 . Information flow in control rooms

Control rooms are complex systems where operators interact with each other and with an information system to make informed decisions. Information is handled, stored, and processed simultaneously by both operators and the technological system. Understanding the main issues in control rooms requires understanding the flaws and challenges operators have while collecting and managing information, that can lead to uninformed or poor decision-making. I propose to describe the information flow that connects operators' work and the monitored environment to better understand and situate these challenges (see Figure 2.1). Information flow refers to the movement of data and knowledge through a system or organization. It describes the process of how information is produced, transmitted, processed, and used by individuals and machines. A proper information flow allows control room operators to receive the right information at the right time, therefore enabling them to make informed decisions and facilitate coordination and collaboration between operators. I identified shared elements among control rooms and used them to generate a generalized high-level information flow.

I follow the information flow from the monitored system (bottom-left in Figure 2.1), to the control room (top left) where operators receive the information through different tools in their monitoring station (top right) and mentally process the information (bottom right) to make informed decisions that lead

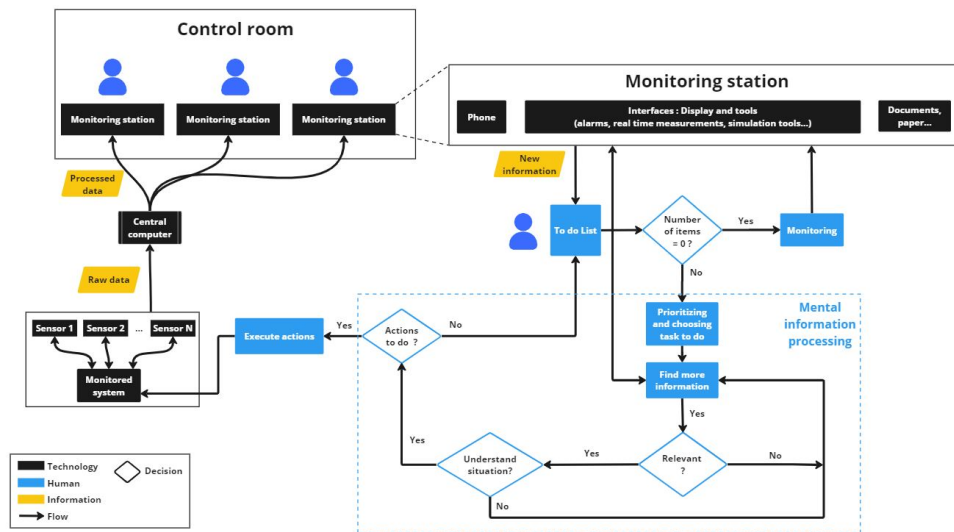


Figure 2.1. **Information flow in control rooms**

to actions on the monitored system.

Information from sensors to user interfaces

This part encompasses everything that comes between the monitored system and the control room providing operators with information. My understanding of this part was influenced by Kang and Park [53] explanation of the information transfer from data to humans and the transformation from raw data to usable information.

The monitored system is equipped with different sensors collecting data in real-time. For instance, the power grid control room monitors the stability of the electric network using power sensors. These sensors measure different metrics needed to supervise the system such as temperature, voltage, or pressure, etc. At this stage the quantity of raw data is enormous, and this information is not sufficiently coherent for operators to understand the actual state of the system and make necessary actions if required. For the operator to process this information, they will need a long time, and a very detailed mental model of the monitored system to understand what each piece of information means. This makes providing operators with this low-level data, hard to process, especially since they come continuously in big quantities. The raw data is transmitted to a central computer system equipped with software specialized in processing this data and validating its accuracy. At this stage, the data will be reduced in quantity and synthesized into indicators that will give insights into the status of different system parts. The quantity of this data is still unmanageable for operators, but it still reduces the detail level of the mental model needed for the operators to understand the state of the system and make decisions.

Information from user interfaces to operators

In order to provide the operators with the right and relevant information, the processed information will be categorized into different tools and prioritized based on the gravity or danger of the situation. This information would be provided in different tools such as SCADA ¹ systems, alarms, trend and data analysis tools for real-time information. The control environment is also equipped with other tools for different purposes such as documenting and reporting (procedures, incident reports), simulation, real-time control (control panels), communication and collaboration, and potentially predictive systems. All the data is presented in the different tools to facilitate finding information (see Figure 2.2). The operators provided with all this information, will first decide which tools to look at, and what information to take into account. All these choices are made based on the operator's knowledge and training.

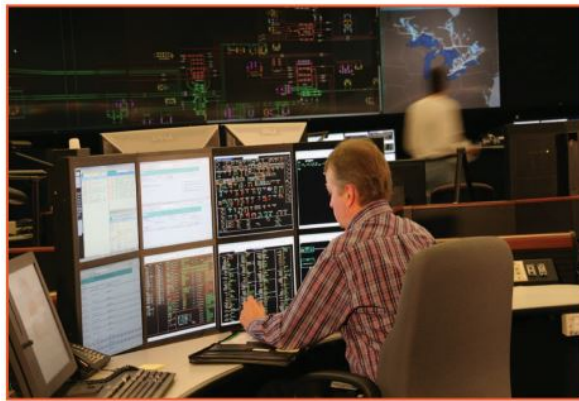


Figure 2.2. **Energy Management system operator [39]**

Information processing by operators

The literature describing the operator perspective is dense. For instance, in the domain of nuclear power plants, Endsly's [31] situation awareness, Li et al [60] explain the situation awareness error's model, and Kim et al.[54] describe of operators' tasks. These references help identify the last part of the information flow as a repeated cycle of processing information, which consists of 3 steps: (1) acquiring and perceiving the information, (2) prioritizing the different information, and (3) filtering the irrelevant ones.

First, the operator perceive a limited amount of information due to "looking-but-not-seeing" [75]. Based on this limited information, the operator does a cycle of choosing which information is relevant to the situation and needs to be pursued. It is possible to have multiple relevant information, in this case,

¹SCADA (Supervisory Control and Data Acquisition) is a system that monitors and controls industrial processes using sensors, remote terminal units, and centralized software for real-time data collection and analysis.

there will be a prioritizing and order made by the operator and potentially documenting this order on their tools or on paper. Once this information is perceived and prioritized, it needs to be better understood, which leads to another round of processing information, by looking for more details in different tools, then potentially more cycles to find appropriate actions to take, execute them, and confirm they achieved their intended objectives. This leads to an updated state of the monitored system and thus restarts the cycle. Operators do not rely solely on their tools for information. It is very common for operators to communicate and collaborate with their colleagues to share tasks or to exchange and confirm information. Communication in control rooms can take two forms: (1) Real-time communication allowing improved collaboration and coordination (2) Handover allowing operators to transfer the responsibility to their replacement, by summarizing the shift and explaining the current state of the system and ongoing operations.

In the next section, I discuss in more detail the challenges faced by operators in the human part of the flow, from the interfaces providing information (monitoring station) to executing actions. While the technology part is interesting and can present different possibilities to limit, downgrade or pollute the information, such as faulty sensors, I am more interested in understanding operators' challenges which can give us insights into the root causes of human errors. This information flow serves as groundwork to explore and map the different challenges operators face trying to manage their workload and the massive amount of information provided by the tools, to monitor the system, make informed decisions, and maintain the system's functionality.

2.3 . Identifying key issues in the control room

Situation awareness (SA) as described by Endsley [30] is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". In the perspective of situation awareness [30] the transfer of information from interfaces to the operator should be made in a way that provides a shared understanding between operators and their tools. The tools should provide just the right information that will help the operators understand the system's state and any anomalies that are worth mentioning, without overloading the operator. This information should be presented, categorized, and prioritized in accordance with operators' mental models which allows them to build and maintain their awareness.

Situation awareness (SA) is a key factor in control rooms, as it enables operators to make effective and timely decision-making. This factor was identified as one of the main causes of several electrical disturbances such as past blackouts (August 14, 2003 in north America [89]; Italy blackout in 2003 [42]).

Which is why I used it as a starting point to identify control room issues from the operators' perspective. Errors in situation awareness can stem from different reasons according to Panteli et al. [89]:

- Software applications: failure in tools can prevent operators from receiving early warnings about problems in their system.
- Real-time measurements: failure in sensors or communication systems or lack of information can lead to uncertainty and slow the decision-making process.
- Environmental factors: alarm overload in crises can lead to confusion and neglect of critical information.
- Automation ("out-of-the-loop" syndrome): highly automated systems can lead to a lower awareness if the operator is de-synchronized and not aware of their actual states.
- Individual factors: lack of experience or inadequate training can lead to software misuse or insufficient use.
- Communication with others: Communication should be limited to important and relevant information to reduce disturbance.

I summarize operators' issues in the control room (see Figure 2.3) and try to understand them from the operators' point of view. From the operators' perspective, they are caused by two reasons: (1) Inadequate or insufficient information provided to the operator (which includes software applications, real-time measurements, automation, and communication) (2) Operators' overload due to fatigue, stress, insufficient knowledge and expertise, and increasing workload. (including environmental and individual factors). Failures in providing the right information will be discussed in the first subsection, I will focus on operators' overload, specifically, knowledge and expertise in the second subsection.

2.3.1 . Challenges due to mismatch between information provided by the tools and operators' needs

The control room generates and provides operators with a massive amount of information from different sources, including alarms, calls, real-time measurements, etc. which they are required to manage and process to ensure the functionality of the system. However, several challenges can jeopardize or slow down this information processing. These challenges include information overload and inadequate information presentation, which leads the operators to employ additional tasks in order to align the provided information with their actual needs. I start by presenting operators challenges related

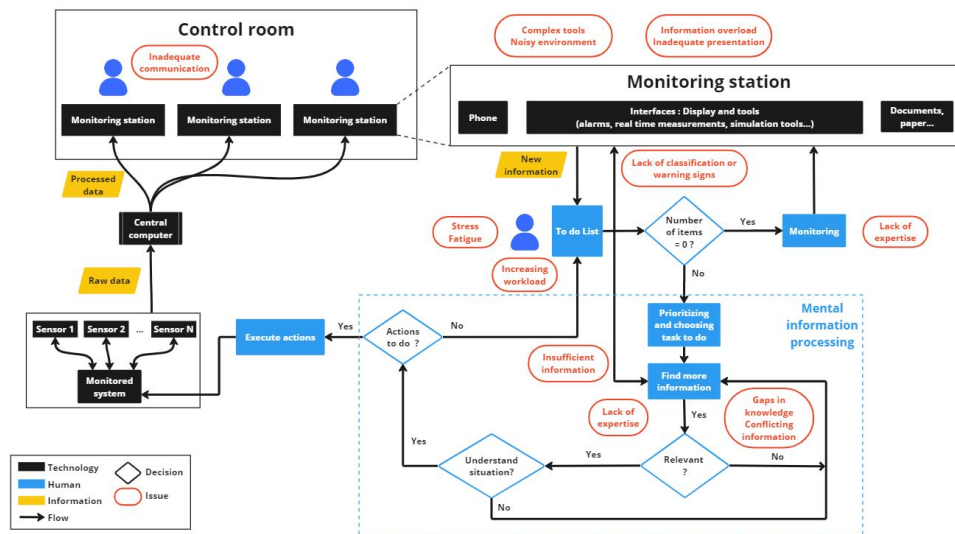


Figure 2.3. Issues in the information flow

to the quantity of information which leads to information overload, then I discuss the issues that arise from a poor information presentation.

Information overload

Operators suffering from information overload is one of the main issues in control rooms. Based on the alarm rate measurement in four power grid control rooms, Baranovic et al. [3] indicate that the SCADA system generates more information than the operators are able to process, specifically during critical moments when there are many faults in the grid. Too much information and the rapid pace of its presentation can lead to a complex, noisy monitoring environment that overloads the operator to the point where they can not perceive all the information, which is known as the effect of "looking but not seeing" [75]. Presenting too much information means that operators need to regularly go through multiple tools to find information, some of which are complex to interpret or not relevant to the situation. Then filter the information, and choose what is important and relevant to the situation. This complex process, which is done manually by the operators, can distract operators from their monitoring. Distractions by doing routine tasks can lead to a reduction in problem detection or even failure to do so [90]. Furthermore, malfunctioning or faulty sensors can lead to providing conflicting information to the operators, which can result in incorrect mental models and cognitive errors [110].

On the other hand, some systems provide very limited information to the operators. For instance in maritime surveillance, Nilsson et al. [82] observed that the overview display does not provide operators with enough information to build situation awareness. Likewise, in nuclear power plants, the de-

centralized distributed automation system fails to provide operators with accurate and reliable information about the plant's behavior[25]. In this case, the operator has limited information, which augments the level of uncertainty and prevents the operator from building an accurate mental model. A limited situation awareness and high uncertainty will limit the operators in their decision-making, and push them toward a more reactive style of monitoring.

Inadequate interface design

Information access and display present several challenges such as hardships in accessing relevant information lack of shared space and overviews, and lack of support in novel and abnormal situations. The design of interfaces, interactions, and visualizations for systems in control rooms is a challenge. There are several reports explaining that information presented failed to satisfy operators' needs. For instance, operators in the power grid control room, face too many obstacles when trying to obtain relevant information. These obstacles can take the form of excessive display pages, lack of information synthesis grouping or classification, or non-visibility of information such as certain equipment's status and condition, and future maintenance requests [98]. Similarly, it was observed in radio astronomy observatory that the original user interfaces consumed too much screen real estate, required many unnecessary interactions to access relevant information, and fail to provide operators with a clear mental model [95]. This poor access to information leads to inadequate situation awareness, which increases cognitive load, and potentially lead to human errors and unreliable decision-making.

Moreover, information is usually scattered in different tools, obliging the operator to find and collect information from different views [79] due to a lack of shared information space [34] or an overview with context-sensitive information. [61] For instance, air traffic control situation data displays do not include weather information, leaving the operators to manually collect external forecasts to re-plan flight paths [83].

Furthermore, relevant information is harder to identify in abnormal situations or with low trust in equipment. Han et al. [46] observed a lack of systematic classification of abnormal work conditions, lack of notification of irregular situations through the interface or sound, and inefficient display of warning signals in the interface. Operators can also have low trust in the information provided by their sensors in mineral processing control room [61]. Thus, there is a need to better manage uncertainty and unpredictability, especially in control rooms where operators are far from the system they control such as railway networks or power grids [34].

2.3.2 . Sources of operators inefficiency

Control room operators tend to use their knowledge and expertise to navigate through complex situations, understand root causes, and apply correc-

tive actions. However, there are factors that can jeopardize their performance such as increased workload, stress, and fatigue. While operators are trained to work in stressful environments, long exposure to these factors increases their risk of errors.

Increasing workload

Control room operators can face an excessive workload in different situations, such as emergencies, unexpected events, or system failures or malfunctions. The workload can also increase due to inadequate task allocation, working with different stakeholders and decision-making in a limited time. The workload can arise from inadequate management and organization, inadequate task allocation, and inadequate communication. Based on event analysis in nuclear, aviation and shipping industries, these issues can slow down the monitoring process and contribute to a reduction in problem detection [107]. Collaboration can also include some hardships, especially when working with different people outside the team, mainly because of differences in priorities, hardships keeping a mutual SA, and an uneven workload distribution [34, 80].

An increased workload can negatively impact the operator's efficiency and decision-making. Operator's workload can increase in situations such as incidents where there is a limited time to respond. In this case, operators need to review a considerable amount of information or do several tasks in a short time period, which leads the operators to look for easier solutions. These solutions or shortcuts can take the form of focusing on narrow information, not noticing or acknowledging any information that does not fit the operator's narrative and convictions. The workload can also increase if operators do not understand or trust their systems or automation. For instance, operators in nuclear power plants, needed to make ad hoc reconfigurations and modifications to the highly automated control system just to make it function properly, due to lack of adequate information about the status of automation system [25].

The workload is also heavily impacted by uncertainty and novel situations. When the monitored system displays new behaviors, never seen before, operators have to recognize that the issue is not a standard routine one, but rather a new one. Operators have to step outside of the familiarity of routine problems with defined well-known procedures and return to the fundamental knowledge to find solutions. The workload will increase even more in case of a lack of automation or procedures to help resolve the new issues [29]. As limited automation can lead to limited support in non-routine diagnostics, and a lack of memory to store information and trends, [117] making it harder to recognize the trends or incidents' causes, which could be easily found with automation. Limited automation also means limited or insufficient tools to help predict and analyze information.

Control room operators are also prone to sensory overload which can stem from the noise in the control room. The overload either due to increasing workload or the environmental conditions, as well as novel conditions, can lead to stress and fatigue [27]. It can result in errors and delayed response time, as well as impacts on the operators' well-being. Zhang et al. [125] study suggest that fatigue leads to a lack of attention to details, slower reaction times, and decreased situation awareness. Stress leads to longer decision-making, and decreased performance. The combination of fatigue and stress lead to more severe impacts on performance than either alone.

Insufficient knowledge and expertise

Operators' lack of knowledge and expertise can also lead to several issues in the control room, such as delayed or inappropriate responses, which can lead to potential risks to the system. Inadequate knowledge of the control system and insufficient operator training were found to contribute to a reactive style of monitoring in mineral processing plants which can slow down the operator's responses and reduce the ability to prevent incidents [61]. This issue is further aggravated when operators are oblivious to the existence of their knowledge gaps, which was observed in pilots [106]. Operators rely on their knowledge to recognize patterns and anomalies in data, which helps them identify subtle cues and anticipate issues before they escalate. With gaps in this knowledge and a lack of expertise, operators might struggle to distinguish between routine fluctuations and critical deviations, leading to either useless interventions, or overlooking warning signs. The expertise plays a crucial role in emergencies, as operators usually draw from their experience and extensive knowledge built throughout the years to make fast and well-informed decisions. Therefore, gaps in expertise can lead to indecision or incorrect responses that might aggravate the situation.

I examined a variety of challenges faced by operators in the control room, ranging from information overload and inadequate interface design to the burdens of fatigue, stress, increased workload, and limited knowledge and expertise. In response to these challenges, frameworks and tools have been developed to alleviate operators' stressors and improve control room productivity. In the next section, I review solutions meant to improve operators' efficiency by reducing information overload, improving interface design and interaction, and integrating technology like automation to enhance operators' capabilities. Exploring these solutions will help uncover the different possibilities to improve operators' capabilities and optimize the control room.

2.4 . Potential guidelines to mitigate the issues in the control room

In this section, I review solutions and guidelines from the literature that were specifically developed to improve control room productivity and enhance operators' situation awareness. These solutions include improving the information provided by the tools in order to highlight relevant information and reduce information overload, as well as improving operators' efficiency, by reducing their workload and integrating technology to support them.

2.4.1 . Bridging the gap between information provided by tools and operators needs

Operators are exposed to a constant stream of information, which includes real-time and forecast data streams, notifications, and alarms. Maintaining situation awareness and making informed decisions requires effective management of this information overload. To manage this information overload, operators develop strategies through training and experience. To better find the right information, operators rely on knowledge-driven monitoring, using mental models, documenting, asking, and confirming the information provided. This knowledge-driven monitoring approach relies on seeking specific information based on the given situation or context, operators also build and maintain a mental model of the state of the system [116]. In particular, operators exploit their own knowledge of the plant and the context information in order to create external reminders that they can use as warning signs of state changes [81]. Operators in nuclear power plants tend to confirm the information provided by the system and expectations about the system state. They pursue unexpected findings and check for likely problems, to find more information that might not be highlighted by the system [102]. Information is also confirmed through communication with other operators and stakeholders. In contexts where operators are far from the monitored systems, such as railway control rooms, operators will usually ask operators that are closer to the situation to obtain trustworthy information, or as a follow-up after implementing a solution [34]. There are also improvements in tools to provide operators with accurate and relevant information. These improvements involve improving alarm systems, which provide real-time prioritized information about anomalies, and interface design and visualization of the different systems to provide and highlight the right information.

Reducing information overload

Alarm systems are important for the control room, as they alert operators when there is any problem or event that require their attention. They can also contribute to different issues in the control room, such as alarm flood, false alarms, or inadequate prioritization. Thus, optimizing and improving the

alarm systems, can help reduce the quantity of the information and present prioritized and easily distinguishable alarms, that provide just the right relevant information. Optimizing the alarm system can be done by reducing the number of alarms and prioritizing them. Romero and Diez [101] proposed their *Alarm Trend Catcher* for power grid control rooms which filters and prioritizes alarms and projects future power grid states, providing operators with additional operational insights. To reduce the number of alarms Hwang et al. [51] included a pre-alarm system that provided early warnings, which allowed the reduction alarm's frequency in both normal and abnormal states. Their study results suggest that the pre-alarms significantly reduce operators' workload since it allowed the operator to maintain a lower level of vigilance while monitoring.

