Decision Support Tool For Dynamic Workforce Scheduling In Manufacturing Environments

by

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Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

Scheduling for production in manufacturing environments requires an immense amount of planning. A large number of factors such as part availability, production cost, space constraints and labor supply must be taken into account. Considering these factors, tasks are scheduled into shifts and allocated the required human resources. However, when actual production begins, the original schedule must be updated regularly due to the dynamic nature of the environment. An enormous challenge in these rapidly changing environments is the re-allocation of workers to tasks in real-time due to events such as worker absences, emergent tasks and unanticipated delays. The focus of this thesis is the development of a decision support tool that can assist shift supervisors to rapidly generate new worker-task assignments during a shift to ensure that production stays on track.

This research discusses the systems engineering development process of the aforementioned decision support tool including the initial planning and analysis, the interface design, and the resource allocation algorithm. The development process was iterative, with evaluations and feedback at every step facilitating the refinement of the tool. Emphasis was laid on creating a collaborative framework between the human operator and the automated planning algorithm. While automated planning algorithms are a critical component of resource allocation systems since they can solve complex multivariate scheduling problems much faster than humans, they are inherently brittle and unable to respond to uncertainties in dynamic environments. Thus, in this system, the human operator is given high-level planning tasks and the ability to set goals, while the automation handles the creation of the detailed planning and scheduling assignments. Another factor that was stressed was the inclusion of ergonomic risk. Worker-task assignments that do not take into account ergonomic risk exposure can lead to repetitive stress injuries over time, causing manufacturing plants to incur substantial medical expenses. Any system that allocates (or re-allocates) workers to tasks must take into account the ergonomic risk that workers are subjected to due to the tasks they perform in the given shift.

The system was evaluated through extensive interactions with individuals from an aircraft production line, including senior level management and representative users from the

production floor. The evaluations yielded positive results. Both the management and the representative users were able to identify the applicability of the tool immediately, and all individuals agreed that the system could be very useful in real production environments. The shift supervisors from the shop floor affirmed that the tool captured all major pieces of information they consider while making re-planning decisions. To better assess the potential of the tool and to refine it further, future research should initiate pilot studies to compare the proposed tool with current methods used for decision-making, which are paper schedules and best judgment of human operators.

Thesis Supervisor: Mary L. Cummings
Title: Associate Professor of Aeronautics and Astronautics

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LIST OF ACRONYMS

ALBP: Assembly Line Balancing Problem

BCA: Boeing Commercial Airplanes

BR&T: Boeing Research and Technology

BT: British Telecommunications

CSP: Constraint Satisfaction Problem

DFS: Depth-First search

EAWS: European Assembly Worksheet

EFD: Event Flow Diagram

EJRSP: The Ergonomic Job Rotation Scheduling Problem

HAL: Humans and Automation Laboratory

hCTA: hybrid Cognitive Task Analysis

IE: Industrial Engineering, Industrial Engineer

ILP: Integer Linear Program

IR: Information Requirement

JSI: Job Severity Index

MORE: Metodo de Orientacion de Rotaciones Ergonomicas

MRV: Minimum Remaining Values

NIOSH: National Institute for Occupational Safety and Health

OCRA: Occupational Repetitive Action

OSHA: Occupational Safety and Health Administration

REBA: Rapid Entire Body Assessment

RRT: Rapidly exploring Random Trees

RTWSA: Real-Time Work Schedule Adjustment

SAR: Situation Awareness Requirement

WMSD: Work-Related Musculoskeletal Disorder

CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

1.1.1 WORKER ABSENCE RECOVERY

In current manufacturing systems, extensive planning is done to split tasks into shifts based on factors such as availability of parts, production costs and labor at hand. Further planning is done to allocate workers to tasks within a given shift. In order to meet defined production milestones, it is important that tasks scheduled in each shift be completely staffed according to the planned worker requirement. However, many times shift supervisors must deal with the situation where one or more workers assigned to the shift cannot cover all or a part of their shift. Unplanned employee absences in the U.S. production sector cause 1.9% lost work-time rate, which measures hours workers are absent for as a percent of hours usually worked [1].

Staffing losses from unplanned absences have the potential to disrupt operations. Absence recovery, or the managerial response to short-notice staffing losses due to unplanned absences, first acknowledges unanticipated capacity losses, then generates and evaluates feasible alternatives to replace the lost capacity, and finally selects and implements an appropriate option. There are two main types of absence recovery methodologies: passive absence recovery and active absence recovery [2]. In passive recovery, organizations simply dissolve the work of missing employees among the existing shift workers. This option is usually selected in small units with high skill requirements or in situations where the shift was originally over-staffed [3].

