# Distributed Planning Over Time and People: Balancing Sampling Effort and Information Accuracy*

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**Abstract -** *Coordination of dynamic schedules in complex environments requires the sampling of current status of the system. In many such systems, the information is unavailable or unreliable. Optimal sampling theory focuses on monitoring current situation for changes, with limited consideration of future changes or missing information. Models of sampling for coordination and scheduling must consider resolving missing or ambiguous data points. Human behavior involving this type of sampling balances the need for specific information with the effort required to attain the information. The effort exerted is inversely proportional to the projected uncertainty of the information obtained. Furthermore, informational uncertainty is mitigated through a process of collaborative "grounding and correction." This paper uses the coordination of Operating-Room Suite activities to demonstrate these factors, and discusses communication strategies within the operating room context.*

**Keywords:** Sampling, scheduling, coordination, distributed planning, communication.

## 1 Introduction

Complex endeavors require considerable effort toward planning. One aspect of that planning to ensure success is the coordination and scheduling of events and resources. In dynamic, uncertain environments, the plans must be able to be adapted to changes and the coordination system flexible to accommodate continually changing circumstances. These characteristics of uncertainty and dynamism are present in a number of domains in which reliability of the system is paramount, such as aircraft carriers [17], air traffic control [8] and nuclear power generation [16], railway dispatch [12], and medical care [1].

In systems that are complex and dynamic such as these, the responsibility for the coordination of the system often falls to a designated coordinator. In the case of the surgical operating room schedule, that person is the coordinating "charge nurse" (CN). While the CN is ultimately responsible for planning and facilitating smooth operation and efficient scheduling, the CN does not act alone. Rather, a more accurate representation of the OR coordination process involves a collaboration among different actors, including nursing staff within and outside the OR suite, anesthetists, surgeons, facilities workers, technicians, and others. These collaborators are not all present during the planning and operation, so collaboration with this "team" is distributed throughout the institution, both spatially and temporally.

The essence of the scheduling and coordination task is not the *establishment* of a workable plan or schedule. Instead, it is the *monitoring* and coordination of resources to implement a schedule, and subsequent adjustment and adaptation of the schedule to accommodate the changing needs that arise.

With the need for coordination and monitoring of complex systems widespread, and considering the efforts to meet the demands of such tasks with the support of technology, it is important to understand the ways in which this coordination takes place. The domain that will serve as a testbed for our exploration of complex coordination will be the coordination of a suite of operating rooms, centered around the activities of the CN.

This paper will examine the ways in which the CN monitors the OR processes, and seeks information about the OR system status. In this examination, we compare the CN's monitoring and sampling behaviors to models describing monitoring and sampling behaviors developed to examine visual sampling behaviors in the monitoring of other technical systems. Models developed to describe the most efficient ways of monitoring (or "optimal sampling theories") can provide insight into the factors which affect the monitoring process.

## 2 Monitoring and Optimal Sampling

Optimal sampling theory was developed to deal with the problem of how to monitor a continuous process, like the status of an airplane in flight as viewed from the cockpit, or the production of electricity at a power plant as viewed from the control room. Modeling of optimal

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sampling behavior is generally predicated on the assumption that the stream of information being sampled is of a known or constant rate of change (bandwidth). Within this paradigm, it is possible to calculate an optimal frequency with which to sample (check) the indicators of the parameters being monitored. These calculations consider a number of factors related to the process being sampled.

Using displays analogous to airplane cockpit instruments, Senders, Carbonell and others [2, 3, 7, 15] developed and tested some of the first models of optimal sampling. They asserted that the optimal frequency for sampling of a given cockpit display instrument would be in proportion to the likelihood that the information would change (i.e. its bandwidth). The rationale was that upon sampling a display instrument, the knowledge of that display's status was perfect. As time passed, uncertainty grew, and the uncertainty was proportional to the bandwidth of the sampled information. Specific sampling of a given display would then depend on the bandwidth of the item being sampled, as well as the importance of the information being sampled (i.e. the cost of missing a critical event brought on by a failure to monitor the information source). When the uncertainty in the monitored parameter reached a point at which there was a danger of missing a critical event (a threshold), the value of the parameter was re-sampled. This type of sampling was considered within the context of a queuing model, in which the decision to sample a given item was made by selecting which display to sample from a "queue" of candidate items to sample. The order of the queue was determined by the priority of the items as determined by the aforementioned bandwidth and threshold considerations. These studies were validated by tracking the eye-movements of pilots in the cockpit, or in laboratory analogs of a cockpit-display monitoring task [7].