Another way of reducing alarms is to use software and algorithms to find the root cause and remove false and redundant alarms. Baranovic et al. [3] *intelligent alarm monitor* correctly analyzes and represents the root cause of the corresponding faults, allowing it to select 98% fewer alarms than the existing SCADA system. Schleburg et al. [108] software reduces the number of alarms in process control rooms by 70-80%, by grouping related alarms together but their grouped alarms still need to be analyzed by a human expert to validated. Similarly, Cai et al. [17] used a multi-round alarm management system (MRAMS) to improve alarm accuracy and reduce false and redundant alarms. After being tested in a simulation experiment, MRAMS was implemented in a real petrochemical plant for pilot application for 3 months. However, there was no evaluation with operators, or collecting their feedback during the pilot application.

Finally, automation can be employed to automatically reset alarm systems, which place an alarm in an unalarmed state once the alarm conditions no longer exist. Huang et al. [49] evaluated the effect of automatic reset on alarm systems in nuclear power plants on operators, they found that their system helped participants manage a large number of alarms during plant accidents, and reduced their workload and operating errors. However, integrating auto-reset into the alarm system has some drawbacks including neglecting alarms when the information is unclear, missing important alarm information, which may increase the potential for safety issues, and the need for experts to re-adapt to the auto-reset system.

Improving interface design

There are several studies focusing on the design of interfaces and visualizations for control rooms. This work is mainly focused on information visualization with the goal of presenting information in an intuitive way and highlighting relevant information in control rooms. For power grid control rooms, Kang & Park [53] argue that improving information visualization is critical for transforming massive quantities of data into useful information. Giri

et al. [39] consider that the correct visual representation to improve situation awareness and efficiency of power grid operations should be around the operator's goals, which can be helped with different visualization trends, such as geospatial displays, mapping tools, and visual correlation techniques. He et al. [47] visualization framework can provide context-sensitive information and data manipulation algorithms generating visualizations. Zhu et al.[126] employ a data-driven approach to visualization allowing the exploration of the power system from various levels and perspectives. Li et al. [62] interactive 3D visualization framework demonstrates the integration of different types of information such as historical records and real-time information in a geographical information display. While Giri et al. [39] present different visualization frameworks that try to summarize the current state of the control room, collect and correlate data from various sources, and provide concise display visuals for energy management systems' operators. However, neither of these studies involved operators in any kind of study or interview.

Similarly, advanced interactive visualizations are also developed for air traffic controllers. For instance, Yasufuku et al. [123] developed two visualization programs: a fly-through program that helps understand aircraft behavior by visualizing its movements, and a flight route analysis program that allows detailed analysis of flight routes. Ohneiser et al. [83] try to include more context in the radar display by integrating weather visualization with the radar targets, which provides air traffic controllers with accurate weather information along with the air traffic, allowing them to make informed decisions and efficiently manage the air traffic flow. Pertl et al. [93] also proposed a method that summarizes the current state of a control room so that operators can anticipate and take appropriate preventative measures. However, neither of these systems was evaluated by operators to assess the impact on their situation awareness or productivity.

2.4.2 . Improving operators' efficiency

To enhance the efficiency in the control room, it is important to create an environment that allows operators to maintain and improve their knowledge and skills, keep an updated situation awareness, and have an optimal workload level. This can be achieved through regular training, communication and collaboration, and integrating the right level of automation which helps maintain good communication and situation awareness with operators.

Reducing operator's workload

To reduce operators' stress, they can offload some of their workload, either by communicating to receive relevant information to maintain an updated situation awareness or by sharing tasks with other colleagues or automated systems.

Collaboration and communication

Waller et al. [118] emphasize the importance of communication in the control room, both to facilitate collective sense-making and ensure timely and effective action during a crisis. They describe the phenomenon of “talking to the room” where an operator shares information with the entire room as opposed to conversing with specific individuals. This non-directed talk helps teams interpret and explain ambiguous information and facilitates shared understanding and coordinated action. Similarly, Carvalho et al.’s studies of a nuclear power plant control room [18] found that operators use informal talk to maintain continuous verbal interaction with each other, not only enhancing mutual awareness but also helping operators anticipate and prevent errors.

For collaboration among operators, systems usually incorporate large displays to facilitate data sharing, increase situation awareness, and encourage inter-operator communication [99]. For instance, Conversy et al.’s interactive tabletop for Air Traffic Controllers [21] enabled operators to communicate more effectively, both orally and with deictic gestures. They emphasized the need for “feedthrough” to help controllers maintain awareness of their colleagues’ actions.

Similarly, Luo et al. [65] used a digital desk to visualize the power grid status for power plant control rooms to help enhance learning and communication among the collaborating operators, and found that digital tabletops helps operators communicate more efficiently.

Integrating automation and advanced technology

Integrating advanced technology and modernization in control rooms allows to reduce operators’ workload, increase their situation awareness, and improve the control room’s overall efficiency. However, these changes in control rooms also bring new challenges. Indeed, the change from analog to digital control systems has affected how operators access, perceive, and process information. This change in the Human-Machine interface, from physical control panels to screens, made the information harder to access requiring operators to make extra effort in interface management tasks to access it. The process has also changed from using operators’ memory to relying on computer interfaces [23, 54]. Operators need to keep adapting whenever there is a new change.

Moreover, advanced technology can negatively impact the workload of the operators, as they struggle to collect relevant information to understand the system’s behavior, by building complex mental models based on cause-effect relationships between the different elements of the system [56]. Operators’ work is evolving as they are faced with new tools predicting and anticipating problems. For instance, Marot et al. [78] explain how power grid operators’ roles will change with the introduction of automation to help manage real-time operations, freeing the operator to focus more on planning, coordina-

tion, and risk assessment. With new tools, operators need training to adapt to them, to learn how to efficiently use them and to trust their information, to fit them in the workflow, and to master these different information systems [104]. Porthin et al. [97] point out that increasing automation in nuclear power plants might reduce operators' errors, but it might also reduce the situation awareness and the skills needed to do the automated tasks manually. Similarly, Stevens et al. [112] discuss how increased reliance on automation in the control room, can lead to a decrease in situation awareness, which can result in more errors and longer outages when the automation fails. The inability to track and know the state of the automation and why it is behaving in a certain way can lead to gaps in the operator situation awareness which can be due to the interface not allowing users to track the automation's state or activity [106]. Furthermore, having automation, for example, handle all routine cases or specific and defined cases, basically leads the operators to lose the skills needed to do these tasks. If the automation for some reason can not handle a situation, the operator would have lost the skills to do it themselves, as a result the problem will last longer.

Improving operators' knowledge and expertise

Operators' insufficient knowledge and expertise can lead to increased workload and the risk of human errors. To improve operators' knowledge and expertise they need regular training, in order to maintain and improve their skills, particularly in managing abnormal and rare situations, along with occasional training whenever there are new changes in the monitored system or the tools. Knowledge and expertise can also be offloaded to an intelligent system, that monitors operators in order to support them, or to point out their mistakes or missed steps. Boring et al.[11] discuss that human performance variation is the reason there are safety lapses and performance problems in nuclear power plants. To reduce these human errors, some researchers suggest monitoring the operators' cognitive load, and employing different strategies to remediate the situation, when there are inconsistencies in the operator's cognitive load. These strategies could take the form of correcting the operator or pointing out missing steps, presenting better information, providing increased decision support, or seeking a relief operator. The eye gaze analysis could be used to prevent human errors by identifying operators' cognitive states [58]. Using eye-tracking technology, Das et al. [24] observed that operators do not show a lot of change in their cognitive state (fixation and duration) during routine tasks, while they change frequently during hard or critical events. Similarly, operators' postures and behaviors can indicate their cognitive load, fatigue and potential human errors. Zou et al. [127] presented a behavioral coding method and analysis to understand the relationship between operator behavior and their mental state. Singh et al. [110] propose EYE-on-IHM framework, which uses computer vision and image-processing

technologies to capture and analyze data from interfaces, in order to provide a quick diagnosis or inform the operators of missed steps. On the other hand, Lee et al. [59] propose a model to estimate human error probability values using independent event trees. They suggest that their work can be used to quantitatively calculate a more reliable operation failure probability for an advanced Main control room.

As I was exploring different solutions and guidelines, such as improving alarm systems and visualizations, integrating automation, and monitoring operators, I noticed limitations in their ability to improve control room productivity. First, these solutions tend to be designed and evaluated with few operators if any. Moreover, there is a tendency to focus on specific issues in isolation, neglecting the integration of these solutions within the broader context of operators' workflows and the integration in control room environment. As operators seems to be rarely engaged in the design process of these solutions, it leads to overlooking their valuable knowledge and insights. These gaps emphasize the need for a design methodology that actively engages the operators and considers the seamless integration of solutions in the control room.

2.5 . Discussion

This review of literature shows that current research work on control rooms consist of two main areas: (1) research to understand how operators work and (2) research to build technology for the operators. Much of the work focusing on improving control room efficiency by integrating new tools replacing older ones. While these tools achieve their intended technological goals, they are usually not designed with the operators' involvement that would allow to ensure that the designed tools match operators' actual needs. In many cases, operators have to relearn how to use the new tool and re-adapt their workflow accordingly. I also notice that these tools design is usually not preceded by any field study (observation, interviews, questionnaires...) with operators, nor they are evaluated with operators to assess if they are fit for their workflow or enhance their productivity. These tools overlook operators' expertise, mental models, and the strategies they developed throughout the years, that help them navigate complex situations.

2.5.1 . Lack of operators' involvement in the design process

When the interface and interaction design are technology-centered rather than user-centered, operators struggle to understand their tools and thus not use them to their full potential. Information and functionalities that developers consider important to provide in the tools might differ from what operators need [66]. Technology-centered design can lead to a passive approach

to monitoring where operators mistrust the information provided, only deal with urgent alarms, which means they end up dealing with consequences instead of anticipating and resolving problems in a timely manner [61].

It can also lead to developing tools that are not needed such as *GOTRIS* [74] which was developed to support river ships pilots by providing them with information regarding bridges openings. But upon testing with pilots was considered not needed for everyday practices and mostly ignored during safety critical bridge passing.

Therefore, taking the operator's needs into account while designing tools for them, will ensure better issue detection, and information management and reduce operator confusion [61]. There are examples in the literature such as Mackay's work "Is paper safer?" [68] and its continuation into different tools developed for air traffic control such as *StripTIC*[50] which uses of augmented paper strips and digital pen technology to keep the qualities of the paper and enable the updating of instructions in the system. The same goes for these different research that actually took operators' needs into consideration, such as Mikkelsen et al. [79] who did preliminary studies to investigate operators' needs. They found that operators face some issues when navigating between overview and details and alarm management. Based on their results, they designed coordinated views, visual interactive filtering, and parallel coordinates to support operators in their sense-making process in the power grid control room. Their findings from field studies and user feedback indicate that these solutions enhance the way operators interact with data in the system.

2.5.2 . Resolving specific issues while neglecting the overall workflow

To my knowledge, there is limited research that focuses on the overall workflow and work conditions of the control room. SA-oriented design tries to resolve this issue, it relies on doing a goal-directed task analysis and identifying the information needed for each level of the situation awareness (Endsley's three level model [33]). Followed by SA-oriented design focusing on what information to show [32], and finally measuring the SA [85]. This method seems to be technology-oriented, it takes into account predefined goals and normal working situations, but it does not take into account interruption, breakdowns or how to enhance SA in case of emergencies with overflow of information. SA-oriented design focuses on the main and generic part of providing the information to the operator at the right time to make decisions but it does not discuss, for instance, how operators confirm this information, collaborate, or all the personal or individual tasks operators do that are not generic.

Oliveira et al. [84] followed an SA-oriented design to develop an interface for emergency management systems. The interface used different views to

visualize the details of incoming events, the geo-located data in a map and historical information. The aim is to build an accurate and up-to-date situation presentation which will help experts in analyzing emergency situations. They also employ the use of color to highlight the quality of information (completeness, uncertainty). However there were no evaluations with users to confirm the enhancement of their SA through this interface.

Decision support systems (DSS) can also focus on the overall workflow, usually starting from diagnosing issues to providing relevant information and recommendations. For instance, Boring et al. [11] propose a Control Room Operator Support System (COSS) for nuclear power plants. This support system integrates several tools (such as a digital alarms system, procedures, instrumentation diagrams, and a recommender system), and performs several functions (including detection, validation, diagnosis, mitigation, monitoring, and recovery) to assist operators in responding to plant faults. COSS is meant to advise and provide operators with recommendations, relevant information and available actions and procedures when needed, and allow operators to take manual control of any automated procedures, or disregard and turn off the COSS system. While such a system can provide great support for the operators, it was not evaluated to confirm that and it can also have some drawbacks such as enhancing cognitive biases.

2.5.3 . Lack of a defined limit between supporting and replacing the operators

Operators are the main decision-makers in the control room, and therefore they should not lose skills that allow them to make the right decisions at the right time. There is a need to support the operators as much as possible but without deskilling or replacing them. However, the line between supporting and replacing is blurred. We can also argue that providing operators with recommendations can lead to deskilling overtime. When presented with a good recommender system, operators might be skeptical at first and verify the recommendations, but over time, if the recommender keeps providing good recommendations and trust is established, operators might become over-reliant on the recommender without questioning or understanding its rationale, which can lead to decreased familiarity with the system, reduced situation awareness, and deteriorated critical thinking and decision-making skills. While this could be a desired effect in some domains allowing the total replacement of the human operator, it is definitely undesirable in control rooms where operators are responsible for the decisions they make since they can have serious impacts.

All technology that does something operators used to do on their own is technically replacing the operators. Consequently, there is a need to define what tasks need to be done by the operators in order to preserve their skills

and what tasks are less important and can be replaced by tools and automation. For instance, operators could benefit from assistance depending on the importance of the task, where the assistance can take over peripheral tasks, and help users focus on their most important tasks [105]. To that end, there is a need to investigate what skills are crucial for control room operators and define clear limits to tools purpose.

2.5.4 . Limitations

The limitations include limited coverage of the literature available despite efforts to review all the existing literature, the literature on control rooms is vast and encompasses several domains. A second issue comes from the restricted access to studies and reports in the control rooms, particularly in safety-critical control rooms due to the sensitivity of these environments and security concerns. Finally, control rooms differ from each other in their layout, technology, and operators' roles, making the identification of common ground harder.

2.6 . Conclusion

To better understand the issues faced by control room operators, I traced the information flow in the control room. Operators face issues in control rooms either due to individual factors such as increasing workload, or lack of knowledge and expertise, or due to information overload and inappropriate interface design. I found that research tries to resolve these issues, by reducing irrelevant information and improving the information presentation through better categorization and visualization, and by filtering operators' workload through automation, collaboration or even monitoring the operators to provide additional support or point out missed steps. I uncovered two key limitations : (1) lack of operator involvement in the design and evaluation process of the tools intended for their use, (2) lack of consideration of integration of these tools in operators' workflow or environment. We recommend involving operators in the design process to build tools that support their workflow, defining the limit between the important tasks and skills that are meant for the operators to prevent deskilling, and the peripheral tasks automation can do.

To design tools that support operators' workflow and actual practices, We engaged in a participatory design project with operators from a specific control room. Working closely with operators allowed us to understand their specific needs and the limitations and challenges they face in their current environment.

3 - Participatory design workshops

3.1 . Introduction

My literature review shows that technologies and tools in the control room usually change rather than support operator's existing ecosystem and practices. These technologies become a source of new tasks for operators and potentially deskill operators. I believe that new technology should be designed by involving operators in the whole process rather than restricting their involvement in the evaluation. Excluding operators from the design process of the tools they are supposed to use, can result in consequences such as a mismatch between operators' needs and the information provided by their tools which can result in reduced situation awareness and passive monitoring style, leading to a reduction in operator's efficiency.

Designing tools that support operators and potentially enhance their capabilities over time requires a shift from traditional techno-centric approaches that focus on creating more efficient and optimized algorithms to focusing instead on designing the interaction from the user's perspective in what we call a human-computer partnership [70]. This in turn requires a detailed understanding of the operator's real-world work practices, not only how they monitor the system to build situation awareness but also how they capture, interpret and communicate information under both normal and crisis situations.

To that end, we ¹ used a participatory design [41, 69] approach to capture the day-to-day activities and decisions of control room operators at RTE. Since RTE operators have limited availability, we could not observe them. We conducted a series of participatory design workshops where we applied different methods which helped us identify and illustrate the details of operators' issues and then explore and prototype potential solutions. This information allowed us to provide better support for their current activities, with a longer-term goal of capturing in-context data about how and when they made their decisions to inform an intelligent agent. This is particularly important since the operator's decisions are judgment calls that balance a variety of trade-offs, only some of which are captured by the system.

¹These workshops were organized in collaboration with Wendy Mackay, Nicolas Heulot and Robert Falcasantos. The workshops were conducted in collaboration with Antoine Marot, Alexandre Rozier, Mathieu Dussartre and Laure Crochepierre. Each workshop was followed by a debrief among the researchers involved in it.

3.2 . RTE control room organization

The literature review describes the different issues faced in different control rooms such as information overload, inadequate interfaces, increasing workload, or insufficient knowledge and expertise. However, the details of these issues and the operators' job are different from one control room to the other. To design tools that truly support the operators, we need to focus on one control room and involve the operators in participatory design to better understand their specific issues and needs and design for them. We chose to work with RTE control room. This section provides a description of operators' job in this center and their environment, to understand the context of our participatory design.

3.2.1 . Operator's job description

RTE's control room operators manage different information in their environment and collaborate with different stakeholders, in order to ensure that the power grid functions normally, and that electricity is provided to all clients at all times. To manage the power grid, each operator is responsible for a part of the grid in a defined geographical zone. Operator's main objectives are balancing production and consumption in real-time, implementing operating strategies to minimize operating costs while ensuring system reliability, and controlling the consequences of planned outages (for maintenance) and unplanned congestions (alarms and incidents).

This means that operators use all the information available to them in the tools to continuously monitor the grid, learn to recognize warning signs, manage outages, prevent congestions if possible by using prediction tools to predict constraints and implement preventive measures, employ actions to return to a stable grid state as soon as possible after an alarm, and prepare for planned outages by redirecting electricity flows without overloading (surcharge) the lines. It is important to note that RTE's operators make decisions based on expert-knowledge rather than implementing defined procedures.

Their job is specifically challenging due to :

1. Nature of the grid: the power grid relies on a complex and interconnected infrastructure, generating enormous amount of data and possibilities for contingencies [19, 79, 42, 88].
2. Transition of the power grid: The current grid starts including more renewable energy and becoming more interconnected with the neighboring countries, [76, 78] resulting in a way more complex and less predictable infrastructure.
3. Unpredictable anomalies: anomalies caused by human error, natural disasters, or cyber-attacks are hard if not impossible to predict and an-

icipate, which increases the difficulty to recognize and respond to them in real-time [19].

4. Human communication and error: power grid supervision is prone to human error since it requires high operator attention and memory load [98].

These operators work in collaboration with different teams, such as planning teams for predicting consumption, and a real-time collaboration with maintenance team, clients, or operators from other control rooms. Operators are supported by a day-ahead planning team that provides them with predictions for consumption and planned outages a day ahead. This team is supported by a week-ahead planning team who are supported by different teams managing the electricity exchanges. For real-time interventions, operators collaborate with maintenance team who support them by doing interventions on the field. They also work with clients when they need them to do interventions from their side or to ask for permission to act on one of their equipments. Finally, they also cooperate with the national control room for the supervision and interventions on 400KV lines and other control rooms for equipments or lines between their zones.

3.2.2 . Environment

The main control room I studied is designed to support four operators: three who supervise a particular zone (east, west and south) and a senior manager who oversees them. During busy times, a fifth operator may also be included. Operators are trained (for 6 months) on all three zones and spend approximately seven weeks in one zone before shifting to another. The manager supervises all three zones.

The three operators' desks were positioned to face a wall-sized display on the back wall with a huge map that displayed the entire energy grid (see Figure 3.1).² The manager's desk is positioned behind them, with a view of all three desks. Each operator has a large U-shaped desk with an interior approximately three meters wide. We counted about a dozen "stations" for different tools and information sources, including multiple screens, a printer, two telephone stations, and areas for other devices. One set of three screens is operated with a single mouse and keyboard, whereas other tools have dedicated keyboards or control panels. Some tools provide overviews and details about the current status of the energy grid, some sound and monitor alarms while others help operators research re-routing solutions to current failures, expected maintenance or other projected problems. The size of the desk area requires them to use rolling chairs to transition from one station to another.

²This wall has since been removed as part of a major renovation that will consolidate multiple control rooms.



Figure 3.1. **RTE's control room**

Currently, RTE is changing the control room organizations, from 7 regional control centers and one national control center to 3 control centers covering the whole country [103]. With this transition, the organization of the control room is also changing to regroup 3 or 4 control rooms with their operators into one control room. The operators' team size will also change to accommodate the amount of work to do, which increases the number of operators during the day and reduces it at night.