Active absence recovery can be accomplished with several strategies including holdover overtime (keeping existing workers on duty a few extra hours beyond the scheduled end of their shift), call-in workers (activating an on-call employee not scheduled for the shift), and temporary external workers contracted to cover unplanned absences [4] [2]. The absence recovery approach employed at any firm must take into account differences in employee capabilities, availability constraints, and associated costs.

Regardless of whether the recovery mechanism employed is active or passive, ideally, absence recovery mitigates the effects of unplanned absences without a serious impact on employees or production rates. In most organizations, the basic absence recovery process is very similar in that after learning of an unplanned absence, managers first evaluate feasible alternatives for covering the loss of productive capacity (including "do nothing") by weighing the costs and benefits of each, selecting the most promising option and then implementing it [3]. In most manufacturing processes, the cost-benefit analysis of each feasible alternative depends greatly on real-time factors including the capabilities of workers present, availability of workers for overtime at a short notice, the cost of schedule delays, the priorities of understaffed tasks as well as the preferences of shift supervisors. As a result, there is no one solution that can be designed for worker absence recovery for all shifts even within the same manufacturing plant. Instead what is needed is a decision support tool that can enable shift supervisors to analyze the possible alternatives for absence recovery in real-time, and to generate a feasible worker-task assignment for the given shift. The worker-task assignment produced must attempt to staff all tasks given the constraints of the scheduling environment, or in case no such complete assignment is present, must staff the maximum number of tasks.

1.1.2 ERGONOMICS IN MANUFACTURING

The Occupational Safety and Health Administration (OSHA) agency of the US Department of Labor estimates that there were over 300,000 work-related musculoskeletal disorder (WMSD) cases in the United States, which accounted for 33 percent of all work-related injury and illness cases in 2011[5]. Further, workers who sustained musculoskeletal disorders required a median of eleven days to recover before returning to work, compared to eight days for other work-related injuries. Also, the manufacturing industry registered one of the highest incidences of workers taking days away from work due to work-related injuries. It is estimated that employers spend as much as $20 billion a year on direct costs for WMSD-related workers' compensation [6], and even more for indirect costs, such as those associated with hiring and training replacement workers, lower worker productivity and higher defect rates in work. In addition to these monetary effects, the OSHA reports that WMSDs often impose a substantial personal toll on affected workers who can no longer work or sometimes even perform simple personal tasks required in their daily lives.

Scientific evidence associates WMSDs with stresses to various body parts caused by the way certain tasks are performed. The positioning of the body and the type of physical work that must be done to complete a job may cause persistent pain and lead to deterioration of the affected joints and muscles. The longer the worker must maintain a fixed posture, repeat the same movements, experience vibration, exert force, or handle heavy items, the greater the chance that such a disorder will occur. These job-related stresses are referred to as "workplace risk factors" or "ergonomic risks", and exposure to these risk factors, particularly in combination, significantly increases an employee's chance of developing WMSDs. In the last few years, there have been several legislations that require firms to regulate workplace ergonomic risks by taking

measures such as non-hazardous working conditions, limited exposure to toxic substances and adequate rest time [7]. Moreover, management of manufacturing firms also realized that reducing ergonomic risks results in overall higher satisfaction of workers, increased company loyalty, less absenteeism and consequently higher productivity and less failures (e.g. [8]; [4]; [9]).

Worker-task assignments that do not take into account ergonomics risk exposure can lead to repetitive stress injuries over time causing manufacturing plants to incur substantial medical expenses. Any system that plans or re-plans worker-task assignments, including systems that are used for worker absence recovery, should take into account the ergonomic risk that workers are subjected to due to the tasks they perform in the given shift. The benefits of incorporating ergonomic risk in assigning workers to tasks include reduced worker injuries, decreased delays in manufacturing, more efficient scheduling and reduced manpower costs, enhanced productivity and worker morale as well as improved quality of production.

Currently, there is no decision support tool in the open literature that assists shift supervisors to effectively address worker absenteeism and ensure that tasks in a shift are completed, while at the same time assesses the ergonomic risk workers could be subjected to as a result of changes in task assignments. The development of such a tool is the objective of this thesis.