Other research added a richer set of considerations to this modeling, introducing contextual factors, such as the operator's control actions input into the system, and the onset of particular stage or phase of a monitored process [9, 10].

There are also models of sampling that consider the cost of attaining information in the calculations of the optimal frequency for monitoring that information. These studies were done in a context in which the sampling cost depended on the physical distance of a display indicator from the current visual fixation point of the person monitoring the displays [13, 14]. The shape of the cost function was determined by considering head- and eye-movement, with greater eccentricity from the point of visual fixation leads to greater information access cost. The shape of the cost function for these types of considerations has been described by Sanders "functional visual field" [13] and expanded upon by incorporating factors such as proximity to other information and visual clutter [18].

Many of these "optimal sampling" models operate on the simplifying assumption that people function as "uncertainty reducing machines" with the sole goal of reducing the level of risk and uncertainty in the processes they monitor. The results of numerous modeling experiments support these conclusions -- that scanning behavior is indeed influenced by changes in the level of uncertainty (i.e. bandwidth of monitored processes and therefore their information value). Researchers do not necessarily assert that people operate solely in such a way, but they do assert that the factors considered by the models do predict performance in the limited conditions simulated [15].

Visual sampling paradigms are examinations or models of predictable information seeking based on the urgency of the need for the information sought. They describe reasonably well the behavior of an individual person monitoring a system through its displays. These models are generally simplified, and neglect issues of collaboration between information seekers/operators. The visual sampling research also generally models situations in which the information sampled is valid, accurate, and readily available.

In the domain currently studied, few of these assumptions and conditions were followed: the status indicators are generally not dynamic visual displays; the pertinent information is not readily available; and information provided in readily available format was often inaccurate (due to dynamic changes in the system). Nonetheless, this history of sampling theories provides a foundation on which models for this new domain can be established.

Establishing these new models requires insight into the practices of operators within this domain. Data from observations and interviews can provide such insights. To such an end, a study was carried out examining the CN's coordinating activities.

# 3 Methods

Observations of the management of information flow within a six-room OR suite were performed in a Level I trauma center (See [11] for expanded description of domain and task). Observations of communication among and between the OR personnel and other hospital departments were performed by two observers (one a registered nurse) at the apparent hub of the information exchanges and coordination for the OR schedule i.e.: the dry-erase display board or "whiteboard."

Twenty-four hours of observational data were collected between the hours of 6 a.m. and 4 p.m. because these hours are generally the busiest. Data collection relied on a combination of Critical Incident Technique (CIT)[5], knowledge elicitation interviews [6], and field observations. Open-ended knowledge elicitation interviews and CIT-type interviews were carried out for three charge nurses (out of 5 total working regularly in that position at the institution), two anesthesia charge coordinators (out of 3), as well as 4 surgeons (of over 20), and 12 other staff members. Through a series of probing and clarifying questions, personnel whose position impacted the OR's daily operations were asked to provide examples of instances when daily plans were successfully executed and examples of instances when plans failed. Respondents were asked to specifically note factors that influenced the success or failure. This data was then synthesized with the data obtained via observation.

Data collection in the current efforts focused on the collaborative activities surrounding management of the OR suite, information seeking and status monitoring.

# 4 Results

Examination of these data revealed patterns of activity associated with the task of managing the OR schedule, and strategies for coping with complexity of collaboration between the users in this distributed system.

The "status indicators" or information content that the CN monitored were identified within the data, and included room availability, patient condition, equipment availability, etc. (See Table 1, "Information type"). Disruptions affecting these components on the day of surgery were routinely observed, and usually required an alteration in the schedule and collection of additional information to reformulate a new plan of action. Coordination of this process drew upon input from many different team members to exchange information. This exchange of information continued as the plan changed based on input from the various components of the system.