Software tools

Energy grid operators are trained on over 50 different software tools that present information (real-time information about the grid status, sound alarms, and predict potential constraints), simulate solutions, execute actions on the grid, allow access to historic, and create warning signs. These tools have been introduced over several decades with correspondingly different, often incompatible user interfaces. Operators must collect information scattered across their work area and they struggle to form a coherent overview of the power grid. Most information is presented as raw data that rarely matches the operators' mental models. Worse, some information is cumbersome or difficult to retrieve in real-time and junior operators reported that instructions and guidelines were often difficult to understand.

Paper-based tools

Operators also use paper-based tools and documents to ensure that all relevant information is saved in non-digital support. An A1-sized paper map of the energy grid, reprinted monthly, is used to note current breakdowns which they must remember to erase when the problem is solved. Although this paper map provides a concise overview of the grid, it is usually out of date

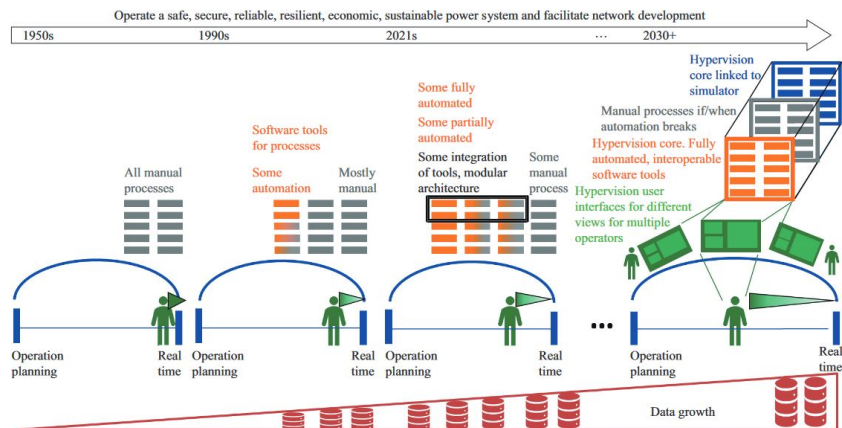


Figure 3.2. **Power grid operators' environment and tasks evolution [77].**

since it is not linked to any online software tools. Other paper-based supports include a large ring binder, exchanged monthly, with hand-annotated print-outs of specific “incidents”, sheets for preparing maneuvers and an A3-sized log sheet for recording completed ones and “floating sheets” for informally recording notes, reminders, and information for the shift handover.

3.2.3 . Changes in the power grid

Marot et al. [77] explain how the power grid is changing due to several reasons internal and external to the power grid. External reasons include (1) the tendency of electrification from sectors such as transport and agriculture, to reduce carbon emissions which leads to the need to improve the reliability and resilience of the power system, (2) the increase of micro-grids or local energy communities who aim to balance their own energy demands and introduce the opportunity of flexible congestion management and balancing, but also new challenges such as uncontrollability and unobservability, (3) the increase of new mechanisms and market participants will lead to an increase in the amount of interaction with these participants as well as more flexibility and more operational constraints (4) the increase in sharing open data and information which might add new manual reporting tasks for the operator.

The changes inside control rooms are (1) new technology for monitoring and control which might make the system more complex and harder to manage, (2) new construction added to the established and aging infrastructure requiring outages of the existing grid, which can further stress the grid, and the risk of human error since the outages require a significant coordination between operators, (3) more coordination and collaboration.

These changes will require changes in the control room systems and with that an evolution of the operators' tasks (Figure 3.2).

3.3 . Procedure

Methods such as task analysis [111, 40] or goal directed task analysis [10] focus on providing an exhaustive and comprehensive overview of the different operators goals, tasks or needs to achieve their work, they are rather abstract and tend to focus on generalities over specifics. We aim to design tools to support the operators unmet needs rather than understanding their job description to redesign the whole environment, which is why our focus was on getting grounded, detailed and situated feedback from the operators about what their environment is currently lacking, specifically the needs they perceive as important, to design tools that are better suited for their needs and workflow. As participatory design is an extensively used methodology in design, and we were able to have access to the end-users we decided to use this approach, to communicate directly with the users without a third party and avoid making mistakes by designing for what we assume to be the end users' needs. We followed an iterative participatory design process and methods described by Mackay [69].

We used a participatory design approach to familiarize myself with the users' needs in their environment. We did not know what areas of the users' workflow or tools needed enhancing or improving. At this point, the only information we had about our users were short presentations of their job and some of their tools. This information was not enough to identify the problems they face and their sources. To understand the breakdowns they face, and any workarounds and innovations they employ to resolve them. We conducted two story interviews and a series of five participatory design workshops over the period of 9 months (Figure 3.3)

3.3.1 . Participants

We recruited a total of two active participants who contributed to multiple activities over several months and one additional operator who contributed to a specific workshop. One very senior operator participated throughout the entire design process. The junior operator (9 months of experience) who participated in the first series of activities left RTE after the first year. Another operators participated in an individual workshop and others contributed information or joined discussions at various points in the process.

The low number of participants is a direct result of the nature of their job, which makes them difficult-to-access users with significantly reduced availability. We compensated having more participants for having a long-term engagement with the same participants to allow us to have better involvement in the design process.

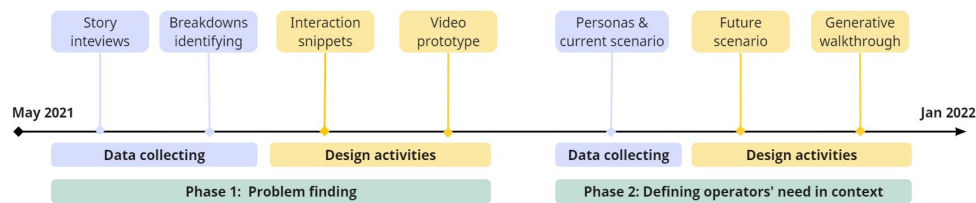


Figure 3.3. **Design workshops: we conducted a serie of workshops in two phases, the first focused on general problem finding, while the second focused on defining operators needs and exploring design space within a specific context. Each phase consisted of data collection and design activities**

The long-term engagement with the users allowed us to have a better understanding of their needs and limitations. I used the period between the workshops to reflect on our findings, identify the gaps in my understanding, and explore potential ideas, which allowed me to clarify and rectify misunderstandings and have a deeper understanding of their needs in the following workshop.

3.3.2 . Workshops

The procedure consisted of two main phases. (figure 3.3) The first phase consisted of general problem-finding and freely exploring the design space, while the second phase aimed to have a grounded exploration and design in a realistic context. Although we were committed to using a participatory design process [67, 69] in person with RTE operators, the project began in the midst of the COVID-19 pandemic, which prevented face-to-face contact with operators or access to their control rooms.

Phase 1: Problem finding

In this phase, we wanted to collect as many notable instances and stories as possible, describing in detail users' breakdowns while interacting with their systems and environment and how they were resolved. Describing these situations in detail allowed us to build a shared understanding with the participants, and to have insights into the source of the issues. We conducted story interviews [69], brainstorming sessions and other participatory design activities to get insights about the context and type of breakdowns users are currently dealing with.

Data collection

We ³ first conducted one-hour individual story interviews [69, 72] with the junior and senior operator separately, our interview approach emphasizes concrete personal experiences over abstractions, allowing us to learn

³Robert Falcasantos and me

about characteristics of the breakdowns they face while working, we probed for more details concerning when they happened, what was done to resolve them, and any innovation they used to encounter these breakdowns. In order to establish trust, we explained that interviews would not be recorded (although we did take notes) and nothing they said would be reported to their employer. The two interviews resulted in 12 specific stories about recent breakdowns that formed the basis for future design activities. These stories consisted of oral and abstract descriptions, which were harder to understand since we had not seen their environment at the time. Following the interviews we conducted a workshop to deepen our understanding of their breakdowns and to get more insights about the operators' environment.

The first workshop was conducted online due to COVID-19 restrictions, with six participants (two operators and four researchers⁴). The goal was to discuss as a group the previous breakdowns to better understand them, to check if the operators experience them differently and identify new breakdowns. We first sent the operators an explanatory video that detailed the workshop activities with examples of what we expected. We also asked all participants, both operators and researchers, to prepare a one-minute video that illustrated a specific breakdown that they had recently encountered at work. Finally, we asked them to have blank sheets of paper and pens to support paper prototyping. Each participant explained their video and we probed for more details about what actually happened. The goal was to avoid generalized descriptions of what usually happens and instead, capture the nuances of what happened that particular time. We then conducted an online brainstorming session to collect additional breakdowns. (summarized in Figure 3.4)

Findings

Our focus on their perspective on their experiences rather than forcing them to adopt a system-oriented design perspective gave us access to a very scarce resource — the operator's time — and provided a solid foundation for understanding their work practices. We found that the environment might not respond to all the user's needs, which leaves them with different additional tasks to adapt the raw information they receive to the mental model that they rely on for decision-making.

With only 4 hours of contact with operators, we were able to identify the main issues they are facing, and operators were very engaged and actually enjoyed talking and discussing these issues. The senior operator appreciated our grounded interview approach:⁵ *"I really see the work we can do together from a concrete usage perspective... I am really satisfied since this really makes things concrete for me... I am excited to continue!"* The junior operator agreed:

⁴Wendy Mackay, Robert Falcasantos, Moustapha Zouinar and me

⁵Quotations are translated from French.

Preliminary design workshop results

Information mismatch

- Paper and screen-based views out of sync
- Paper and electronic systems are not linked
- No shared view when collaborating with someone
- Display not adapted to current operation, risks confusion
- Lack of real-time visualization overview
- Cannot access views of adjacent sectors

Interruptions

- Phone calls interrupt work flow
- Distracted from a document and forget where I was
- Switching from tool on one screen to another

Risk of forgetting

- Need to update the schema (paper map) after each maneuver
- When busy, easy to forget information for the handover

Wasted time

- Always have to search for options
- Instructions are complex, confusing and not adapted for real-time operation
- System should propose actions relevant to the current alarm

Figure 3.4. **Preliminary workshop results include issues with information mismatch, interruptions, risk of forgetting and wasted time.**

“This allows us to really make the things we talk about concrete and to clearly show you the problems that we encounter every day, whether they are simple problems or profound problems in the organization we have today... despite the frustration of the fact that we can’t be in the same room and interact with even just our hands, you have managed to find tools that are practical enough for us to feel like we are making progress, even if we can not be together physically.”

Our main findings can be summarized in these four categories:

Information mismatch: Operators’ current environment is constituted of numerous raw information scattered in different tools, which makes it harder to collect all the information and have an overview. We were surprised to discover that the operators’ environment is constituted of more than 50 specific tools.

Interruptions: Operators tend to be interrupted by calls and alarms. They are obliged to re-prioritize their tasks whenever there is a piece of new relevant information. To do so they should interrupt their ongoing task, take in all the information (by gathering them from different tools) to understand the different tasks needed to be done, and decide in which order they should work on them. Currently, there are no tools that support operators in these interruptions and prioritization. Operators rely on paper to take notes of the different tasks, tracking where stopped the task and what they had done, and making reminders or to-do lists.

Risk of forgetting: As a result of the interruptions, operators usually tend to forget anything they did not take notes of, or even forget to check the paper for their to-do tasks (that they wrote) when they are busy. There is a consider-

able amount of forgetting especially during the handover due to mainly relying on operators' memory and note-taking to summarize the notable events of the shift and warn about ongoing and future events.

Wasted time: Information given in these tools is usually raw, which might not match operators' mental models and representations, leaving them with the additional task of transforming this information into their own representations to update their own mental image. Furthermore, not all information is easy to retrieve, for example, instructions and guidelines were considered hard to understand, and not easily accessible in real-time (specifically for junior operators).

Besides digital tools, oral communication is also needed inside and outside of the control room, however, there is no support to capture this information other than note-taking and relying on operators' memory. In addition, they have paper documents, whose purpose is to ensure that necessary information is saved in non-digital tools. which adds the additional task of updating the paper documents (paper maps) whenever an action is done on the grid.

Design activities

The issues discussed in the previous activities were still incomplete and rather abstract for our understanding, as we did not have a full understanding of how they happened. To better understand these issues we conducted a second workshop, which was an all-day event with seven participants (three operators and four researchers⁶). Six were physically present and one operator joined via video from the control room.

We started by brainstorming ideas for additional breakdowns. To probe for more details and start exploring the design space we paired operators with researchers and asked them to draw *interaction snippets* [69], it consisted of dividing the breakdowns into specific user-system-user (or system-user-system) interactions. (Figure 3.5) Participants were also encouraged to use interaction snippets to demonstrate or illustrate how a potential solution might be used to resolve those breakdowns.

To better understand these solutions we used video prototypes to demonstrate their functionalities. Each pair created paper mock-ups (Figure 3.6) and shot short video clips where the operators demonstrated how they would interact with each idea. These solutions' purpose was to help characterize the design space, rather than to be used as final solutions. The operators especially liked the video prototyping activity because it gave them a concrete way to communicate both the problem and the solution. The workshop resulted in 10 interaction snippets and five video prototypes, all of which highlighted the need for centralizing information.

⁶Wendy Mackay, Robert Falcasantos, Alexandre Rozier and me

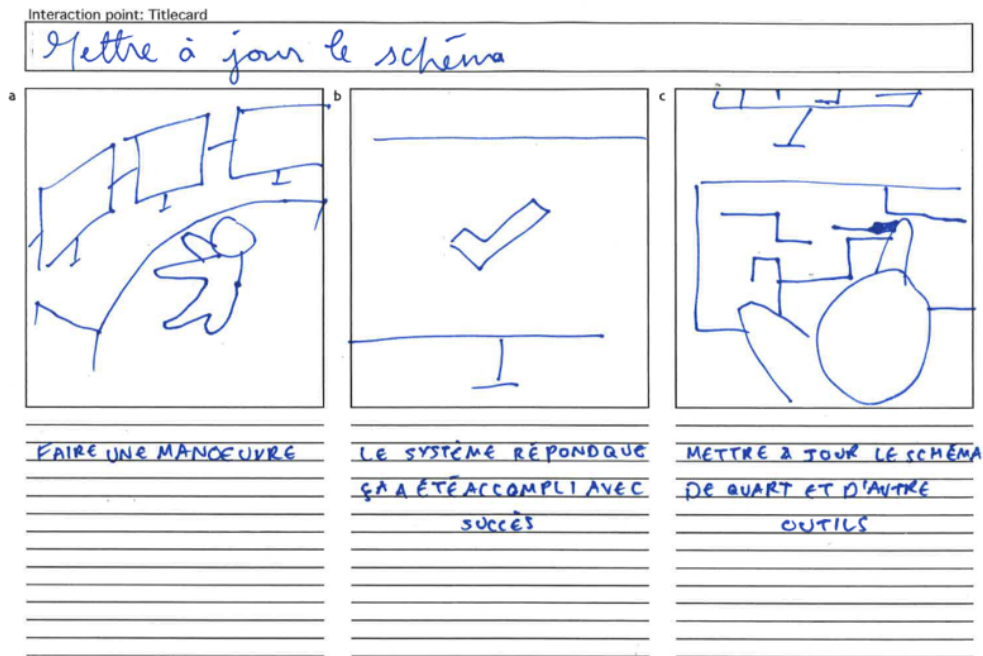


Figure 3.5. An interaction snippet explaining that operators need to update paper map after each action on the grid. First snippet: doing a maneuver, second snippet: system respond maneuver accomplished successfully, third snippet: updating the paper map and other tools.

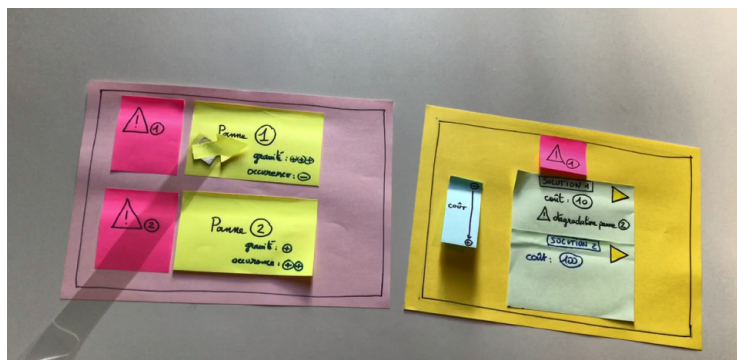


Figure 3.6. Example of a paper prototype on the information summary presented with an alarm

Findings

We found that participants focused more on centralizing and enabling easy access to information through different examples. Participants demonstrated in three different examples how they would like to have different information (context, guidelines, impacts...) presented to them when they have an alarm, and how they would like this information to keep getting updated as they work on resolving the alarm. The difference between these three examples was the context and gravity of the alarm presented. The other examples also focused on centralizing: either centralizing all tools in one master tool dedicated to resolving alarms or centralizing information of the shift in a wall display to be able to communicate the information for the handover.

Phase 2: Defining operators' needs in context and exploring the design space

Our goal in this phase was to investigate the needs and breakdowns and how they happen in context. As these issues do not happen in isolation, they usually happen in a realistic and imperfect context which might complicate the issue resolution due to other constraints, uncertainty, information overload... We chose to use a realistic and problematic scenario as a context in order to push the limit of the future design.

Data collection

Once we had a better understanding of the operators' work context and environment, we decided, in the third workshop, to construct with the participants (two operators and four researchers ⁷) a contextual structure based on this information, through realistic *personas* based on the operators, and a *current scenario* that describes a realistic day for the operators including different breakdowns and how they resolve them using their current system.

We asked the participants to give us the characteristics of a junior and a senior operator, including the important traits of their personalities and backgrounds. We then constructed a realistic and coherent scenario with the help of the operators, who drew from their experiences to adjust the scenarios, especially with respect to the ways in which small errors, particularly in communication, can cause problems or complicate the situation. *The current scenario* describes a busy day including different types of breakdowns and issues. For each breakdown, we asked the operators for more details including context, people involved that must be informed or contacted, such as impacted clients, how would a person of the expertise of the persona would deal with such an issue, and any possible complications that can occur.

The workshop resulted in scenarios related to two personas: Charles and Julie. Charles is a senior operator with 12 years of experience and Julie is a junior operator who just finished training. The scenario includes three main

⁷Wendy Mackay, Antoine Marot, Laure Crochepierre, and me

situations: a busy morning for Charles who just returned from vacation; a rushed and poorly prepared handover to Julie and an afternoon filled with complex problems for Julie.

Findings

This activity allowed us to discover a new layer of details concerning the breakdowns, specifically the little complications that can elongate or complicate simple tasks. We specifically discovered that communication and coordination takes a big place in the control room work, while it was described before as something that was done, we did not fully understand, at that point, how much time communication takes and how it can impact the operators' work by complicating an issue, delaying, or canceling it.

We also found that operators rely on paper as a tool to organize their tasks and annotate what needs to be passed on during the handover, which sometimes results in forgetting to do some tasks or forgetting to pass on information. Forgetting to pass information during the handover can prevent operators from anticipating problems early enough, which makes them harder to resolve. The handover information should also be adjusted to the receiving operator's expertise, as junior operators might need more information or explications to understand, specifically in areas they never operated on. However, giving junior operators all this information can elongate the handover, and potentially impact their cognitive overload.

Design activities

For this phase, we used the current scenario to start exploring solutions that would improve the breakdowns within it. The fourth workshop was conducted in our labs with five researchers⁸ and two operators. We developed a "future scenario" based on the scenario created in workshop 3, we discussed the different breakdowns and explored potential solutions to resolve them. We supplied prototyping materials and simulated their environment with paperboard "screens". (Figure 3.7) We then created paper mock-ups of the different tools and created video prototypes of various solutions proposed by the operators and researchers. (Figure 3.8) The results included four specific solutions designed to improve communication with the planning team, visualize cognitive load, and visualize failures as they evolve over time.