1.2   PROBLEM STATEMENT

The goal of this project is to design and develop a decision support tool that enables shift supervisors to re-plan an already constructed shift schedule and decide the best way to cover last-minute gaps in the schedule, without significantly impacting the ergonomic risk to workers. The

tool should enable shift supervisors to answer questions such as —

1. If one or more workers are missing on a given day, is it possible to distribute the tasks among other workers already assigned to the shift or should they bring in additional workers (possibly resulting in overtime)?

2. If bringing in additional workers is essential, how many workers are required? Further, who is most suited to performing the tasks that are understaffed?

3. What would the impact be on ergonomic risk exposure if the work were distributed among the existing workers versus the case where additional workers are called in?

4. In case the supervisor does not want to bring in the required number of additional workers required or if an adequate number of additional workers are not available, how can the tasks be assigned such that a maximum number of tasks are staffed, and workers are not subject to high ergonomic risk? Also, what is the resultant impact on the schedule in terms of tasks staffed and ergonomic risk in these situations?

5. What would the impact on the schedule in terms of delays in task completion and ergonomic risk be if the supervisor forces the system to assign certain workers to a given task?

To answer the above questions, the tool would have to take as input such variables as the existing workers in the shift, additional workers who can be called in if required, along with each worker's availability, their skills and certifications as well as any medical restrictions they may have due to history of light duty or work-related compensation. On the tasks' side, the system should take into account in the tasks that need to be to be staffed in the shift, their respective priorities and scheduled times, as well as the risk each task poses to workers.

1.3   RESEARCH OBJECTIVE

The primary objective of this research effort is the development of a decision support tool that re-plans worker-task assignments and allows shift supervisors to collaborate with an automated algorithm to effectively manage worker absences and also control ergonomic risk exposure.

1.4   RESEARCH METHODOLOGY

The problem statement was investigated via the following research objectives (each of these will be elaborated upon in subsequent chapters)—

- Objective 1: Conduct a cognitive task analysis to generate the information and functional requirements for a decision support tool that re-plans worker-task assignments during a shift while mitigating ergonomic risk exposure. Following a human-systems engineering approach, display requirements are generated through a hybrid Cognitive Task Analysis (hCTA) [10].

- Objective 2: Use the results of the task analysis to develop a user interface that allows shift supervisor to work together with an automated planning algorithm for the purpose of assigning workers to tasks to cover last-minute gaps in the shift schedule without subjecting workers to high ergonomic risk. The interface is developed using an iterative design methodology, a specialization of the spiral model for software development [11] for user interface design. A sequence of prototypes is designed, with each iteration having a higher accuracy and fidelity than the previous. Each prototype is evaluated for usability and user feedback is incorporated at each stage.

- Objective 3: Implement a planning algorithm that re-plans the worker-task assignments in

an attempt to staff the maximum number of tasks given the constraints of the scheduling
environment and the preferences of the shift supervisor.

- Objective 4: Evaluate the interface using usability inspection methods such as heuristic
evaluations, pluralistic walkthroughs and cognitive walkthroughs.

1.5   THESIS ORGANIZATION

Chapter 1, Introduction, describes the motivation**,** problem statement, research questions and
research methodology of this work.

Chapter 2, Background, summarizes research done in the areas of ergonomic risk
management during scheduling for manufacturing operations as well as dynamic scheduling
(specifically dynamic workforce scheduling) including both computational approaches to
solving the real-time workforce scheduling problem, and decision support tools previously
developed for this purpose.

Chapter 3, Planning and Analysis, details the process undertaken to conceptualize the design
of the decision support tool. The application of the hybrid Cognitive Task Analysis (hCTA)
process to generate the information and functional requirements is elucidated.

Chapter 4, Interface Design, introduces the main components of the interface. The various
human factors elements utilized in the design of the display are examined and the shift
supervisor's interactions with the interface are also detailed.

Chapter 5, Planning Algorithm, provides an overview of the scheduling problem formulated
mathematically as an optimization problem, describes how the problem was solved
computationally, and also explains the results produced by the algorithm.

Chapter 6, System Evaluation, describes the results produced by the system as well as an

overall evaluation of the system. The interface is assessed using pluralistic walkthroughs and cognitive walkthroughs, which analyze the cognitive processes required to perform the various functions of the interface.

Chapter 7, Conclusion, summarizes the motivation, objectives, and key findings of this research initiative. Suggestions for future work are also provided.