Analysis of the exchanges observed revealed three general means for accessing information. These were (1) information systems and documents, (2) direct observation, and (3) social networks. Assessing the information obtained by the charge nurse through each means provided for an illustration of information needs and disruptions to the information exchange process (Table 1).

## 4.1 Information Needs and Disruptions

Information use was analyzed to elucidate the information seeking and monitoring used by the charge nurse to coordinate the OR schedule effectively (Table 1). The first column listed in the table, "information type," describes the data sought by the CN. The remaining columns indicate the broad classes for sources of information used to derive the system status. Two letters are contained in each cell: the first describes the accuracy of the information attained from the given source (high, medium or low accuracy); the second letter describes the accessibility or availability of that information (highly accessible, moderately accessible or low (poor) accessibility, i.e. difficult to obtain information).

Information systems and documents include telephones, pagers, cordless phones and printed documents from both within the OR itself and the system as a whole, e.g., the pre-printed OR schedule for the day. Direct observations are those data points available to the charge nurse from directly observing the activity within the surroundings of the OR. For example, the arrival of a patient to the OR can be directly observed by the CN as the orderly wheels the patient by, and this event provides information about the patient's status and location. Social networks denotes the informal, face-to-face collaboration distributed across the various participants in the OR coordination process of the system.

In evaluating the table, note that there are trade-offs between accuracy and effort both within sources (patient status is accurate, but difficult to obtain), and between sources (equipment status may be accurate when directly observed, but requires greater effort than relying on distributed knowledge of social networking, which can be less accurate). The inaccuracies or lack of obtainable data are perturbations necessitating extra effort to be expended on the part of the CN.

It should be noted, too, that effort from sampling social network was often observed to be near zero, due to the distributed, collaborative relationship between participants. Often information was volunteered by parties who possessed knowledge of the system status, thereby

***Table 1: Sources of information for coordination of the OR suite schedule, and their accuracy and accessibility.***

| Information Type [Accuracy/ Accessibility] | Information Systems and Documents | Direct Observation | Social Networks |
|---|---|---|---|
| Patient status | H/L | ⊗ | L/H |
| Patient room location | L/H | ⊗ | L/H |
| Scheduled surgery | L/H | ⊗ | L/M |
| Anesthesia staff status | ⊗ | H/H | ⊗ |
| Room staff status (e.g. technician, nurse) | ⊗ | H/H | ⊗ |
| Equipment status and location | ⊗ | ⊗ | M/M |
| Special needs (e.g. positioning, equipment) | H/L | ⊗ | H/L |
| Surgeon disposition and availability | ⊗ | ⊗ | M/M |
| Pending changes | ⊗ | ⊗ | M/H |
| Staff location and availability | ⊗ | H/M | M/H |

H = High reliability and accuracy / High accessibility, easy to obtain; M = Medium reliability and accuracy / Moderate accessibility, Moderately easy to obtain; L = Low reliability and accuracy / Low accessibility, difficult to obtain; ⊗ = Not a prevalent method of obtaining information exacting no information seeking “cost” from the CN. For example, one anesthesiologist often volunteered information about patient-status for upcoming cases when he noticed the requisite information was missing from the public schedule-display board.

# 5 Discussion

While the process of sampling display elements in a cockpit or control room is not a perfect analogy to monitoring the scheduling a suite of operating rooms, there are some important concepts that these optimal sampling models introduce.

Sampling theory deals with tracking a changing system status, while the type of monitoring in the current study involves the proactive act of collecting data about uncertain system status, in which more-and-more accurate information becomes available gradually. The coordination of ORs thus contrast with the classical optimal sampling paradigm, and requires a variant on the sampling models to accommodate the differences. Based on a synthesis of the observations and the classical theories of monitoring, we propose a model of collaborative, distributed monitoring for coordination.

We will first discuss differences between the optimal sampling theory and the collaborative coordination environment, then discuss the implication of these factors on a proposed sampling model adapted to this environment.