Finally, we conducted a fifth workshop at the RTE control center with three researchers⁹ and one operator physically present as well as one remote senior operator. The goal of the workshop was to use a generative walk-through [63] to evaluate the scenarios and ideas from workshop 4. We played the video prototypes and discussed how to improve the proposed solutions, including incorporating new information as a situation evolves, automatic update of other information and tasks, tracking and comparing solutions and taking into

⁸Wendy Mackay, Antoine Marot, Alexandre Rozier, Mathieu Dussartre, and me

⁹Wendy Mackay, Antoine Marot, and me



Figure 3.7. **The simulated operator environment with paper screens**

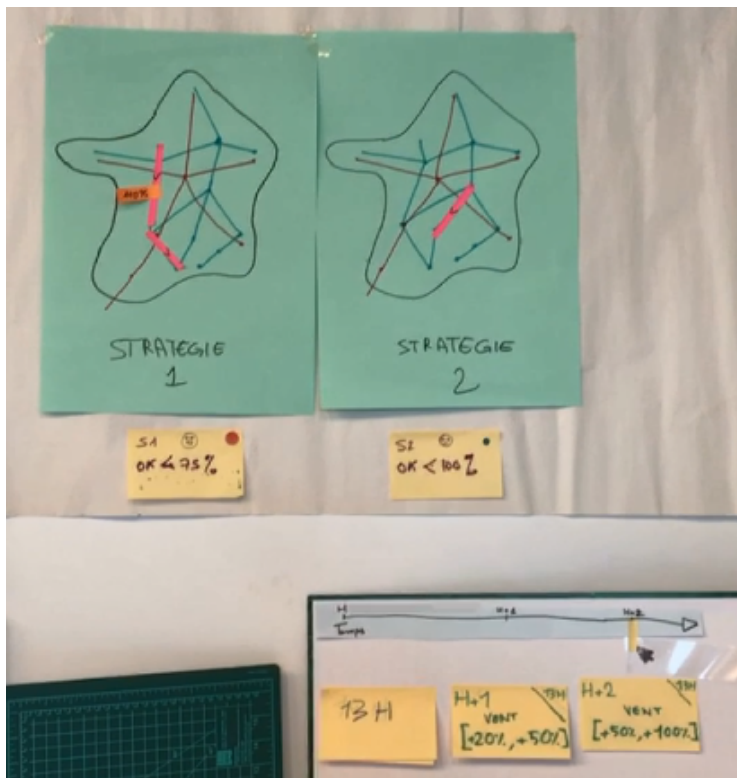


Figure 3.8. **A solution proposed by operators: visualizing the impacts of two strategies (constraints solutions) on the grid, along with their evolution in time**

account the "last time to decide" (LLTD). This workshop highlighted how much critical information is lost, either because it was transmitted orally or it was never captured in the first place.

Findings

In these activities, participants focused on the context and time dimensions in "centralizing information", by exploring how to interact and include different information that comes to light while they are resolving an alarm. They explained two different ways of presenting information such as power grid constraint predictions, potential solutions, and keeping track of these solutions to compare them as they evolve in time. And a way to interact with constraints and solutions through timelines & sliders to explore either their probability of happening or the different impacts they could have on the grid, in order to compare and choose the appropriate solution and when it is best to implement it.

They also presented how they would like to communicate updates to the planning team, and how the manager can have different information about each operator's tasks and cognitive load, so he can come of aid or balance the tasks between operators when needed.

3.4 . Results

The participatory design workshops were overall very enjoyable for all the participants, operators were very engaged and enjoyed brainstorming and prototyping solutions for the issues they currently have. They also helped us adjust our ideas to their context by explaining their drawbacks in real-world use. The workshops allowed us to have insights into three main critical problems operators face which are not well supported by their tools:

Difficulties having an overview

The power grid operators work in an environment containing several screens and numerous specified tools and software. The complex grid produces a large amount of information that is scattered in their different tools and software, making it harder for the operators to get a proper overview of the situation, and to keep traces of relevant information. Furthermore, The current system relies on saving loads of information (about actions on the network) in their tools, without adding any elements of context to understand the reasons behind the action, or highlighting the relationship between these pieces of information, and without an easy way to access them.

Operators need to create an overview of the situation at all times to maintain good situation awareness, which they try to do with note-taking on a paper where they annotate non-persistent information such as calls or simulation results, along with ongoing and future tasks, to help keep an overview of

the current situation and the workload. It would be of added value to coordinate the digital tools among themselves, in order to display the underlying relationship between the information from different tools, within a given on-going task or activity.

Lack of digital support for oral communication

Communication is crucial in a control room as it helps keeping a good situation awareness for all the stakeholders. Currently, this communication is done mainly orally making it more prone to errors, and its details are easily lost or forgotten, which might lead to blind spots or mistakes in the overview of the operator. For example, forgetting to communicate a piece of information during the handover can lead to a lack of anticipation, preparedness, and possibly resulting in a power outage. Therefore, the communication should be better structured, specifically for crisis cases, to ensure that all important and relevant information are communicated efficiently, and saved to be reviewed if needed.

Lack of support for decision making

The power grid operators' decision-making requires a lot of anticipation and preparation as they might not have enough time to solve the issue in real time. They usually review solutions at two different stages; during the prediction stage, and then at the decision stage when the problem occurs. However, they currently do not have any tools to keep track of the solutions reviewed in the prediction stage other than taking notes on paper. This two-stage decision-making helps cover most cases, but it does not cover unanticipated events and it can also be challenging to anticipate all the issues at hand during crisis times.

It can be of added value to be able to track and see the evolution of the constraints and solutions from the predicted stage until the decision and resolution stage. A collaboration tool could also help operators during big incident by supporting communication and information sharing while they are looking for solutions together.

The inability to track future constraint and their solutions, to capture information communicated orally, or have a support for collaboration also prevents operators from having their needed overview, which they try to remedy by using paper as a simple tool to annotate any non-persistent information such as oral communication, but also the future constraints and their potential solutions. These issues could be a result of having a decentralized environment designed to separate information and focus on one specific type of information at a specific time, which prevents operators from having a higher-level overview of the whole situation, how different types of information relate to each other and not only in a specific time but in the whole shift.

3.5 . Discussion

These participatory design workshops highlighted that operators did indeed have some issues due to the tools not supporting their needs, and creating secondary tasks such as taking notes to track information and prioritize them. I found similarities between the issues faced in RTE's control room and the ones identified in the literature review, which prevents operators from having adequate situation awareness mainly due to their software applications and information overload. The main issue identified in RTE was having too many tools and the need for operators to centralize information by themselves, which is since each tool was developed individually and with limited consideration to their place in the environment and operators' workflow. A similar issue was observed by Mikkelsen et al. [79] who developed coordinated views to accommodate the power grid operators' need to collect information from different desynchronized tools. Farrington et al [34] and Li et al. [61] also identified the need to have a shared information space or an overview with context-sensitive information.

Another issue is RTE's operators face information overload during big incidents when there is a flood of alarms, with pages and pages of alarms, that should be treated manually to access relevant ones. Barvanovic et al [3] observed similar information overload in SCADA systems in power grid control centers and Prevost et al [98] observed excessive display and lack of information synthesis, grouping or classification in power grid. While these issues were already identified in the literature review, our workshops provided us with detailed descriptions of these instances from the operators' point of view, which are valuable information that allowed us to design tools that respond not only to the technical needs (such as reducing information or centralizing them) but also to be adjusted to operators workflow and context.

Furthermore, we uncovered issues not mentioned in the literature review such as:

- the redundancy between tools and papers,
- the loss and misremembering of orally transmitted information,
- and the lack of support to operators' workflow (existing practices) including tracking information to adjust to the constant interruptions and prioritization, and keeping traces of solutions when operators are anticipating and preparing for future constraints,
- lack of support for communication and collaboration (especially when it involves more than one control room).

It is relevant that not involving the users in the design process and neglecting their workflow, is what led to more than multiple disconnected and

dis-synchronized tools, while these tools all provide technical added value, they are hard to manage from an operator point of view. Operators' workflow keeps getting complicated with each new tool added to the control room.

3.6 . Conclusion

We aim to design tools to support power grid operators, instead of asking them to re-adapt to the tools provided. To that end, we focused on understanding operators' issues in a real-world context. We conducted a nine-month participatory design project with operators from the RTE French power grid.

The results of these workshops with operators echo some of the literature findings including information overload, inadequate interface design, and increasing overload. The results also uncover new issues specific to RTE control room such as redundancy between tools and papers, the loss and misremembering of orally transmitted information, and the lack of support to operators' secondary tasks including tracking information and task prioritization. In addition, our results provide specific and detailed examples of challenges faced by operators from their perspective. This enables a key opportunity for design for these specific challenges while taking into account operators existing innovation and way of working.

Furthermore, our work shows that participatory design is an effective way of engaging operators of safety-critical systems in productive design activities. For our future design activities, we will focus on the handover process as a use case. The handover is a result of centralizing and organizing information and tasks to provide an overview. Designing a tool to support this process, will also help operators create overviews to make sense of information in real-time or prioritize and track tasks and information.

4 - StoryLines: Influence and concept

4.1 . Introduction

Through the participatory design workshops, we found that operators face several issues in the control room such as a lack of overview and communication between tools, information overload during crises, and a lack of support for all the secondary tasks such as note-taking, tracking, and organizing.

We were particularly interested in the secondary tasks operators do to compensate for the tools' shortcomings. All operators took paper notes that they used to keep track of ongoing activities and manually transfer information from one system to another (which they viewed as a waste of time). They also create reminders for future actions and list key items to communicate to the next shift's operator during the handover. We were also struck by the level of oral communication between operators, not only during shift handovers but also in real-time across zones, and with the manager. Operators were often interrupted by phone calls from clients and other stakeholders.

Based on our observations and discussions with the operators, We decided to focus on the handover between operators at the end of every shift, as the handover is a direct result and summary of these secondary tasks, specifically note-taking of ongoing activities, oral communication, and the results of any research the operator conducted to solve current or projected constraints, and creating reminders for expected critical events.

We prioritized my design goals, to begin with the user's perspective so that the resulting system supports their existing practices and offers them concrete benefits while benefiting from the existing theory. To that end, we took advantage of the work on generative theory [6], and the research literature on handovers to design the interaction with the new system. Generative theories of interaction are inspired by established theory in the natural and social sciences but are transformed into concepts and actionable principles that inform design. I describe how we combined bottom-up participatory design methods with a more top-down theoretical approach based on *Instrumental Interaction* [4, 7] to develop a novel system I call *StoryLines*.

4.2 . Handover

Operators take notes to capture relevant and non-persistent information (such as information communicated orally), but also to note their to-do list and create an overview of the task they need to do. By the end of the shift, these notes serve as a summary of the shift's most important events, the ongoing events, and tasks to do. This summary is used by the operator as a guideline for the information to communicate during the handover. To better understand how the different way of capturing information influence the handover, I reviewed the research literature on the handover process and tools.

The handover is the process of transferring responsibility and accountability to the next shift, it consists of communicating all the necessary information about the system to the incoming shift, to ensure good situation awareness and continuity of work without problem. Inefficient information communication during the handover can lead to a lack of awareness of the system's state and ongoing tasks, and a lack of preparedness for future events, which can lead to mistakes [92].

The handover is a common practice in industries involving complex or critical systems, that might face serious consequences in case of a system failure, such as nuclear power plants, or electric network supervision centers. The research on the handover is most common in the medical field, specifically for the shift between nurses as their work can affect to patient's health state. Each field has its own handover process or procedure and tools but the handover goal remains the same "providing the incoming person with all the necessary information to continue monitoring the supervised system". Since all these contexts handle critical systems, I reviewed the handover methods in these different contexts to better understand its process and the tools used for it.

The handover is usually prepared throughout the shift, to ensure that all the necessary information is collected and organized to be communicated during the handover. The necessary information provided during the handover can be guided by rules or guidelines but it is still abstract. It can be defined differently among different colleagues. It is up to the outgoing person to define the necessary information depending on their expertise, the incoming person's expertise, and the situation.

The handover process is different in each field, for instance Wayne et al. [119] describe the handover process in medical field using spreadsheets (figure 4.1). A generalized handover process consists of three main steps, although the third step might not be considered part of the handover in some fields:

1. Outgoing person prepares the handover throughout their shift.
2. Outgoing communicates the handover information to the incoming per-

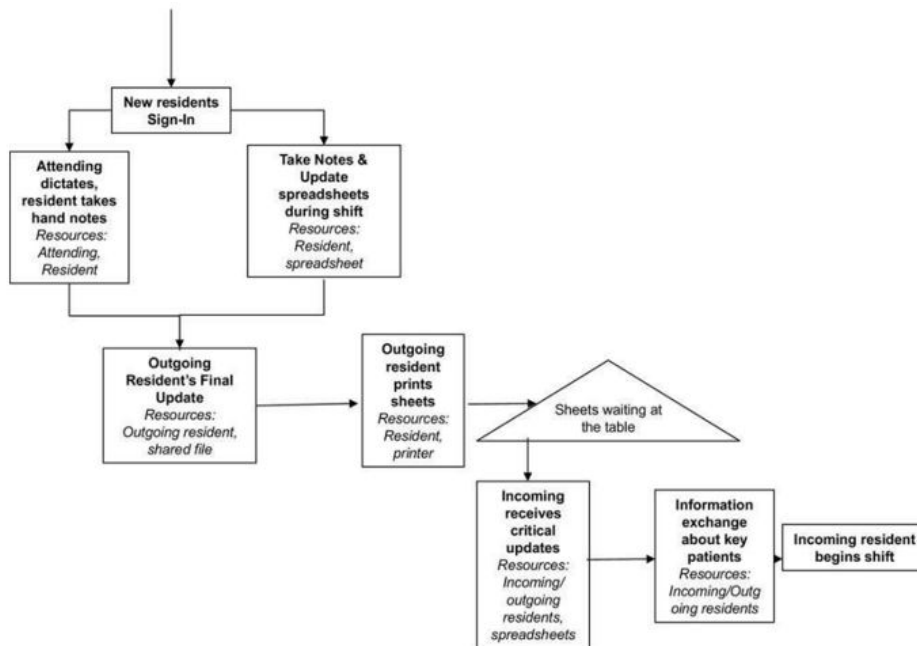


Figure 4.1. Handover process in medical field [119]

son.

3. Incoming person confirms the handover information and uses it during their shift.

The most critical part of the handover is the communication between operators since it is usually restricted in time (15 minutes in case of RTE power grid) which means it should be well prepared and the communication between operators should be efficient and well structured.

Preparation phase involves gathering and organizing the information. Information can be collected using paper, recordings, or data support technology. Using paper or recordings allows users to give informal personalized information, such as explanations and advice... but these methods have the potential of transcription errors or containing not up-to-date information, and recordings exclude the ability to ask follow-up questions to clarify or rectify misunderstanding [113]. On the other hand data support technology can generate structured summaries with all necessary and updated information [94], but it does not include the informal information that completes the "full story".

Organizing the information can be done through a specific structure to improve the handover efficiency and effectiveness [92]. Cornell et al. [22] findings suggest that using *SBAR*¹ structure improved the shift report in four

¹Situation Background Assessment Recommendation

medical-surgical units, this structure enables consistent patient-centric reports, without increasing the shift report length. However, Schoenfeld et al. [109] study suggests that increased structure has the potential to leave out important information.

Communication phase The handover is usually communicated verbally, but it can also take the form of reading a written report, listening to recordings, or reviewing summaries automatically generated, although, to our knowledge, this method has not been observed so far [92]. This phase can have shortcomings in case of lack of preparation by the outgoing person along with the nature of the information provided and the quantity of the information provided which can lead to an information overload. This is the most critical part of the handover, many researchers encourage having conversations and asking questions to conduct this part efficiently.

Confirmation phase is the least common. One of the criticisms of the handover with nurses in the medical field is that its information might not be up-to-date, leaving the incoming nurses to confirm all the information provided before starting their shift [22]. Patterson et al. [92] observed in space shuttle mission control, that the outgoing and incoming person work together for one hour, which allows the outgoing person to correct misunderstandings, they also suggest reading back the information received during the handover to confirm its accuracy. Mackay [68] also observed that air traffic controllers "supervise" the incoming person working for a few minutes to ensure that they are doing things right.

The information-collecting tools used should not be restricted to either collecting data from digital support or writing reports and annotations. Nurses had difficulties transitioning from using paper for the handover to Electronic Health Records (EHR) ² which only allows to access patient records [9]. It was also the case for Cornell et al. [22] study since their digital report tool did not provide any advantages over the paper such as data accuracy or linking to other information. The information also needs to be presented in a more understandable and interpretable way. To that end, Patterson [91] proposes using a flexible narrative structure to improve comprehension and sense-making.

4.3 . Generative theory of interaction

We decided to address the needs identified in the participatory workshops related to the handover, using the strategy outlined in Beaudouin-Lafon et al. [6] for applying a *generative theory of interaction* to a real-world design problem. This strategy combines bottom-up analyses of current work practices

²An electronic health record (EHR) contains patient data, such as demographics, prescriptions, medical history, diagnosis, surgical notes, and discharge summaries.

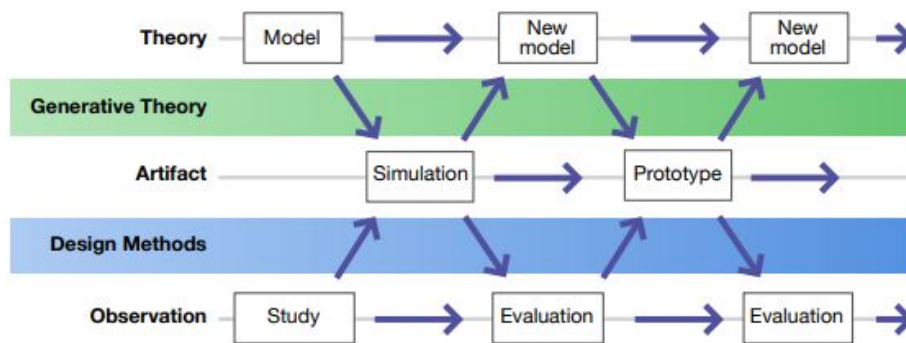


Figure 4.2. **Generative theory helps design artifacts by applying theory (green); while design methods focus on observation about artifacts' use (blue). [6]**

with top-down concepts and principles derived from theories of human behavior, which helps guiding the design process, expanding the design space, and enhancing the design idea.

Generative theory tries to bridge the gap between HCI (Human Computer Interaction) theoretical work and artifact design (Figure 4.2). It helps enhance creativity by combining empirical findings with existing theories and principles. To that end, it presents concepts and principles that can be applied to specific use cases to help generate new insights about the users and interaction design ideas. It provides actionable tools and concepts based on the theories of human activity and behavior with technology to help apply those concepts to specific design problems.

Generative theory describes three lenses (Figure 4.3) that can be used in specific use cases to help enhance design ideas. The analytical lens describes the current practices and use of the current system. The critical lens assesses the advantages and inconveniences of the current system. The constructive lens helps apply the actionable tools and principles to generate new design and interaction ideas based on the results of the critical lens.

We used the generative theory lenses (Figure 4.3) along with the actionable principles of *instrumental interaction* [4, 7] to generate our design idea. *Instrumental interaction* [4, 7] principles *Reification*, *Polymorphism* and *Reuse*, builds upon theories of affordances [38] and human tool use [87, 86, 100] from experimental psychology. The first principle is *Reification*, which transforms an otherwise ephemeral action into a persistent interactive tool. The simplest example as explained by Beaudoin-Lafon [7] is the scroll bar that transforms the action of scrolling into an object that operators can manipulate. The second principle is *Polymorphism* and the ability to apply actions on different types of objects such as using the same color palette to color text,

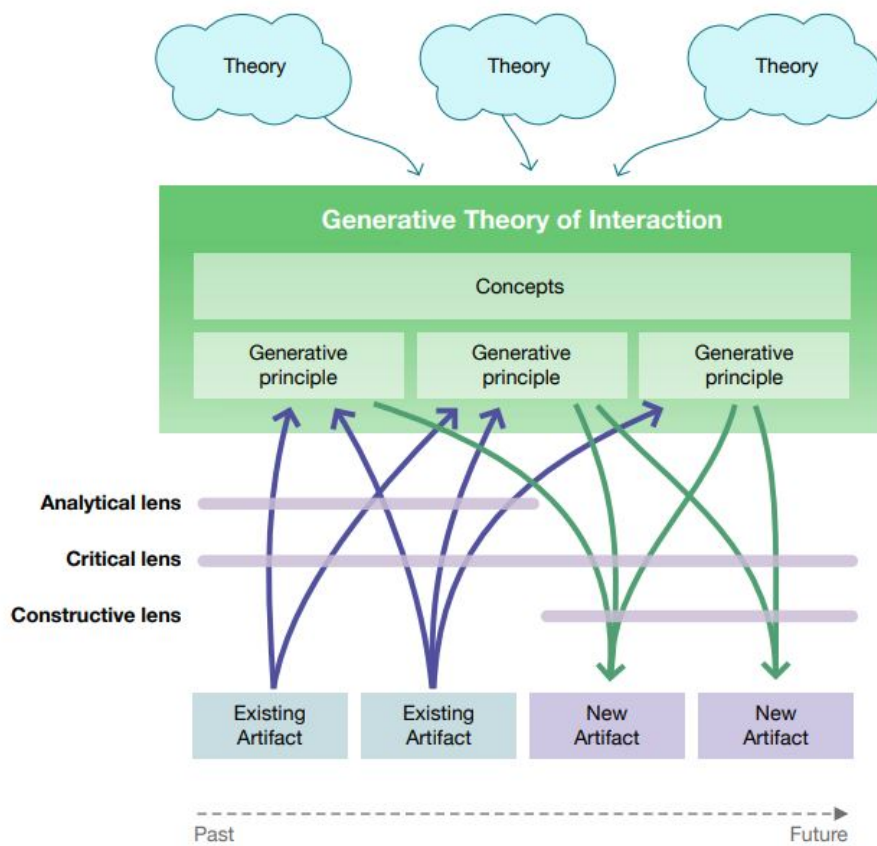


Figure 4.3. **Lenses of generative theory of interaction [6]**

shapes, or images. Finally, the last principle is *Reuse*, input reuse which is the ability for users to reuse previous actions, and output reuse which is the ability to reuse action's results.