CHAPTER 2: BACKGROUND AND RELATED WORK

This chapter presents a detailed discussion of existing work in ergonomics for manufacturing operations as well as dynamic workforce scheduling in the presence of real-time events. The chapter consists of two main parts; the first part discusses ergonomics in scheduling for a manufacturing environment, outlining common techniques used to manage ergonomic risks including job rotation scheduling and assembly line balancing. The second part of the chapter delves into previous attempts at dynamic workforce scheduling, both computational approaches to solving the problem, as well as the development of decision support tools for this purpose.

2.1 ERGONOMICS IN SCHEDULING FOR MANUFACTURING OPERATIONS

Prevention of Work-Related Musculoskeletal Disorders (WMSDs) has become an important objective for companies with manufacturing plants, and involves reducing worker exposure to ergonomic risk factors such as prolonged awkward postures, heavy lifting, repetitive movements, exposure to vibration and other potentially harmful work conditions [12]. Research to mitigate ergonomic risk in production environments is expansive and includes approaches such as redesigning tasks, assigning off-days for workers and incorporating rest pauses to reduce fatigue. For the purpose of scheduling jobs or assigning workers to jobs with ergonomic constraints in mind, research literature primarily focuses on job rotation scheduling and assembly line

balancing. In this section, I first review common ways to assess ergonomic risk to workers and then discuss the different scheduling techniques to mitigate these risks.

2.1.1 ASSESSING ERGONOMIC RISK

There are several ergonomic evaluation methods that have been developed to determine the level of risk to which workers are exposed. For lifting tasks, examples include the Job Severity Index (JSI) [13], a measure that relates the lifting required for a task to a worker's lifting capacity, the NIOSH (National Institute for Occupational Safety and Health) lifting equation [14] that associates the current load weight in a job to the general recommended load weight, and the Siemens lifting index [15], an index that is similar to the JSI but incorporates additional information about demographic characteristics and fitness of workers. For estimating ergonomic risk in tasks involving upper limbs, popular methods include the OCRA (Occupational Repetitive Action) index [16] a unit that estimates ergonomic risk separately for each hand, and the Job Strain Index [17], a similar measure but with additional parameters for task speed and strain duration. For other tasks, common methods include the European Assembly Worksheet (EAWS) [6], a methodology used widely in the European automobile industry that assesses the repetitive task load separately for the whole body and the upper limbs by considering factors such as posture, frequency and duration of repetitions, the Rapid Entire Body Assessment (REBA), a way to record working postures for the primary segments of the entire body, and Sue Rodgers' Muscle Fatigue Analysis [18], a means to assess the amount of fatigue that accumulates in muscles during various work patterns.

Smith et al. [19] developed and patented a method that collects data related to tasks (such as task duration, count, force required etc.) and computes the ergonomic risk score for each task

split into six risk broad categories, namely lifting, hand/arm stress, working overhead, pushing/pulling, bending, and kneeling. These six categories were selected since their research showed that these represent the six types of activities that account almost 90 percent of worker injuries in an aircraft manufacturing plant. Using these numbers for individual tasks, daily accumulation of ergonomic risk in each category is assessed for workers as the sum of risks of all the tasks they work on during a day of production. This is the approach used in this thesis since it covers the majority of causes of injuries in a large-scale manufacturing plant. Appendix A describes these ergonomic risk score assessments more in detail. However, it is worth noting that the tool we developed is independent of the method used to estimate ergonomic risk and can be easily adapted to other measures.

2.1.2 JOB ROTATION SCHEDULING

Job rotation, defined as a schedule design system that allows employees to rotate between different tasks, allows for scheduling operations such that workers are exposed to periodic variations in tasks; job rotation aims to ensure that the demands of jobs do not exceed the capabilities of workers. This practice has become widely adopted in manufacturing systems. One of the most important factors for its extensive adoption is its ability to balance ergonomic risks swiftly at low or even no costs. Jorgensen et al. [20], in a survey of job rotation in the Midwest US manufacturing firms, found balanced ergonomic risks to be one of the two most important perceived benefits from implementing a job rotation scheduling. In this review, I focus on job rotation approaches that have been used in production systems to minimize ergonomic risks associated with WMSDs; there is also literature that minimizes other kinds of ergonomic risks such as noise exposure [21], [22].