## 5.1 Certainty does not decay upon sampling

A fundamental difference between the optimal sampling paradigm and the current paradigm is that traditional monitoring paradigms are concerned with current status, or retrospective determination of the trajectory of the system status. In the current paradigm, information is sampled to gain insight prospectively into the future state of the system. Uncertainty about a given data point (e.g. surgical cases) does not increase over time; it decreases or remains constant. For example, the status of a given surgeon scheduled for surgery is either known or unknown. If the status is unknown, the uncertainty can only decrease. If the status is ascertained as "available for surgery," then the uncertainty level is reduced, but still inherent in the sense that future events are never certain. Significantly, this uncertainty does not intrinsically increase over time, unless other system- or schedule changes propagate new uncertainty through the system. Similarly, the determination that a particular piece of equipment is available for surgery does not become degraded over time in the same sense that the validity of an altimeter reading in an airplane cockpit decays as after the reading is taken. Thus, in contrast to the continual sampling of continuously changing visual displays, information sampling for scheduling is a process in which the initial information sampling results in an incomplete, imperfect representation of the situation. These inaccuracies can pertain to the type of procedure, the time required for the procedure, type of equipment needed for the procedure, or even whether or not the procedure will be performed. Information that is missing can range from patient positioning needs, patient status, room status, staffing levels or staff status.

## 5.2 Threshold for monitoring is dynamic

The inaccuracies and uncertainties cited above are tolerated because of the dynamic nature of the coordination process. Decision making is distributed across the different actors within the hospital system—nurses, anesthesiologists, surgeons, patients. Attempts to resolve all uncertainties too early would likely result in wasted coordination efforts, as plans may be changed by nearly any of the actors, or by forces beyond individual control, such as the addition of an emergency surgery to the schedule, or the cancellation of a planned case.

However, as the appointed time for a given procedure approaches, the tolerance for ambiguity decreases. When the threshold of tolerance is reached, the coordinator (CN) expends efforts to resolve the ambiguity. As the ambiguity increases beyond the threshold, greater efforts are expended to reduce the ambiguity. The tolerance threshold for uncertainty in the status of the schedule decreases as time passes, and approaches zero as a case’s start time approaches.

In Optimal Sampling Theory, the threshold for sampling was generally considered constant (see [9] for exceptions), and the sampled information decayed over time. In the current model, the information does not decay—it remains constant; but the threshold does not remain constant, it decreases as time passes.

## 5.3 Information sources and their characteristics: reliability and access effort

The paradigm used in many of the previous examinations of optimal sampling theory is the scanning visual displays. The appeal of this paradigm is its relative simplicity of factors. However, in monitoring complex environments for the maintenance of an OR schedule, the information sources are rarely visual displays.

Rather, the information sources are sampled through the three classes of information previously noted: personal interactions and social networks, direct observation of events within the operating room suite; and information technology, such as pagers, phone calls, and information systems.

Unlike visual displays, which have relatively constant accuracy and information access cost, each of these sources of information has its own profile of reliability and information-access cost. Consequently, the threshold for sampling each of these sources of information is also dynamic and independent of the thresholds of the other sources of information. For example, information systems are more accurate and reliable than social networking when planning further into the future, and are easy to use for such functions. In contrast, for gathering information about events in the immediate future, information systems are often inaccurate, as they do not contain the most up-to-date, informal knowledge possessed by the distributed, collaborative social network.

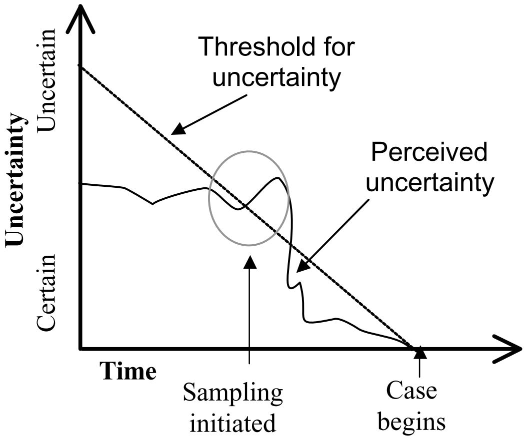

Figure 1. Simplified model of information seeking distributed over time.