Some insights into the analytical lens results were already provided in the previous chapter 3. I describe the critical lens results and constructive ones in the next subsections.

4.3.1 . Critical Analysis

The environment's lack of shared overview pushes operators to consistently take short keywords as notes to keep traces of information. These information pieces are used as a to-do list and reminders in real-time, and then as a guideline to give the handover. However, this information is incomplete and usually requires the users to do extra tasks to retrieve the complete information.

I noticed that information is scattered in different tools in the power grid environment, and operators take much of their time to manually collect and link information on paper. The current environment used by operators is an example of what Beaudouin-Lafon [5] calls "walled gardens and information silos", with no easy mechanisms for transferring information across non-interoperable systems. Therefore, operators rely on paper and memory to build and keep an updated overview, to keep traces of future constraints and their potential solutions, and to prevent forgetting the information that they have to pass on to the next shift.

A considerable source of information in the control room is calls and oral communication. Even though the calls are recorded, operators do not have easy access to them, as a result, they keep track of all this information by taking notes which leads to forgetting or misremembering. Similarly, there is other information that is saved, such as the actions done on the grid, but is not easily accessible by users, as the interfaces to retrieve this information are not user-friendly and do not support easy exploration or research.

Due to this lack of support to track information, operators use note-taking to facilitate their work, however, note-taking is still not an adequate solution and has some drawbacks. Currently, this note-taking is done by writing on paper or post-its, usually writing short information (such as equipment name to event type), with little to no details, which makes it hard to properly remember or find the complete information when it is needed. This information is also diverse; operators handle different types of information (alarm, constraints, maintenance, simulation) which can be either persistent and unchangeable such as documents or procedures, or non-persistent and changeable such as alarms and the state of the system. Non-persistent information is harder to track as once it changes it is difficult if not impossible to retrieve the information of that specific time. As a result, during the handover, operators

keep going back and forth between notes, different tools, and a printed annotated version of the network map to provide complete information. They check their notes for the important points to share, for each point, they review it on the tools, locate it on the printed network map then proceed to explain it orally (which takes longer for information that changed in the tools) along with potential complications in the future and advice on how to resolve them.

Outgoing operators do not share the paper used for taking notes and organizing the handover, since they consider them personal, and sharing them will not be of added value since the incoming operator might not understand their handwriting. This means during every handover, the incoming operators have to retake notes of the information provided during the limited time of handover, therefore they synthesize the information and possibly miss some details.

Operators also use note-taking as reminders or a to-do list for future actions (such as reviewing a solution to a predicted constraint or calling a client) But the note-taking does not serve as a reminder as it does not attract their attention when the actions need to be made. Thus, they should still rely on their memory for these reminders or frequently check their notes.

While note-taking helps accommodate some of the environmental issues such as scattered info, lack of overview, and lack of access to saved information it also has its drawbacks such as incomplete information, hardships in retrieving the complete information, and the need to retake notes instead of augmenting them after each shift. I believe there could be a better way to resolve these issues and improve note-taking.

4.3.2 . Generation

We aim to give operators a tool that supports their needs to have an overview, keep track of relevant information to minimize losing information, especially oral and non-persistent ones, organize and prioritize tasks, and create reminders. We want to simplify the information collection for the operators. To that end we need to transform information specifically non-persistent ones into persistent objects that can be stored and manipulated, We also need to provide a space where operators can create their own overviews and choose the information they want to track and keep in their peripheral vision. The overall purpose is to collect the different types of information in one interface to allow easy access, storing and manipulating this information, to create overviews that match the operators' workflow.

Reification: transforming an abstract command or concept into an instrument or tool.

When we examined the results of the preliminary study, we saw the opportunity for reifying the information and the structure generated when taking notes (such as sequences of incidents and corresponding actions) into a

persistent, interactive object. To do that I reified the structure of the notes in a malleable and personalizable structure called "story" that can hold information related to the stories regarding operational activities or tasks.

Then, we reified the information or events (notes) as a simple object (element) that can be stored in a "story", and allow the users to easily access information or tools. Each operator can collect personally meaningful sequences of events and information, to create coherent "stories" that capture relevant information and actions associated with different tools. For example, a given story could consist of successive elements, such as a trigger (like an alarm), context (detail of the alarm and its impacts), solution search (including simulations), decision, coordination with different stakeholders, applying the solution, and finally solutions' consequences.

The elements allow us to have a portal to easily access information without wasting time looking for it in different tools, and the stories allow us to have a malleable structure to store the information in a comprehensive way. Furthermore, the collection of the stories of the shift allows us to have an overview of the shift and prevents us from overlooking a piece of information if it was not communicated during the handover.

Polymorphism: having the ability to be applied to objects of different types.

While note-taking and talking can be very polymorphic it is not very adapted to this situation, due to the quantity of information, and its need for visual aid. Our design's polymorphism comes from its ability to gather different types of information (text, image, simulation files..), from different tools, and put them into one simple format: a representation that will fit all kinds of information types and allow easy distinction between these types in different levels of details, allowing to easily create a whole history of one shift with all types of information and keeping the link to different provenance.

Reuse: the ability for users to reuse previous actions (Input Reuse) or the results of these actions (Output Reuse).

While the paper is personal and is usually not shared or reused by more than one operator, stories aims to be shared among different operators, it could be passed along with the oral information during the handover, or even shared with other operators within the control room. Stories can be reused to review the information, to understand what was done and learn from it, or to compare them to a similar situation. Our design also allows copy-paste, to copy the story structure desired for a typical event, or the tasks needed to be done for a maneuver, for instance.

4.4 . Concept

We designed *StoryLines* to provide operators with a personal, interactive history and overview of their past, current, and upcoming activities. It serves

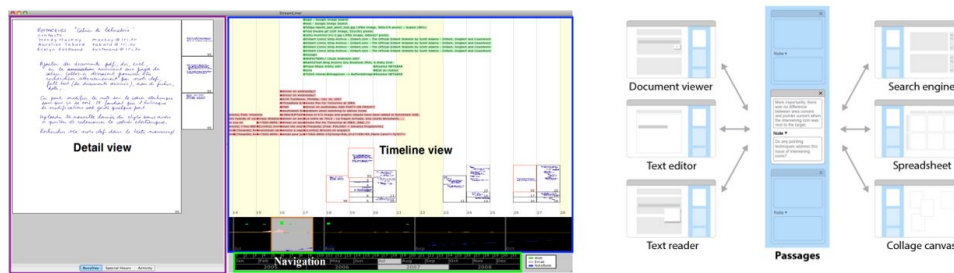


Figure 4.4. **StreamLiner [124] (left) and Passages [45] (right)**

as a shareable repository of relevant information where they can take notes, register reminders, and ensure they have access to all the information they need to handle the handover.

StoryLines offer a lightweight, central location for the information collected from different tools and is fully configurable by the operator. Operators can link relevant information together into “stories” to describe important events.

I chose to focus on event sequence visualization rather than dashboards, because while dashboards give a good overview to help monitor and keep an eye on real-time data and some historical ones, and some dashboards also allow users to personalize them. I do not believe dashboards are appropriate for handover, they are focused on real-time decision support, they provide data with very limited context, especially orally transmitted context and they focus on real-time state rather than history and to-do lists. They contain too much information and usually exclude note-taking.

StoryLines designed was inspired by *StreamLiner* [124] and *Passages* [45]. *StreamLiner* provides a stream visualization that includes different types of information such as course calendars, external events, and assignments. By contrast, *Passages* lets users create a common text representation for transferring information from one tool to another. Like *StreamLiner* [124] *StoryLines* collects information from different sources and centralize them in one tool while keeping easy access to their provenances like in *Passages* [45].

4.4.1 . Functionalities

To achieve its goal, *StoryLines* should capture information, and transform it into persistent and manipulable objects with easily read representations. *StoryLines* should also provide a space to organize tasks, to-do lists, overviews, and information in a personalizable way and allow operators to share information with other colleagues either in real time or during the handover.

To that end, *StoryLines* allows the automatic and manual collection of information from different tools and representing them using elements. All elements have the same type of information:

- Time: the time the element was done or created

- Type: what is the event or information captured such as alarm, prediction, schema, call, maneuver, simulation file, note.
- Provenance: the tool from where the element came from, and link to its source
- Details: explaining what is the element along with screenshots for non-persistent information.
- Association: whether it belongs to a story or not, and which story it belongs to.

Operators can always create notes to add more details or insights. Then to create overviews, they can use a *StoryLine*. I define the *StoryLine* as a digital reusable object symbolizing the structure that helps group and preserve all the necessary elements (information of different types: events, pictures, annotations, files...) to tell a story with descriptions and details. The structure of this information can be used in whatever way makes sense to the users, for instance, through stories narrating the succession of events that took place and are related to each other, or through the process of the handover they are currently using, by creating a *StoryLine* for each step of the process.

StoryLines also preserve the provenance of tools-supplied information, which facilitates future retrieval of additional details and captures the context in which various decisions were made. It can facilitate record-keeping by providing templates for common tasks and help operators track their previous decisions for future reference. Finally, *StoryLines* support sharing information between operators, not only during shift handovers but also with managers and other stakeholders during the shift.

The interface and information representation changed considerably during the design phase (Figure 4.5) since I was trying to find the ones that speak the most to the operators and allow them to get the relevant information from a short interaction. To discover which representation makes more sense I first started by categorizing the information operators work the most with, since we could not represent information from all 50 different tools, I chose 8 representative and important tools, then I did trial representations to assess their coherence *StoryLines's* elements needed at least two levels of detail, an abstract level with only the most relevant information (time, type, title) which could be represented by points images, icons, or text. and a detailed level with all the information. There is also a need to ground this information in a context such as the map of the electric lines, timeline, and categories to facilitate creating and reading the overview. We worked on refining the representations, by continuously presenting our design ideas through scenarios to the operators and discussing their coherence and use.

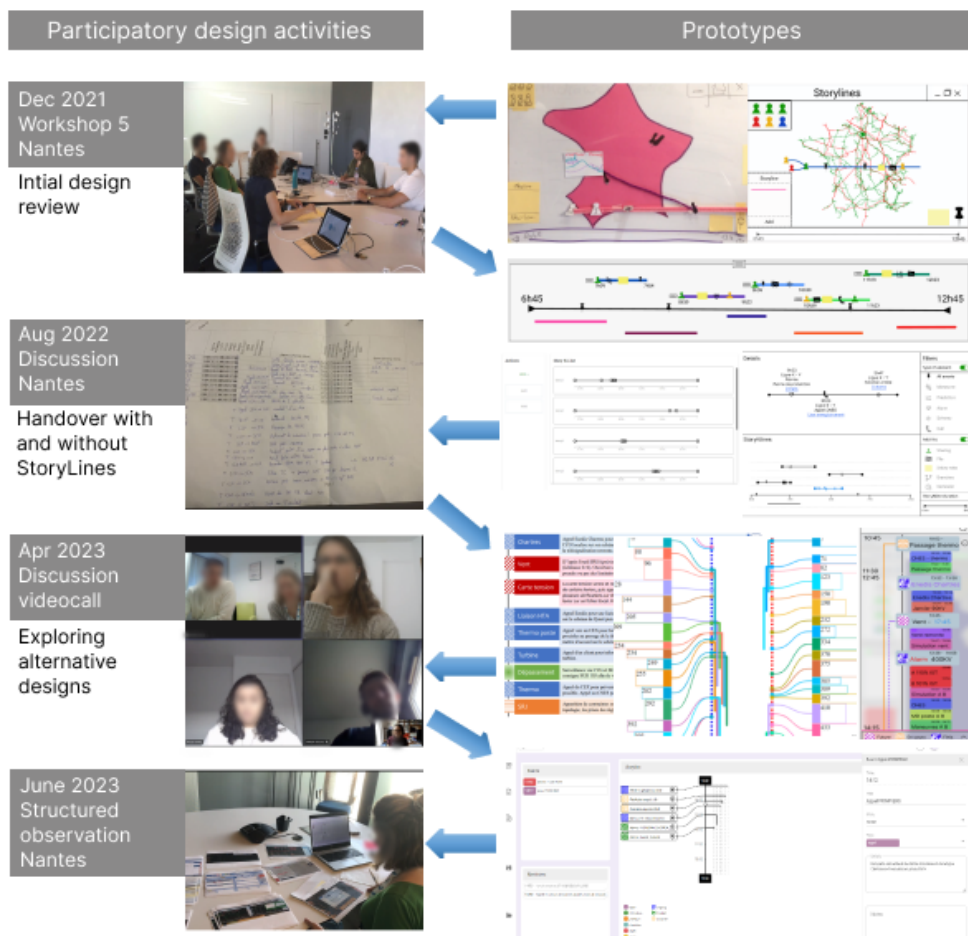


Figure 4.5. *StoryLines* design evolution

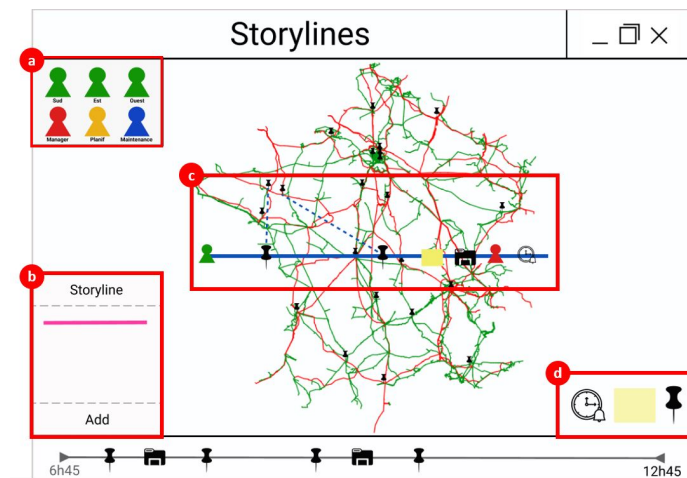


Figure 4.6. **Figma prototype of the first version of *StoryLines*: in this version, only critical events such as alarms, future constraints and simulations are collected and displayed in the timeline and map as pins. (a) the different stakeholders (operators, manager) to share with (b) the repository for creating *StoryLines* (c) active *StoryLine* with all its elements and links in the map (d) functions for adding reminders and sticky notes and accessing collected information, other than alarms, constraints and simulation.**

4.4.2 . Scenario of use

We designed *StoryLines* to help create an overview of the shift, and to provide all the necessary information about the history of events and future activities. The key idea is to allow the operators to tell a story, through a malleable structure where they can easily include information from different tools while keeping their provenances, in case they need more details.

This scenario illustrates how power grid operators use the first version of *StoryLines* (Figure 4.6). Throughout this scenario, Charles and Julie, two power grid operators, will use *StoryLines* to trace information, organize their tasks and share information within the control room.

During his shift, *StoryLines* collect different information, such as the alarms that are triggered or the simulation Charles did. Around 10h, Charles receives a critical alarm he recognizes that he can not resolve the alarm alone. While orally explaining the situation to his manager, he creates a story in *StoryLines*, Charles locates the alarm among the elements added in *StoryLines* timeline or map, and adds it to the created story by dragging and dropping it in the line, he shares it with his manager by dragging the manager icon and dropping it in the line, so the manager can easily access the alarm details. While looking at the details of the alarm the manager and Charles discuss the potential solutions, Charles locates the appropriate file for simulation and shares it through

the *StoryLine*, while the manager proposes two potential solutions by writing the hypothesis on a sticky note in the story. Each one simulates a potential solution in the appropriate file, then they share their results and discuss them orally to choose the appropriate solution

Later during the shift, Charles checks the prediction tool and find that there is a storm coming in the afternoon which creates some constraints in some lines, he opens the simulation file and simulates different solutions, then adds them to a story. He also adds a nearby equipment that might be impacted. Since Charles knows that Julie, the operator replacing him, is a junior operator, he adds a sticky note explaining the choice of optimal solution. The tool might suggest another solution, but he knows from experience that it is not the optimal one, as it requires doing a maneuver on old equipment that malfunctions sometimes, which might elongate the problem resolution. and finally, he adds a reminder to recheck the solution right before the storm to make sure they are still applicable.

30min before the end of his shift, Charles creates stories about all the ongoing events along with relevant information. When Julie, the incoming operator, arrives, Charles goes through each story at a time explaining the different events that occurred. He checks the details of the elements by opening them in *StoryLines* whenever he forgets their details. However, he forgets to explain the storm constraint and potential solutions, due to the limited time they have. While he is explaining, Julie adds sticky notes with explication in each story and occasionally adds reminders for the actions to do.

On Julie's shift in the afternoon, she receives a notification of the reminder to recheck the solution to the storm's constraints. She reads the *StoryLine* and reviews the applicability of the solutions provided by Charles along with their explications which prevents her from applying the wrong solution.

4.5 . Conclusion

Following the participatory design workshops, we chose to focus on designing a tool to support the handover process in the power grid control room. I started by reviewing the literature on handover in control rooms and the medical field and found that currently, the tools used to prepare and communicate the handover either rely totally on users' input or digital information such as EHRs, which prevent incoming users from having full up-to-date information, therefore there is a need to have a tool that combines both types of input and have a malleable structure to avoid restricting the information input.

We employed the analytic and critical lens of generative theory [6] to understand the shortcomings the operators have due to their use of note-taking to organize and track information for their own use and the handover. We

identified some of the operator's needs such as having an overview, keeping track of relevant information to minimize losing information (especially non-persistent information), organizing and prioritizing tasks, and creating reminders.

Based on these needs we designed *StoryLines*, an interactive tool that allows the collection and centralization of information from different tools to track and organize information, create overviews, and create reminders for future critical events. We demonstrated *StoryLines* use through a scenario.

The design of the *StoryLines* involved several challenging design questions: Do operators want a single *StoryLine* composed of multiple incidents or multiple *StoryLines*? Are *StoryLines* associated with a single operator during a single shift or are they transferred from one shift to another? What is the relationship between individual *StoryLines* and the overall history of events? What is the best way to visualize *StoryLines* and what information should they prioritize? In order to address these and other design questions, we engaged in discussions and comparative structured observation studies with operators and members of the research team to better define *StoryLines* and adjust it to their needs and environment.

5 - Evaluating the *StoryLines* concept through comparative structured observation studies

5.1 . Introduction

Based on our participatory design findings, we chose to work on the handover and employed the generative theory of interaction [6] approach to inform the design of a handover tool called *StoryLines*. *StoryLines* is an interactive tool that allows the collection and centralization of information from different tools to track and organize information, create overviews, and create reminders for future critical events. We defined *StoryLines* functionalities, however, *StoryLines* still face several design challenges related to information representation and visualization and the personal and shared use of *StoryLines*. To address these challenges, and better understand how to improve *StoryLines* design and adapt it to operators' current handover practices including note-taking, organizing, and communicating, we ¹ conducted two comparative structured observation studies, one to compare the use of *StoryLines* specifically visualizing events sequences for the handover, to traditional verbal handover with note-taking, we used our findings to improve the design which we evaluated again to assess how operators will and want to use it for busy compared to calm situations, I report on our findings and describe the improved version of the prototype.

5.2 . Handover using *StoryLines* or verbal communication and note-taking

The goal of this study was to get initial grounded feedback about our design idea. We wanted to assess the value of the idea mid-design, to ensure that it is relevant and useful for the operators. For this prototype, we focused on the aspect of presenting the information as elements that could be grouped as stories. We asked the users to receive a handover using this prototype and another handover using verbal communication and note-taking, then compare these two methods, to assess their advantages and drawbacks.

¹The studies were organized in collaboration with Wendy Mackay, Nicolas Heulot. They were conducted in collaboration with Antoine Marot, Alexandre Rozier, Camille Pache. Each study was followed by a debrief among the researchers involved in it.