The ergonomic job rotation scheduling problem (EJRSP), introduced by Carnahan et al. [23], involves balancing ergonomic risk between workers by minimizing the ergonomic load for the worker highest at risk; Carnahan et al. [23] propose a distribution of workloads using integer programming and genetic algorithms, where four workers are allocated to four operations involving lifting using the Job Severity Index (JSI). Building upon their work, Tharmmaphornphilas and Norman [24] used integer programming to present a method for analyzing different job rotation interval lengths in order to determine the proper job interval for various workplace settings. Although the majority of work on solving the EJRSP has focused on genetic algorithms and integer programming, other approaches have been applied as well. For example, Seçkiner and Kurt [25] applied a simulated annealing algorithm and then an ant colony algorithm [26] to generate rotation schedules to solve the problem of balancing the workload among workers; each job is given a predefined workload and the goal of the algorithm is to minimize the cumulative workload any given worker is subject to.

To maximize the benefits from job rotation, Diego-Mas et al. [27] proposed a genetic algorithm that includes multiple criteria that together aim to ensure that the muscle groups involved in the various jobs performed by a worker in the different rotations are not the same, the content of the jobs to be performed involves an effective change of activity, and the preferences and abilities of the workers for certain jobs is taken into account. Their genetic algorithm takes into account all these factors and outputs a job rotation schedule with eighteen workers rotating between eighteen workstations according to a pre-decided number of rotations, and each rotation having a predetermined duration. They implemented their algorithm on a software system called MORE ('Metodo de Orientacion de Rotaciones Ergonomicas') that takes in data related to workers and workstations as input along with parameters of the required output rotation

schedule, and computes a new rotation schedule. The resultant schedule is presented to the human planner graphically. Furthermore, the planner is allowed to make manual changes to the input parameters and see the effects of the variation on the generated rotation schedules, thus allowing him/her to deal with situations that require a change to a worker's job assignment without having to modify the complete job rotation schedule. This tool was the only one that I came across in literature that aims to assist a human planner in ergonomically planning worker schedules, and can also be used for recovery planning in case of worker absences. However, the authors' approach is specific to job rotation scheduling where the output schedule must include workers moving between workstations according to some predetermined rotation specifications.

There have been several studies that have attempted to analyze the effects of job rotation scheduling on ergonomic criteria. There is no definitive conclusion on whether the strategy helps in reducing health risks. Some studies show that using job rotation programs may not be as effective at reducing biomechanical injury risk factors as expected; for example Frazer et al. [28] demonstrated that in some situations, the practice can raise the risk of reporting low back pain. In their study of job rotation in a refuse collecting department, Kuijer et al. [29] found a positive effect of job rotation on the perceived, energetic and postural load. The follow-up study [30] confirmed that job rotation reduces the need for recovery, but was inconclusive about the risk of low back complaints due to possible selection effects in assigning workers to the groups. The study also found that rotating groups of workers had more than two times higher risk of reporting low back complains than non-rotating groups. Aptel et al. [31] found that job rotation has a positive impact on psychosocial factors but is relatively ineffective in relation to musculoskeletal disorders prevention.

The approach taken in this thesis enables shift supervisors to re-plan worker-task

assignments in case of worker absences, and manage ergonomic risk without being limited to implementing specific rotation schedules, which are less flexible and also require significant cross-training among workers. This approach relies on the premise that keeping the daily ergonomic risk exposure to workers below a critical level by assigning them different kinds of tasks sufficiently mitigates ergonomic risk without having to adhere to defined rotation schedules (Appendix A). While the tool may ultimately result in situations where workers rotate through the type of tasks they perform so that the stress on different muscles balances, workers will not have to adhere to fixed rotation schedules of a defined interval length and predetermined job variations.

2.1.3 ASSEMBLY LINE BALANCING

The assembly line is a production system, where a set of tasks with fixed operation times has to be distributed among a set of workstations arranged sequentially with each workstation having a set of tasks associated with it (known as station workload). Each work piece moves down the line at a fixed rate such that each station has access to a work piece for a constant time span (known as cycle time) in which an operator at the workstation must perform all tasks associated with that station. Each station has a constraint that the total time required to perform all the associated tasks for a work piece must always be less than the cycle time. The Assembly Line Balancing Problem (ALBP) is to assign tasks to workstations on an assembly line such that constraints including cycle time and task precedence relations are met, while optimizing other goals such as minimizing time or cost, or maximizing capacity or profit. A feasible task assignment is called a (line) balance.