### 5.4 Sampling Model

In the graph above (Figure 1), a simplified scenario is presented within the proposed framework of a sampling model for the OR coordination task. The graph shows the uncertainty in system status as a function of time. The uncertainty remains relatively constant (i.e. information validity does not decay), and is reduced when information sampling is initiated. The graph also shows a threshold of uncertainty, representing the level of uncertainty that is acceptable to the CN in relation to a specific surgical case. In the context of the model, sampling efforts are increased as the perceived uncertainty approaches or exceeds the threshold for uncertainty.

In the interest of clarity, this graph represents a linear change in the threshold for uncertainty, and represents only one threshold level. However, in the proposed full model of collaborative sampling from various information sources, the model becomes more complex. Thresholds for uncertainty are not necessarily linear, and there are different thresholds for information from different sources. The threshold for a given information source is related to the effort needed to ascertain the information and the perceived accuracy or reliability of the information (Equation 1).

$$T_{ij} = [\, E_{ij} - R_{ij}] \,/\, P_{ej} \qquad (1)$$

Where $i$ denotes a given information source, $j$ denotes a given time, $T_{ij}$ is the threshold for information source $i$ at time $j$, $E_{ij}$ is the effort needed to sample information source $i$ at time $j$, $R_{ij}$ is the reliability of information source $i$ at time $j$, and $P_{ej}$ is the temporal proximity to a given scheduled event, ($e$), i.e. the amount of time until the event starts. Salient features of the model are that as effort required to sample increases, the threshold for sampling that information source increases; as reliability increases, the threshold decreases; and the threshold approaches zero as the time approaches the onset of the designated event ($e$).

### 5.5 Planning distributed over people and time

In considering the model proposed above, it should be emphasized that coordinating was observed to be a collaborative process. It was not carried out by a single CN coordinating and sampling. Rather, it was observed to be collaborative process spread out among different actors. Reliance on informal social networking to resolve ambiguous or inaccurate data was a cornerstone of the information sampling. As noted above, the spontaneous "offering" of information updates by co-workers reduced the burden of information sampling, simultaneously reducing the effort required to sample ($E_{ij}$) and the perceived uncertainty-level of the system.

As the system status at any given time contained a large degree of intractable ambiguity and uncertainty, the coordinating CN did not attempt to resolve the ambiguity immediately. Different information sources were tapped in succession, based upon the level of ambiguity, the tolerance for ambiguity, and the costs and benefits associated with the various available information sources. In this sense, the planning itself was distributed over time.

The process of continually working as a team with an imperfect, ambiguous plan may seem unusual. However, the process is not very different than the process of a conversation. The act of conversation itself is a collaborative one, involving an addressor and addressee in a collaboration to disambiguate the process of speech. Clark and his colleagues [e.g. 4] observed that the utterance in conversations consisted of imperfect information, which is iteratively followed by a process called "grounding" in which the listener provides feedback to the speaker to establish a "common ground." The speaker uses the listener's feedback to correct and adjust the initial speech, with the end result being effective transmittal of information despite imperfect utterances. In many ways, the planning process within the operating room is similar to this process of grounding and correction. The CN presents plans that are known to be imperfect, and the ambiguity of the system-status is unavoidable.

However, the collaborating team members offer the distributed knowledge of the system as feedback, leading to adjustment of the schedules, plans and communications. This "grounding and correction" process is a mechanism by which team members assist the CN in sampling and monitoring the system status, and generating sound and efficient coordination through distributed collaboration.

# 6 Conclusions

The question of how people sample information has been investigated extensively in aviation and process control settings, but less so in the context of team collaboration. However, the framework of classical sampling theory provided an underpinning for expansion of these models into the field of scheduling and planning through teamwork and team processes. The concepts used in optimal sampling theories in other domains proved applicable to the current domain, with some adaptation. Thresholds for uncertainty, information access cost functions, and the general queuing concept all contributed to the currently proposed model of information sampling in distributed planning settings. In the inherently uncertain planning environment for emergency medical surgery, ambiguity of plans and resources is iteratively reduced through collaborative actions distributed over time and over team members.

The model we presented introduced an initial assertion regarding coordination behavior in this setting. The model was developed by examining data from field observations and interviews and adapting time-tested models of optimal sampling theory to accommodate the evidence from the field. While it provides a promising initial step in quantifying these interactions, this model should be validated with further study, and expanded to formalize the dynamics of collaborative coordination.

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