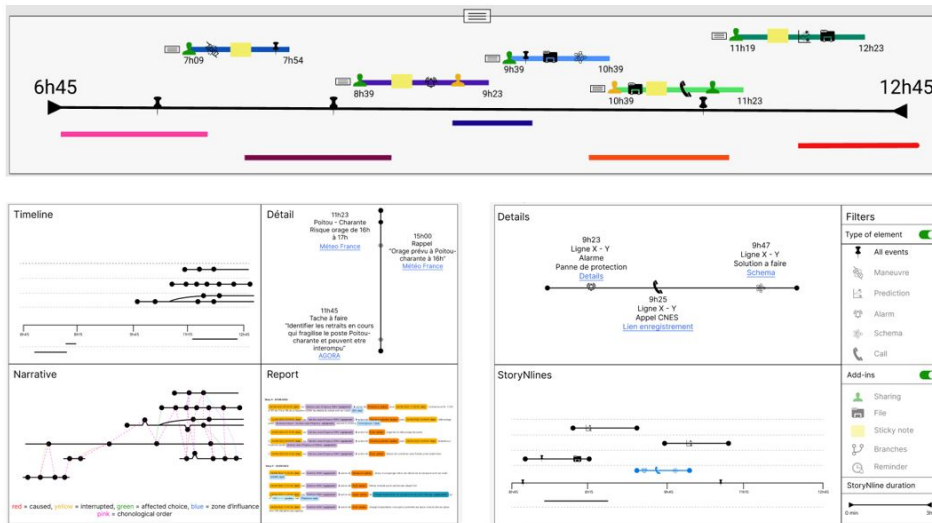


Figure 5.1. *StoryLines* design alternatives

5.2.1 . First version of *StoryLines*

Based on the participatory design workshops, we identified these user requirements:

- collect and preserve different types of information
- notify users for reminders
- allow easy access to information and facilitate retrieving complete information from notes
- allow users to easily trace verbal communication
- provide a shared space for an overview
- allow sharing and enhancing notes
- allow expressivity and customization in creating the overview
- differentiate between tasks for real-time and future

We used these requirements to design alternative interfaces (Figure 4.6 and figure 5.1). We first used a geographic map to capture some context (Figure 4.6), however, after an initial discussion with the operators to demonstrate *StoryLines* concept and first design, we decided to remove the geographic map as the operators believed it did not have any added value, as they already have the geographic information in multiple other tools. For that reason, we switched to a timeline visualization, as operators rely on the time component for their reasoning and is one of the main keywords they take

notes of. We explored different representations using horizontal timelines (Figure 5.1).

5.2.2 . Methodology

We use structured observation to compare the handover with and without *StoryLines*. Structured observation consists of observing participants performing tasks with at least two design alternatives, to generate comparable qualitative data. Both participants and researchers reflect on the similarities and differences between the alternatives to establish a hypothesis and advance the design concept. [37]

Comparing the use of *StoryLines* to note-taking and verbal communication allowed the participant to give us grounded feedback about the benefit of each method, which helped us improve our design idea, by trying to reduce *StoryLines* drawbacks and incorporate the benefits of note-taking on paper into *StoryLines*.

5.2.3 . Participants

We recruited three participants (power grid operators). They did not participate in the previous workshops. They were all males and had different levels of expertise (junior (1 year), intermediate around 5 years, senior more than 10 years)

5.2.4 . Set up

We wanted the users to be able to simulate doing their tasks and to be able to access the information in their different tools. Participants had access to two screens during the study, one with the operators' tools, and a second one with *StoryLines*. The second screen was connected to our laptop, allowing us to add information when needed.

We designed a working prototype, and used a Wizard of Oz protocol to simulate acquiring information from the operators' tools, since we could not access them and connect them to the prototype. As the participants did the tasks on their tools, we added the information "automatically collected" manually to the *StoryLines* tool using a second window, which added the events to the user's *StoryLines* interface.

I prepared two scenarios with the help of a former senior operator to have a realistic scenario with real stories and problems. For each condition (*StoryLines*, without *StoryLines*) the participants received handover information, which consisted of 6 stories : 3 ongoing stories where they had to do some tasks to finish the stories, and 3 finished stories which did not require any task to be done.

For the condition without *StoryLines*, I prepared the narration of the scenario, to prevent having a variation in the information given to each participant. I used this narration to act as the outgoing operator giving the handover

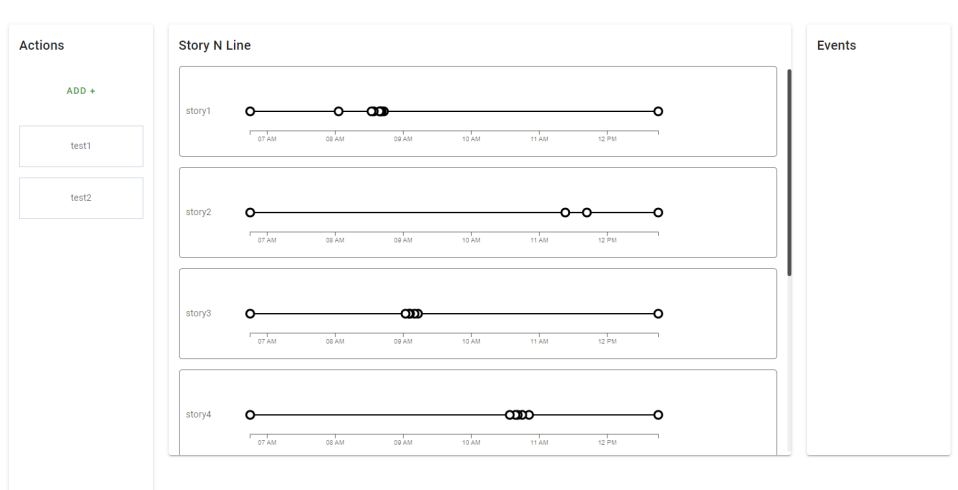


Figure 5.2. **StoryLines' prototype for the structured observation. StoryLines consists of three panels: Actions where collected elements are displayed. StoryLines where the stories created are stored and ordered by the user by importance. Events where we can access elements of each story and their details.**

to the participants.

I prepared a paper version of our prototype to use for reflection and paper prototyping after the structured observation, but unfortunately, the prototype broke down during the first structured observation and we had to use the paper prototype.

5.2.5 . Procedure

Each session lasted around one hour and consisted of 4 main steps: brief, condition 1, condition 2, and debrief interview. The two conditions being with or without *StoryLines*. Once we² welcomed the participants, we proceeded to explain the study and the participant's rights. The participants were allowed time to read and sign the consent form and authorization to record their voice.

After explaining the study, and demonstrating *StoryLines* functionalities, participants had to do the same task in the two conditions (with and without *StoryLines*)

The task consisted of a handover where participants had to :

1. Understand the situation: participants had to get acquainted with the situation through the information given (by exploring *StoryLines* tool, or by listening to the handover and taking notes if necessary).
2. Identify the tasks to do: participants had to identify the tasks that needed to be done in the given situation.

²Alexandre Rozier and me

3. Do the tasks: they had to go through different tools to do the tasks when it was possible, when it was not possible, we acted as the system and gave them the response needed to continue.
4. Take notes for the next handover: finally, they had to take notes of what they judged necessary for the next handover.

Participants were asked to talk aloud as they performed the task in both conditions. The session was followed by a short debrief interview, where we encouraged the participants to reflect on their experiences, critic the tool provided, and discuss how they might use it and how they want to change it.

5.2.6 . Data collection and analysis

All sessions were voice-recorded and transcribed. We also took handwritten notes. I analyzed the data through a Thematic analysis [13] and generated themes and codes using a deductive (top-down) approach and then an inductive (bottom-up) approach to identify new themes.

5.2.7 . Results

This section summarizes the main findings we obtained from the structured observation. I identified the following themes and codes.

Operators want to have control over what information to track.

While note-taking is 100% controlled by participants, *StoryLines* has a shared control, where both the participant and the automated part can add information. Participants were not fully satisfied with the automatic collection of information, as they thought it was adding more information than needed, especially in the cases where the story finished (problem solved) and without consequences : "Now, that I'm back in a normal situation, I'm not sure it's relevant to track the information, I've solved the problem" (P1).

All participants agreed that not all information should be collected and it does not depend on the type of information or its provenance, but it depends on the state of the story and its consequences. They confirm that all stories finished in real-time might not be interesting to collect for the handover unless they have consequences : "I will track the information if I use a solution and it has consequences, I will not track my reasoning" (P1).

However, it is not obvious from the beginning if these events might have complexities or consequences later, which makes them hesitant about whether they should keep or leave a piece of information in real-time (specifically, if it is an additional task to do) Therefore, participants would like to keep the option to be able to collect these pieces of information afterward, in case they were needed, but with minimum interaction.

The perfect handover is one overview, organized in one page, and readable in one glance.

Participants (2/3) pointed out the importance of the transparency of the tools, visualizing everything that needs to be communicated on one page, which is an aspect that one participant appreciated in the paper. "I want to have all the information on one page... my piece of paper (for the handover) is organized and I do it in a very visual way" (P2).

The organization of the *StoryLines* was also appreciated, however, participants felt that they were much information that might not be needed, specifically in the finished *StoryLines*, they would like to have more distinctions and synthesizing of these pieces of information, similar to what they do when annotating on paper: "It will be interesting to have a distinction between finished and ongoing stories, because the ongoing ones are the useful ones that I need to work on" (P1). "it would be better if we could have one sentence in 3 lines maximum (date, time, information), with the use of colors" (P2).

One participant suggested categorizing *StoryLines* in different blocks, depend on the type of events (withdrawals, incidents, alarms...) and using colors to distinguish the state of the story. One participant suggested that there is an added value in categorizing stories automatically, since it will reduce the time taken to organize and prepare the handover. "If it is (organization) done automatically your tool brings a real added value, because it saves us a lot of time. If it is done in real-time and is predisposed, it allows everyone to be able to read things without having to decipher my writing" (P2).

Handover should always be verbal, supported by StoryLines.

For the handover, all participants agreed that it should still be done verbally while supported by *StoryLine*, instead of either verbally or with *StoryLine*. Verbal handover has the risk of communicating incomplete information and there is a need to take note of everything, which leaves participants with less time to question and have a conversation: "When you tell the story verbally, the risk is that I miss some information, because you talk fast or because I do not question, the risk is to miss something if we go fast, I really have to write down everything and I can not write down everything, so I write down the main thing while summarizing " (P2).

On the other hand *StoryLines* provides all the information and the extra layer of details through provenance, without taking notes, nor the ability to question. "With this method, I find myself having all the information, but do I need all the information?" (P2). Therefore using verbal communication supported by *StoryLines* would mean complete information, without the need to take notes while keeping the ability to question and clarify information during the handover.

Operators' main issue in the handover is forgetting.

Reminders seem like the necessary forgotten tool for the control room, all

participants liked this functionality and perceived it as an added value, as their main reason for tracing information is the risk of forgetting, and while currently they do it on paper they still forget to do the tasks. All participants confirmed the importance of distinguishing the tasks that still need to be done, and possibly adding reminders to them: "it (*StoryLines*) would be useful, especially for actions that I need to do, and reminders for those actions, so I won't forget them" (P3).

StoryLines could be a tool for collaboration and coordination in real-time.

Participants overall appreciated the tool and found that it could be useful for use cases other than the handover, for instance for incidents, (2/3) participants found that it could be used to trace information and actions done during incidents to share them with others specifically on the short communication meetings.

"In incidents, each operator in the team has an assigned task, We have short meetings to talk to each other, we still need to talk because it's important to define things, but there are still times when we need to have traceability, a collaborative tool, that is how I see it, having a tool that would allow us to track things down, because we talk to each other and we do it on a piece of paper but it lacks a frame and I see it (*StoryLines*) as a frame for dealing with the incident" (P2).

One participant suggested its use for non-incident related events that happen during incidents and sometimes need to be shared quickly and efficiently, without stopping the work on the incident. *StoryLines* was also suggested to be used as a way of communication to organize and coordinate with other people within one or more control rooms, in order to help reduce the time taken to organize. "When the planning team wants to pass us information on our shift... they can give us a story like that but already pre-filled or we can just have reminders on events that are expected " (P1). Finally, if it is possible *StoryLines* could be the tool en-globing all information which we can use to access other tools. "Maybe in the future, if it (*StoryLines*) is well developed, it can be the central tool from where we have access to other tools" (P1).

Overall operators appreciated the *StoryLines* prototype and insisted that it should not be used as a standalone for the handover but as a support for the verbal communication. The comparison with the paper note-taking allowed them to identify different interesting points that we can improve such as the shared control over the collected information, improving the organization and representation of elements. They also provided us with interesting real-time use cases where *StoryLines* could be useful.

5.2.8 . Discussion

Participants feedback on the use of *StoryLines* compared to verbal communication and note-taking, allowed us to have insights about *StoryLines* chal-

lenges and suggestions to improve its design.

StoryLines should combine manual and automatic collection of information. Participants expressed the desire to have more control over the information collected automatically, so they can only collect important information for on-going stories and stories with consequences, but with minimal interaction so it will not be an additional task to do. To that end, an intelligent system might help, it could run in the back-end, and collect information, without putting them in the *StoryLines* tool, then operators can interact with it to pick up the needed information. However, it is not obvious how the interaction with such a system should be done. It could range from a human-computer partnership [71] where both operators and intelligent system have a continuous conversation, and work together throughout the shift not only to build an overview, but also to provide the operator with necessary information during real-time operations. On the other hand, the intelligent system could constantly collect information and would easily be called to provide information just before the shift, or potentially suggest information on its own (based on users' handover history).

Choosing what type of assistance operators might need will require investigating their performances in different tasks (handover, incidents..) with different levels of assistance and interactions with the system.

Improving StoryLines expressivity.

StoryLines should also be more expressive, in order to enable easy reading of the overview, and a distinction of important elements with one glance. To that end, *StoryLines* should allow different visual aspects to differentiate between the type of events in the stories, the state of the stories (finished ongoing), the tasks to do, and the important events in each story. *StoryLines* should also be able to provide a summary of each story, to reduce the time taken to explore all the information. The challenge would be how to visualize all these distinctions in a simple way without overloading the overview.

Improving StoryLines reminders: created manually, automatically and adjusting to the context.

Participants expressed an interest in having reminders to prevent forgetting tasks to do. They currently take notes on paper, which can not be counted as a reminder since you have to look at it to remember, instead of the reminder manifesting itself to remind you. We still need more investigation to identify how to efficiently integrate these reminders in the operators' environment, specifically investigating how the reminders can manifest themselves and attract operators' attention without conflicting with the sound of the alarms or disturbing the operators if they are busy. The second issue to investigate is the initiation of the reminders, in which cases it should be manual, semi-automatic, or automatic: for example, they could be automatic for anticipated problems, semi-automatic as a result of a less important event

happening while dealing with an important one, or totally manual for whatever the operators want.

StoryLines for real-time use

Finally, since *StoryLines* could be used as a communication tool or an organizing tool, it could also support different aspects of operators' job. To that end, it would be interesting to identify what functionalities might be interesting to add *StoryLines* in order to better support the operators in their job. Adding more functionalities will push the operators to track more of their information, which can be used for quality control or to capture elements such as the operator's reasoning while resolving an issue.

5.3 . StoryLines for handover and real-time

This structured observation was conducted at the RTE control center with four researchers and five operators. Our goal was to present the operators with a working prototype of *StoryLines* and obtain their feedback, suggestions, and ideas. We worked with pairs of operators who followed two scenarios, one extremely busy with multiple overlapping events and the other relatively calm. They performed tasks, interacted with *StoryLines*, took notes, and prepared for the handover to the other operator, after which they continued with the second scenario. Half of the operators first performed the "busy" scenario, followed by the "calm" one. The other half performed the "calm" scenario first. We conducted two sessions with two operators each and then ran a debriefing session with the operators who participated plus another senior operator.

5.3.1 . Second version of StoryLines

Based on the previous structured observation, we identified these three additional user requirements:

- enable shared control for collecting and organizing information
- allow easy interaction to find information collected automatically
- allow better expressivity and organization

We used these user requirements to improve the design of *StoryLines* and try to resolve as many of the problems they had as we could. We had multiple discussion sessions with operators over Zoom where we presented different design alternatives (Figure 5.3) and discussed their use. Operators also voluntarily provided us with notes of real data from their 5 different shifts to help us better shape *StoryLines*.

Related work

Event sequence visualization tools usually serve to collect and make sense of large amounts of information users are not familiar with. They usually allow

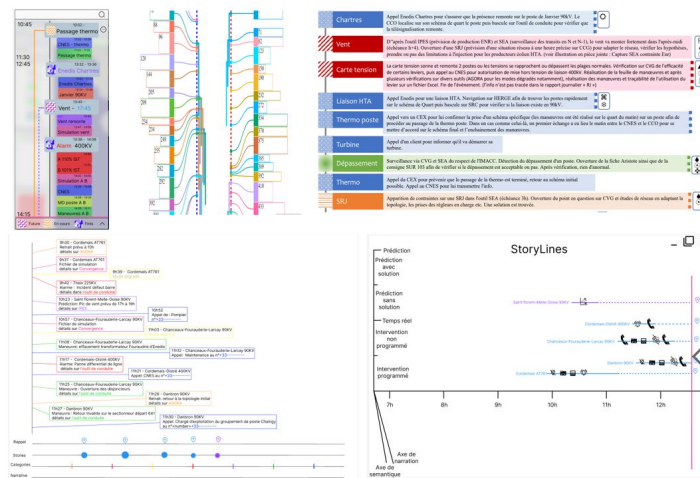


Figure 5.3. **StoryLines second design alternatives**

users to do different tasks such as Wehrend and Lewis [120] 11 tasks (identify, locate, distinguish, categorize, cluster, distribute, rank, compare within entities, compare between relations, associate, correlate) or Amar et al. [2] 10 tasks (Retrieve Value, Filter, Compute Derived Value, Find Extremum, Sort, Determine Range, Characterize Distribution, Find Anomalies, Cluster, Correlate). On the other hand, a handover tool should allow to access information users are usually familiar with and already understand but it should just help prepare the handover by organizing, shaping the overview, and adding annotations or advice to augment the information. Thus, it should support the following tasks:

- locate and filter digital information both real-time and historical
- distinguish and categorize information
- annotate information
- associate information with each other
- highlight relevant information

which are not that different from the visualization tool tasks, especially filtering, distinguishing, and categorizing. Therefore, to inspire the design, I reviewed some event sequence visualizations' goals taxonomies and representations, which can help us create overviews for the handover to communicate important information.

There are tools ([16, 12]) that serve journalists to explore documents or create interactive timelines, these types of tools allow users to do it with no coding skills, but it takes a significant time and allow them to create one visualization at a time these visualizations tend to be very expressive and well-suited

for sense-making or narration purposes. On the other hand, some tools ([122, 64, 28, 36]) allow the visualization and exploration of a large amount of data, quickly (provided that the data is organized) they also allow different interactions, but they lack in their narrative and expressive part, and they can overwhelm users with the quantity of information. A handover tool should allow fast, easy, and expressive visualization, with the ability to interact with the information, which is why both types of tools are interesting to review.

I reviewed taxonomies such as Guo et al [44] event sequence taxonomy, TimeViz browser [115] and Timeline Storyteller [16] which is an authoring tool offering sandbox functionalities to create expressive visualizations about narrative event sequences [15], which helped me explore how different timeline dimensions can fit our use case. I also reviewed the different dimensions for event overview representations. For instance, EventRiver [64] visualizes events using size for temporal influence, color and location for related events, and text for semantics. While LifeFlow [122] visualizes an overview of patients' events sequence, using a different color for each event type (arrival to the hospital, intensive care..) along with the time spent between them, which allows medical researchers to analyze the patterns to improve medical care and identify the best practices.

An interesting aspect of these tools is they usually allow automatic grouping of event sequences. For example, EventThread [43] clusters the event sequences by grouping the threads based on similarity in time-specific clusters. TimeStitch [96] allows users to interact with an event of interest to visualize the chronology of events surrounding it. Outflow [121] combines multiple event sequences, through different events and their outcomes. These event sequences usually have at least one exact event they all share that is meant to be compared, which is not entirely the case for the handover information. However, it will be interesting to test these automatic clustering to allow a shared control on organizing information in *StoryLines*.

StoryLines Modifications

We could not implement all the suggestions from the previous comparative structured observation study, we focused mainly on the expressivity and organization of the *StoryLine*. We made the following modifications:

- switch timeline from horizontal to vertical: as suggested by the participants, we needed to include more text and keywords to identify the stories and elements. Our pilot tests (among ourselves with real data) showed that horizontal timelines did not allow better management and visualization of the text, and it severely limited the quantity of text (and therefore stories) that could be displayed (Figure 5.3).
- changing stories' format: in the previous versions stories were identified by the elements inside them and their time, but this format did not

give the operators the information they needed, they suggested having a short summary for the stories to be able to easily identify them and know their state. We decided to use an editable title (mainly including keywords) that will allow the operators to know what the story is about in one glance, along with a pattern next to it informing about the type of story (ongoing, predicted, finished).

- More rich elements: the old format included all the information but needed the user to interact with the elements to access this information, therefore we wanted to add a preview of the element that is always displayed, it included information such as the time and title (where we can have keywords representing the information) and color to categorize the type of information.
- Reminders are not elements: we chose to differentiate between the reminders and elements, to better highlight the reminders instead of hiding them within the elements.

Following the modifications made to the prototype we conducted a structured observation to compare how the operator would use the *StoryLines* in real time and handover for a calm and stressful situation.

5.3.2 . Methodology

We used the same comparative structured observation as the first study, which consists of observing participants performing tasks with at least two design alternatives, to generate comparable qualitative data. Both participants and researchers reflect on the similarities and differences between the alternatives to establish a hypothesis and advance the design concept [37].

Comparing the use of *StoryLines* for real-time and handover in two different scenarios, allowed the participant to project into the use of *StoryLines* in their daily job and give us grounded feedback on how to better adapt it to their context and workflow.

5.3.3 . Participants

We recruited four participants (power grid operators) (2 females, 2 males), with levels of expertise ranging from 6 months to 5 years. One of these participants took part in the previous comparative structured observation study, while the other three participants were not included in the previous workshops and study.

5.3.4 . Set up

Participants had access to one screen with *StoryLines*, and printed screens representing their different tools.

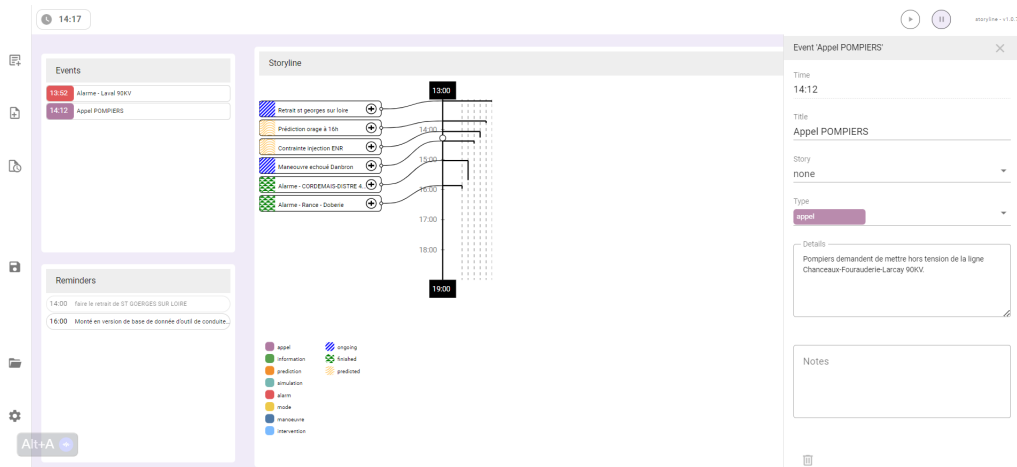


Figure 5.4. *StoryLine's* second prototype. This version consists of four panels: Toolbar to add stories, elements, and reminders, save the *StoryLine*, or load another *StoryLine*. Events where "automatically collected" elements are displayed, they are color coded based on their type (calls, information, prediction, simulation, alarms, degraded modes, maneuvers and interventions). Reminders to send notifications for actions to do. Stories where all the stories are stored with a little line representing their duration, and colored patterns representing their type (finished, ongoing and future). Event details containing different information about the events.



Figure 5.5. Structured observation set up.

We used a working prototype, which added new elements in *StoryLines* as the participants advanced in the scenarios. We timed the prototype and controlled the scenario in a way that each time the participants read something on the printed screens, that information is added to the list of elements, in the prototype. As the participants followed the information in the printed papers, the prototype added the events to the user's *StoryLines* interface. I prepared

two scenarios using five note-taking observations describing different shifts made by an operator. The first scenario was rather calm and involved several down-times, while the second scenario was busy, and involved having different problems at the same time and needing to prioritize (with little to no downtime).

5.3.5 . Procedure

We ³ conducted the sessions with two participants at a time.

Each session lasted around ninety minutes and consisted of 7 main steps:

1. a brief to explain the study then the prototype and let the participants familiarize themselves with it
2. each participant did the first part of the scenario,
3. handover from the first participant to the second,
4. handover from the second participant to the first,
5. a short discussion,
6. participants exchanged scenarios and did the last part,
7. and finally a debrief discussion.

The task consisted of following the scenario and preparing the handover. Following the scenario consisted of receiving a trigger (based on time) it could be a call or an alarm... then doing the tasks that the trigger requires, by reading the papers of the appropriate tools for the tasks. We encourage the participants to use *StoryLines* whenever they see the need for it and to prepare the handover in it.

Participants were asked to talk aloud as they performed the tasks. The session was followed by a discussion, where we asked the participants to reflect on their use of *StoryLines*, and compare its use in different situations.

5.3.6 . Data collection and analysis

All sessions were recorded and transcribed. We also took hand-written notes and saved files of the *StoryLines* created by each participant.

5.3.7 . Results

We frame the result in three parts: the user with *StoryLines*, *StoryLines* between users, and *StoryLines* in the environment.

³Wendy Mackay, Antoine Marot, Camille Pache and me

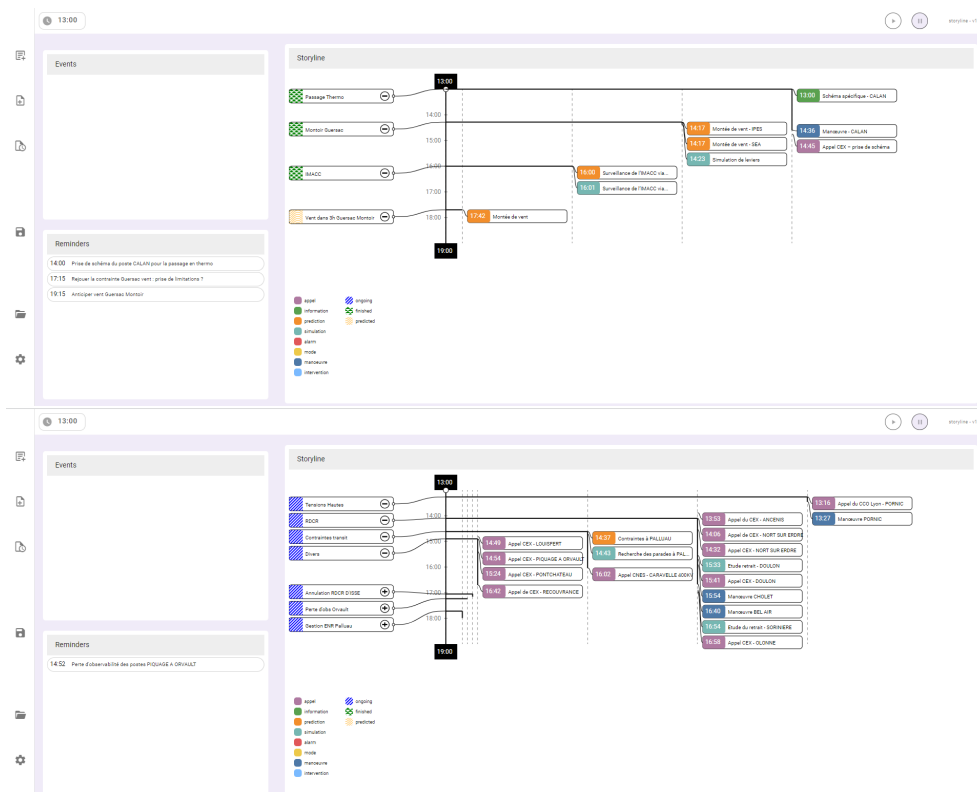


Figure 5.6. Examples of Stories created by participants in *StoryLines*

StoryLines with a user: defining the story

An important task that participants needed to do early on was to define the identity of the story, which they did by answering the following questions:

- How to group information: the participants used two forms of grouping or categorizations: either by equipment or by type of events (outages, alarms, ...)
- What information to include: The stories created usually did not include all the elements of the story, but only a few representative ones. One participant actually changed elements' titles and notes to make them more relevant. Another participant (the junior one), added new elements because they found it was easier to add elements than to look for them. However, their elements had very limited information and details.
- What to do with passed-on stories (after the handover): It seems like the participants considered the passed-on stories as a to-do list since they only changed their status to finished one, without updating them, or continuing the unfinished ones. 3/4 participants created new stories for updates about events that were already included in the stories passed on during the handover.

Participants generally did not use *StoryLines* in real-time, except to create reminders. In the busy scenario specifically, participants ignored the *StoryLines* until they finished their task and wanted to create the stories for the handover.

I believe that having little time to reflect during the scenarios reinforced the idea that *StoryLines* was just to organize the handover for the incoming operators, since participants needed to think about how to group information not just for themselves like they do in a paper but for the incoming person, which means they were looking for some more logical grouping or standardized way of doing it. This can potentially prevent them from creating their own overview because it means that they will have to reconstruct it for the other person.

StoryLines between users: different notes for oneself and others

To prepare for the handover, participants especially in the busy scenario relied mainly on taking notes (mostly equipment name and type of problem or event), then transcribing them in *StoryLines*.

The same information taken in the notes was actually included in the elements in *StoryLine*, however, participants still chose to take notes first. This could be because they are more familiar and used to taking notes, or they use the notes as a way to filter and keep in mind important issues before they transcribe them in *StoryLine*

They relied on the list of elements and their note-taking to create the stories in the handover. The participants in the busy scenario, specifically reviewed the list of elements multiple times to ensure they did not forget anything.

To easily identify elements in the list, we used colors to categorize them, however, 2 participants did not notice the colors, while the 2 others found the colors overwhelming.

All the handovers were relatively similar, going through each story and explaining, checking the details of the elements when they forgot the information, and occasionally adding reminders for actions to do. One participant (the junior one) chose to open all the stories at once since it provided a more complete overview. This participant suggested storing the stories in categories instead of a timeline since it was more relevant for them.

StoryLines in the environment: integration in the control room

StoryLines was meant for centralizing information which it was appreciated for, but its integration in the control room is still ambiguous, specifically:

- The use of *StoryLines* for the handover: operators are still uncertain if it will be the only tool for the handover or just one of the tools used during the handover.
- *StoryLines* integration with the other tools: it is unclear whether the communication between *StoryLines* with the other tools should be mono-directional (all the tools providing *StoryLines* with elements) or bidirectional (where *StoryLines* could send information to other tools, maybe to provide or change information).

5.3.8 . Discussion

Participants feedback on the use of *StoryLines* for real-time and the handover, allowed us to identify new challenges and suggestions to improve *StoryLines* design.

StoryLines should converge to current practices of note taking.

StoryLines would have to include more functionalities to allow input and interactions similar to the actual practice used for the handover. The organization by grouping on a low-level hierarchy might not be the best representation for everyone, neither are the colors to distinguish between the different types of information and stories. We need to explore more dimensions for distinguishing types of information and stories and explore thoroughly different ways of grouping and creating overviews, such as mind maps, branching, and categories.

Note-taking helps externalize information and create reminders. Paper and pen offer a very simple and intuitive way of doing it. Operators can write while doing other things without looking at the notes. They can also express

themselves in different ways through interaction with the pen and paper. It would be interesting to explore the use of an iPad and a stylus to combine the steps of taking notes and transcribing them in *StoryLines* into one, and enable an easier, more intuitive, and more expressive way for story and element creation.

We can also add functionalities to pre-make stories, or automatically pre-fill them, to reduce the workload of creating and filling all the stories. It could be helpful for certain important events such as critical alarms since they definitely need to be documented. *StoryLines* could automatically create a story and start filling it with relevant information, whenever a critical event occurs. ***StoryLines should adapt to the users' style of note taking and organizing information.***

We also noticed through the experiment that participants have differences when it comes to how they group information and what information is relevant to them, which might be the reason participants did not appropriate the stories passed on during the handover. Thus, it would be interesting to allow transitions between different types of categorizations.

It is important to distinguish these two types of note-taking, which was not completely considered while designing *StoryLines*. Introducing *StoryLines* as a tool that centralizes information for creating overviews and giving information during the handover might push operators to think that there should be a standardized way of grouping information and therefore push them to create stories and overviews just for others rather than for themselves which reduces their use of the tool, thus *StoryLines* just adds tasks to operators with limited gains for them. *StoryLines* also need to be able to distinguish the different styles of grouping and organizing information and adapt to the different users. It would be hard to try to come up with a set of rules for how each operator creates and organizes their overview. We could separate the two types of note-taking through different spaces, one space for oneself to create their own overview and organize their own tasks, and another space where the user takes only a fraction of the information they want to share and organizes that for others. *StoryLines* could use a more standardized way of organizing information just for the handover, operators would choose what information from their personal overview need to be included (by tagging them for instance) in the handover and the system would standardize this part. The standardization can follow the normal structure of the handover currently in place, but could also use different categories such as:

- importance levels (urgent, important, normal)
- types of events (alarms, predicted constraints, planned outages)
- stakeholders involved (oneself, maintenance, client, other centers, other countries).

StoryLines should adapt to the new control room organization.

A challenge for *StoryLines* is to adapt to the new organization of the control room. In this organization, the operator's job will change and they will start working in pairs for each zone: an operator for control and planning in the short term and a second to focus on actions in real time. *StoryLines* could be used as a tool to support collaboration and continuous communication between these two operators.

The new organization will also reduce the number of operators working at night, which means that the day zones allocated to operators will be different than the night ones. In this case, all stories should be associated with pieces of equipment or localizations instead of operators or zones. There is also a need to create a new protocol for the handover.

To be used within this new organization, *StoryLines* needs to address three subjects:

Collaboration in real-time between each pair: *StoryLines* should provide a shared space where the pair can create a shared overview and they can share information along with their context through the interface, they can create reminders and tasks for each other and notify each other when there are new inputs or the tasks are done.

Handover prepared in pairs: Each operator should add things that need to be in the handover, then discuss and organize them by importance. It also could be interesting that each person passes the handover to the operator continuing their job when it is a transfer from 3 pairs to 3 pairs, however, if it is a transition from 3 pairs to 2 or vice versa, it would be more important that both operators in the pair have a good knowledge of the whole zone.

Asymmetrical handover: Under the assumption that one of the zone will cut and shared, *StoryLines* should allow tagging the stories and elements and categorize them by zones for 3 pairs and zones for 2 pairs. Operators who work in the cut or reassembled zone would have to either do double handovers or do one handover with double the operators and inconvenience, either way, the time of the handover would double. A potential solution to explore is to organize the handover in *StoryLines*, the incoming operators would familiarize themselves with the handover through *StoryLines*, before having a discussion or Q&A with the outgoing operators.

5.4 . Improved version of *StoryLines*

Based on the results of the structured observations, we identified new user requirements:

- enable personal and shared use of overview
- adapt to personal style and organization (categories or maps) of note-

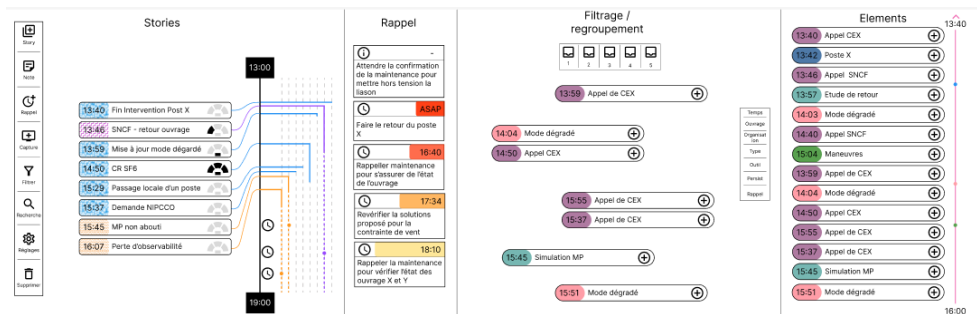


Figure 5.7. **StoryLines improved version**

taking

- enable the ability to link reminders to stories
- converge to actual practices of note-taking in paper
- allow bidirectional communication with tools

We used these requirements to design an improved version of *StoryLines* (Figure 5.7). This version included four panels, the main one is the story panel which is always visible, while the other can be hidden or collapsed. The order of the panels can also be switched based on operators' preferences.

- Story panel: this is the main panel, it consists of the main functions (adding story, element, or reminder, capturing information on the screen, filtering researching, managing parameters of the automatic collection, and deleting), for each story we visualize its time, type (color and pattern), title (keywords), sharing (through the icon we can choose with which colleague we want to share the story) duration through the timeline which can be expanded to display the elements inside, and finally the reminders associated with each story.
- Element panel: this panel displays all the elements collected either manually or automatically, it hides all the elements already used in the stories and allows users to hide further elements if needed.
- Reminders panel: The reminder panel consists of all the reminders, which can be also seen as a to-do list, we differentiate the different types of reminders (do as soon as possible, do at a certain time, and do once we have this information) we use color bands to visualize the time needed until the reminders to help with the peripheral vision. Users can always reorder the reminders or collapse them to their main components, they can also snooze the reminder by sliding it down.

- Filtering and grouping panel: this panel helps to group and make stories. Users can filter using types of information, they can create trees of filtering that they can store on the boxes above. For each collection, the system uses the space to create clusters and groups of the elements that correspond to the filtering. these filtering trees can be helpful as they can be used to filter and find ongoing and critical events easily.

5.5 . Conclusion

We conducted two comparative structured observation studies with the operators to better understand how to integrate *StoryLines* in the environment and how it can support operators' existing practices. The structured observation studies results enabled us to have some insights into operators' handover practices and the use of *StoryLines*.

We compared using *StoryLines* to verbal communication and note-taking for the handover and found out that while with note-taking operators usually lose information, it helps them keep information organized, distinguished, and in an optimal quantity, which was an issue with *StoryLines* as it provided too much information. Based on those results, we defined new users' requirements and used them to improve our design, we focused specifically on improving the organization and distinguishability of the information.

In the second comparative structured observation study, we compared the use of *StoryLines* in real-time and handover in a busy compared to a calm scenario. Our findings suggest that while operators appreciated the use of *StoryLines* for the handover, it was less used for real-time and personal organization (which might be due to the unfamiliarity of the tool and lack of time). Our main finding is the need to separate the note-taking for oneself and for others and to include more interactive features that help operators find information, to facilitate the organization of overviews. We used all this information to enhance the design of *StoryLines* and adapt it more to the use of the operators. However, we could not evaluate the improved version of *StoryLines* due to the limitation of the information we can have and access to the environment and the limited availability of the operators.

6 - Discussion

The original motivation for this work was working on the interaction with an AI decision support system without deskilling the operators, as my initial understanding was that control rooms needed the integration of AI to enhance their decision-making. My main focus in the beginning part of the thesis was on decision-making methods, tools, and their interaction. However, within the first 2 hours of discussing with the operators, I discovered that the operators' needs were very different from what I anticipated. Throughout this thesis, I learned that decision-making is actually the last part of the process, while it is an important part it is a result of the information flow and management and building SA. Operators did not need a system that added to their information overload by suggesting solutions to them, they rather need support in all the steps that precede the decision-making to help them reach this step alone. This allowed me to shift my focus from "What can technology provide to the operators?" to "What do operators actually need?". While the two questions might sound similar the second one allowed me to identify operators' needs in an open-minded manner which helped me focus on the needs operators perceive as important, rather than the ones that would focus on employing some type of technology.

In this thesis, I asked three main research questions: First I aimed to understand from the research literature how the technology and tools in the control room support or fail to meet operators' needs. I found out that many tools in the control room are designed with little to no operator involvement, or consideration to the way they can be integrated in the control room's existing environment or operator workflow. This has a serious impact on operators since these new tools change the way they access and perceive information. The integration of digital tools usually adds new interface management tasks, and they overall change operators' workflow. Moreover, technology-centric tools can lead to a passive style of monitoring when the interfaces are not adapted to operators' needs, in this case, operators do not fully understand the functionalities of the tools and do not take full advantage of their potential. To enhance the productivity and efficiency of the control room, it is not sufficient to integrate advanced technology. The output of these technologies should be relevant and easy to access to operators and they should understand how to manipulate and take advantage of these technologies. Thus, it is crucial to involve the operators in their tools design process to better identify their specific needs and understand their workflow.

Second, I set out to understand the power grid operators' needs and the breakdowns they face while interacting with their environment. My findings

suggest that operators are provided with all types of information they could possibly need. However, they do not have tools that support their secondary tasks, such as creating an overview of all the information they are provided with, organizing and re-prioritizing their tasks, and capturing non-persistent information. All these secondary tasks are currently done by relying on memory or taking notes on paper, which leads to a huge loss of information, especially during the handover where operators should transfer important knowledge about the system state and future constraints orally in 15min, which limits the quantity and completeness of information transferred.

Finally, I tried to understand if providing operators with a tool that captures and centralizes information and allows them to take notes and create their own overviews through information grouping can help support their secondary tasks, especially during the handover. Operators appreciated the ability to capture and preserve the information and most importantly have a shared space for the information from different tools. However, they are still attached to note-taking on paper since it is simple and intuitive to use especially during busy situations, it also allows them to create a barrier between their personal notes and the shared ones. Operators involvement in the design process since the beginning made them more accepting of this new tool. They appropriated it and considered it their own tool, since it was designed based on their needs and adjusted based on their feedback. They are pushing toward developing more advanced prototypes in order to eventually integrate it in the control room. To that end, we are exploring different modalities to enhance data captures such as handwritten note-taking with Apple pen on iPad or reMarkable, voice recording, and tablet-based interaction. They are also more open to participating in workshops and evaluations in the future.

This work is a use case of using participatory design methods with difficult-to-access-users combined with generative theory to design for operators in a realistic setting. Moreover my thesis provides insights about the unmet needs of power grid control room operators and how they compensate for these needs using note-taking, which can serve as a basis for designing tools that support control room operators workflow and secondary tasks. It is important to remember that operators are the backbone of control rooms, they should not be replaced or deskilled by their tools.

I believe that designing for control room operators should involve the operators and take into account the imperfections of real-world use. While designing the environment based on tasks or goals analysis, it should also take into account the constant interruptions, tasks re-prioritization and operators inputs, specially the ones communicated orally.

To round back to my original motivation concerning interaction with AI decision support system. I believe that there is still a challenge to improving communication and interaction between intelligent systems and operators to

reach a successful Human-Computer-Partnership [8], where both agents can work hand in hand. Systems would provide suggestions and insights based on operators current needs in their workflow, and operators would be able to challenge and correct system feedback, inquire about the system operations and their underlying reasons, and add information to the system or correct the system.

To my knowledge, so far there are not any example of how this could work in control rooms, the closest that comes by are creative tasks, such as writing or mood boards, but there is a ground of theoretical work that could help create Human-computer-Partnerships for control rooms.

Creative and critical tasks both require intelligent systems that will allow users to have control, and use their skills while supporting them and helping them improve these skills, Taking advantage of both human and intelligent systems skills can be achieved through *Mixed initiative* approach [48], which allows human and intelligent systems to collaborate by negotiating who is going to do a task based on the knowledge and skills of each agent [52]. However, we can take this support a step further with *Hybrid intelligence* [26], which aims to use intelligent systems to challenge human thinking and improve its strengths rather than replacing it or reinforcing human biases [1].

Various research tries to define how to efficiently integrate intelligence in creative tasks. For instance, Clark et al. [20] proposed *Machine in The Loop* approach and demonstrated it through the task of creative writing. During the task, the human takes full agency and the machine plays a supporting role by providing suggestions to inspire creativity. Their results suggest that the users were satisfied with this collaboration and would use their system again if the quality of the suggestions improved. Koch et al. [57] proposed *ImageSense* a collaborative ideation tool, allowing users and intelligent agents to work together to create mood-boards. The intelligent agents allow the users to explore and visualize new or hard-to-express ideas by suggesting new images, providing semantic labels, and generating tags and color palettes. Both of these systems demonstrate how users can be supported by the intelligent system while keeping control.

I believe that *StoryLines* could serve as a basis to create a human-computer partnership in the control room, it would provide a shared space like *ImageSense* [57] and *Machine in The Loop*[20] for both agents where they can have a shared understanding of the context (current system state, future constraints, relationship between information and tasks). This shared space should be led by operators and allowing mainly their input, while giving them the control to invoke or collaborate with an intelligent system when needed. With *StoryLines* operators can have a shared control with the AI to collect and organize information to create overviews of the current situation. These overviews would serve both operators and AI, it would help operators to organize their

tasks and keep an eye on all the important information, and it could give AI an insight into what is important for the operator at any given time and more context on what the operator could need. Operators can always validate or dismiss AI suggestions, they can also adjust AI involvement and intrusivity.

7 - Conclusion

This thesis focuses on how to design tools to support control room operator's workflow, rather than their technical needs. To that end, we conducted a participatory design project with operators from the RTE French power grid, to investigate their unmet needs in their actual environment. I examined the research literature on designing tools to improve control room to investigate whether these tools support or interfere with operators workflow (RQ1) and found that there is usually a lack operator involvement in the design and evaluation process of the tools intended for their use, and a lack of consideration of integration of these tools in operators' workflow or environment. As a result, operators face increasing workload while reducing system awareness and trust in the system. Operators would benefit from interactive incident logs that can be augmented to highlight trends and the ability to register reminders of future actions, both for themselves and others. Finally, they need better support for collaboration and communication with other operators. We conducted participatory design workshops to understand how operators capture and exchange information about the system state (RQ2). The results of our studies with operators provide specific examples of operators' challenges, such as the lack of support in capturing and centralizing information, specifically non-persistent ones, which is compensated by memory and note-taking but still results in information loss. They also suggest a key opportunity for design, i.e. targeting the operators' existing use of informal notes to support the handover to the next shift.

The handover accentuate information loss since it reduce the information passed on, resulting in fewer information, rather than enhanced ones and with limited ability to access or retrieve non-persistent information. To improve information capture and exchange (RQ3), I combined participatory design methods with design inspiration from Instrumental Interaction to create *StoryLines*, an interactive timeline that helps operators collect information from diverse tools, record reminders, and share relevant information with the next shift's operator. *StoryLines* illustrates a successful application of the principle of "reification" by transforming a series of ephemeral events into a persistent, interactive timeline that serves as a repository for key information during the operator's shift.

We refined this concept through multiple design iterations and discussions, including a comparative structured observation study that compared the use of *StoryLines* for the handover to oral communication and note-taking, which helped us better understand operators' need for shared control with the system in collecting information, and their need for personal organiza-

tion that echoes the one they have in paper. We also compared the use of *StoryLines* for real-time compared to the handover in busy and calm situations. My findings suggest that while operators' appreciate the ability to capture and centralize information from different tools, paper still offer a simple and intuitive use, which is harder to obtain with digital tools, and operators' note-taking needs differ for personal and shared use, which is why they used paper for personal notes and *StoryLines* for the handover. My work shows that participatory design is an effective way of engaging operators of safety-critical systems in productive design activities and that combining participatory design with a theoretically based approach can lead to a simple yet effective user-centered design.

7.1 . Limitations

This thesis faced some limitations mainly due to the the limited access to the control room and the inability to retrieve real data from real tools due to confidentiality, and the operators' limited availability. The limited number and availability of the operators constrained the types of activity and evaluations we made and also limited the feedback. I compensated for the inability to retrieve data, by asking for tool screenshots and notes from the operators, which I used to create data. The limited access to the tools made it difficult to create realistic scenarios and settings for the comparative structured observation studies.

7.2 . Direction for future research

While this thesis focused on information management in control room, there are other research direction worth investigating.

Collaboration tools for the control room The current control room does not have any tools to support collaboration and communication, which is specifically important during crisis situation and when working with other control room. Currently operators rely mostly on communication tools such as phones, teams, gmail and Skype, which are not adequate for resolving constraints in the control room. Moreover the new organization of the future control rooms will involve bringing three control room together in one bigger control room, and dividing the work of one zone between two operators, one for anticipating constraints and the other for real-time monitoring and With this new organization, there would be new specific challenges for operators. thus, there would be a need to design an appropriate collaboration tool for this new dynamic to support communication and information sharing, for internal use (for each team and for the whole control room) or external

use (with other control rooms and stakeholders). Future research could help identify the specific requirement for this new tool regarding operators' challenges, supporting individual and mutual situation awareness and efficient collaboration during crises.

The role of AI in the control room Another potential direction is the integration of AI in the control room to improve efficiency and productivity. However, an improper AI integrating in such safety-critical system can risk losing operators skills and potentially developing an automation bias, which can lead to serious consequences when AI fails. Future research could explore several aspects of AI integration in the control room, including, operators' perception of AI, when and where AI could strategically be employed in the control room, the use of different type of interactions to invoke, correct AI, and their impacts on operators' automation bias. These exploration could help define a limit between tasks suitable for AI to enhance operation speed and the ones forbidden from AI as they risk deskillling operators.

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Appendix

Story Interviews Results

An alarm from a phone call: There is an issue in the grid, but the alarm is received by maintenance alone and not by operators, the operator is notified by a call from maintenance and would not have known about the alarm otherwise. The operator resolved the issue after 20min exchange with maintenance, then 20min to find a solution, and about 5 min to make the maneuver.

Inability to resolve a problem: South and east operators had an under-consumption problem, they relied on verbal communication to resolve the issue. They applied everything in their list of solutions but still could not resolve the issue, so they ended up just supervising and waiting for the situation to return to normal while collecting data to write an incident report.

A tool not working: One of the tools (a database) stopped working while the operator was doing a periodic maneuver, which prevented him from finishing it. Operators could prepare their maneuvers but not act on the grid unless it was an emergency until the system was fixed.

Prediction tool not working: The system that is supposed to show future constraints and their potential solutions was not working. The operator improvised and used another function in the simulation tool and took notes of all possible future constraints on paper, then tried to find solutions for these constraints before they happened and took notes on paper.

Incomplete information during the handover: Operator A is giving the handover to Operator B after working for 12 hours. Operator A was exhausted, and Operator B had trouble understanding everything Operator A was saying. Operator A was talking about some schema without explaining why, so Operator B just took notes and had to check later in different tools to understand why that schema was important.

Forgetting to transmit information during the handover: The problem is related to a deviation that is systematic but its value changes. The value change was not well communicated during the handover. During the shift, an alarm is triggered indicating that they have exceeded a threshold which is related to the deviation, but the operator finds that this threshold is not normal, he needed to find this issue in the technical instructions in pdf to help him to understand that the situation is normal and that the threshold is normal, before resolving the alarm.

Novel situation: The incident started with a call from a client, they made a mistake and opened a disconnecting switch that belongs to RTE, and they

asked if they could close it. The operator did not know what to do in this situation, he first made sure no one was hurt then he asked his manager, who decided to send someone from maintenance to see the situation. The manager notifies the head of maintenance and his own superior to discuss the situation. The maintenance informs the operator that he can close the switch, and the operator checks that he has the right to close it before doing so.

Electricity outage: The power cut in an electrical zone due to a fault on an electric post in a rather large zone. Two operators and the manager were tasked to do simulations to find a solution and then discuss after 5-10min to ensure that they have the same analysis to define a recovery strategy. One of the operators used different study files and thought they found the solution when they did not.

Incident between two regions: an incident happened in regions A and B. The source of the problem (a maneuver) was done in region A and the impacts were seen in regions A and B. Finding the link between the incident and the maneuver took a very long time. A strategy was defined between the two regions beforehand, but the operator changed it in real-time without communicating it. If the strategy had been shared beforehand, someone would have seen that this maneuver was not correct.

Emergency: An important client had a circuit breaker that was opened by protection, they thought there was a problem with RTE and what they were seeing were faults. RTE reassured the client that the grid was functional, and the issue was on their side. The client made a diagnosis on their side and was able to solve the problem, but it still led to a lot of tension with the client and a legal battle, cause the client wanted to show that the tension was linked to RTE.

Loss of control: The main monitoring system stopped working. The neighboring control room had to take over for them, they kept in contact with the neighboring control room using phone and Skype to help them manage the grid since they were experts on their own region (The work of both control rooms was reduced to the main tasks).

Forgetting during the handover: Operator A forgot to pass the storm warning for the afternoon to Operator B. Operator B noticed the constraint late so he could not do the mandatory maneuvers with the storm, which needed several hours to put the structure in operational condition, and was obliged to do it during the storm.

Interaction snippets



Figure 7.1. **Management of a very urgent alarm:** There is an urgent alarm, and the system displays all the necessary information (referential, maneuver preparation...). The operator reviews the information and validates the maneuvers. then he is presented with a summary of the impacts: the impacted customers, and the interlocutors who could be impacted.

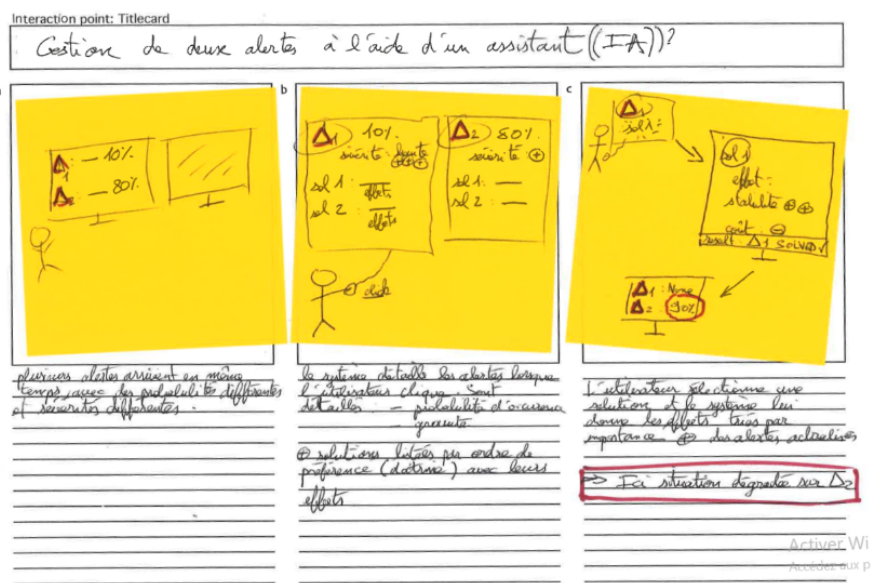


Figure 7.2. **Operator with several alerts at the same time: Several alerts arrive at the same time. For each alert, the system details the different solutions, their effects, and possibly the disruptions that could happen in other areas. Once a solution is chosen the operator is presented with a summary of the action and its impacts on other alerts and their solutions.**

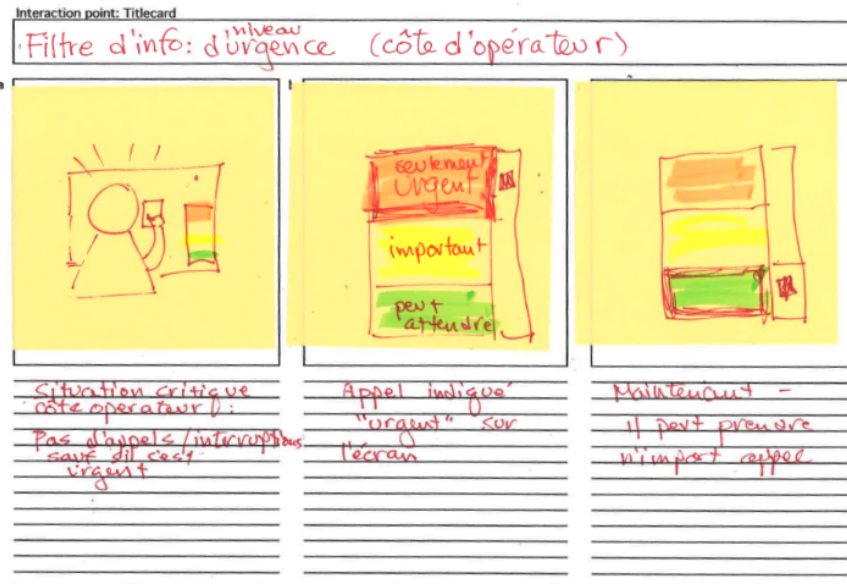


Figure 7.3. Call filter - operator side : When the operator is handling an urgent situation, he sets the call filters to urgent to not receive any non-urgent calls.

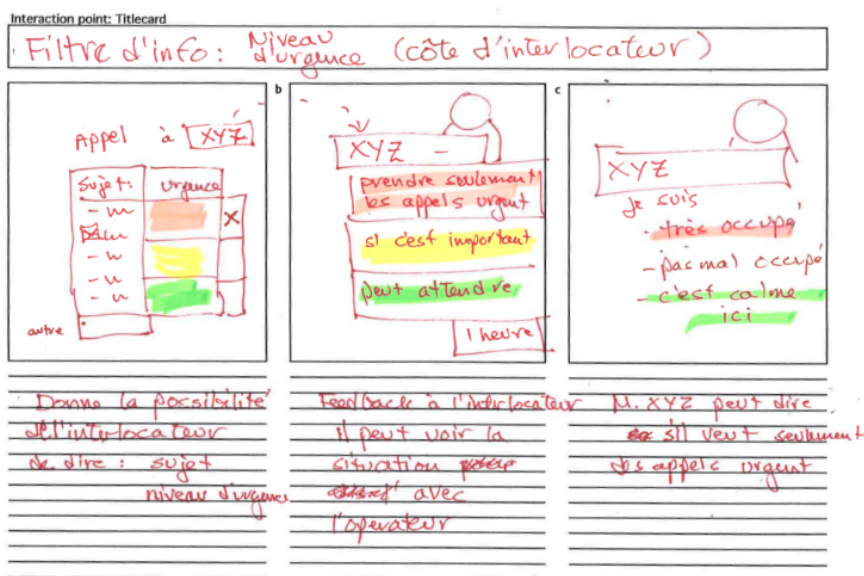


Figure 7.4. Call filter - caller side The caller can indicate the subject and the urgency level of his call. He can see that the operator is in an urgent situation and can decide himself if it is important to bypass the filter

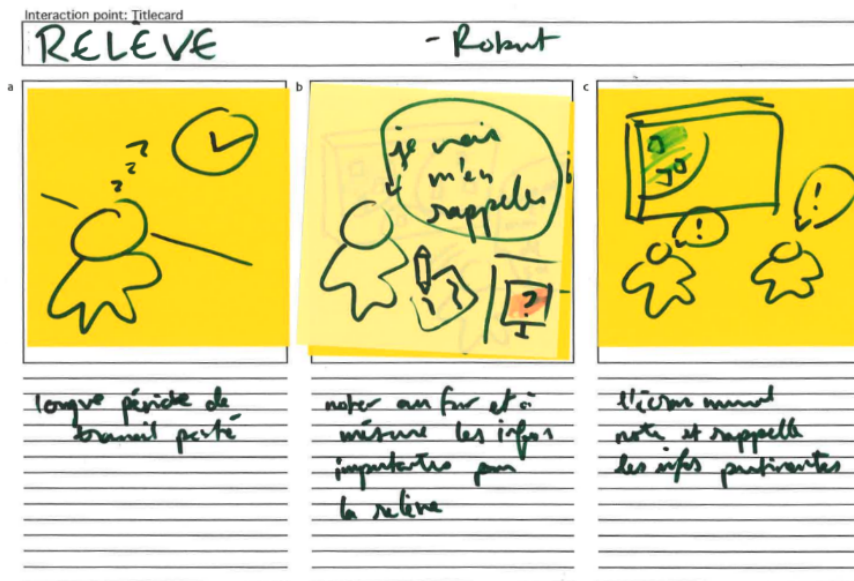


Figure 7.5. **The handover:** The operator notes the information that must be passed during the handover as he performs the maneuvers. All this information can be visualized on the wall screen so that all the people concerned can see it during the handover.

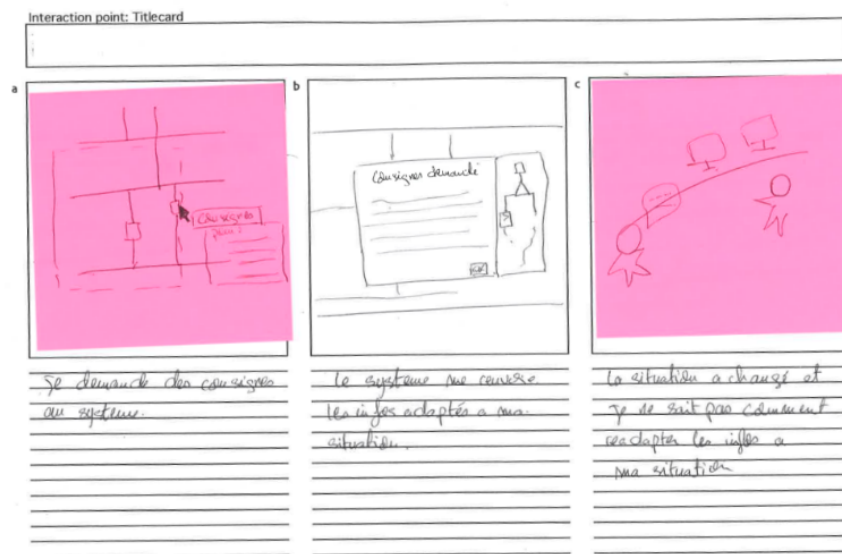


Figure 7.6. **Looking for information:** From an alarm, the operators can select a zone of interest, and click on consigne, the system would then provide a flowchart with instructions adapted to the current situation. If the situation changes, the system allows the operator to insert new information and then the system adapts to the new situation and changes the recommendations.