Ergonomic aspects have not been extensively considered in assembly line balancing

literature, though they are becoming increasingly important in practice [6]. Some works that incorporate ergonomics into assembly line balancing include Miralles et al. [32] as well as Costa and Miralles [33], who introduce and analyze a problem of assigning workloads to stations and to workers with different abilities and disabilities. Carnahan et al. [34] examine an assignment of a certain class of tasks (such as gripping tasks) along with its influence on fatigue and recovery dynamics of workers in an assembly line. Hilla [35] showed that if ergonomic risks are detected, re-balancing of the assembly line is recommended as an effective method in the short-run. Building upon Hilla's work, Otto and Scholl [6] present the first attempt to incorporate ergonomic risk estimation methods already used in practice into assembly line balancing models. Their experiments indicate that re-balancing often leads to a substantial mitigation of ergonomic risks. There have also been works that have focused on incorporating job rotation scheduling as a means to re-balance assembly lines such as the work of Otto and Scholl [36].

While the approach in this thesis is more in line with assembly line re-balancing than with job rotation scheduling, this work is more general than assembly line re-balancing. Assembly line re-balancing methods are specific to assembly line production environments with predetermined workstations arranged sequentially and work pieces moving through the line. The goal of all ergonomics-related approaches in these environments is to ergonomically assign tasks to the workstations (and consequently to workers). This thesis attempts to develop a decision support tool that, given a set of tasks and a set of workers, enables shift supervisors to ergonomically re-assign workers to tasks during worker absences and other dynamic events on the shop floor. It is worth pointing out that current assembly line balancing literature includes little discussion of worker absence recovery mechanisms. The tool described in this theses can be adapted for re-planning worker-task assignments to cope with worker absences in an assembly

line environment by adding in additional requirements and constraints that are specific to assembly lines such as station workload and cycle time constraints.

2.2 DYNAMIC WORKFORCE SCHEDULING

Scheduling is defined as the allocation of resources to jobs over time, and is a decision-making process with the goal of optimizing one or more objectives [37]. The objectives may include the minimization of the completion time of jobs, mean flow time, lateness of jobs, processing cost, etc. Scheduling plays an important role in many manufacturing and production systems. Since manufacturing systems operate in dynamic environments, inevitable unpredictable real-time events may cause a change in the scheduled plans, and the optimal or near-optimal schedules with respect to the estimated data may become obsolete during execution. The problem of scheduling in the presence of real-time events is termed *dynamic scheduling* [38].

A significant volume of research on the issues of scheduling with execution uncertainties has been developed, and the different existing approaches can be classified into four main categories [39–42]: completely reactive scheduling, predictive-reactive scheduling, robust predictive-reactive scheduling, and robust pro-active scheduling. In *reactive scheduling*, no firm schedule is generated in advance and decisions are made locally in real-time. In *predictive-reactive scheduling*, a schedule is first generated with the objective of optimizing performance without considering unpredictable events; the schedule is then modified during execution in response to real-time events. However, in this approach, the new schedule may deviate significantly from the original schedule, which can seriously affect other activities that are based on the original schedule. *Robust predictive-reactive* scheduling tries to overcome this problem by generating predictive-reactive schedules that minimize the effects of disruption on the current

schedule. Finally, *robust pro-active scheduling* approaches focus on building schedules, which satisfy performance requirements predictably in a dynamic environment, while at the same time providing the schedule the ability to absorb some level of uncertainty such that in case unpredictable events occur, rescheduling is not always required.

Although considerable research relating to dynamic scheduling in both production and service environments has been done, most of the work has focused on how to effectively shift jobs around (both between shifts and also within a given shift) and not on re-planning the assignment of workers to tasks. The work in this thesis focuses on dynamic workforce scheduling, particularly the allocation of workers to jobs in real-time. In the problem of dynamic workforce scheduling, there has been some work done in service environments. Academic research has focused on how to develop optimal work shifts, decide shift staffing and assign staff in advance of the day of service. For example, Thompson [43] did some initial work on real-time schedule adjustments in a restaurant environment to determine the optimal time for managers to schedule shift changes or break times. Thompson [44] also did some work to determine, early in the day, whether the actual demand for staff during the day would match the forecasted demand, allowing managers to detect in time whether they need to bring in more workers that day.

Specifically for worker absence recovery, Easton and Goodale [3] performed a comparison of various absence recovery strategies such as scheduling holdover overtime, calling in other workers and calling in temporary workers from external agencies. They simulated a service environment in which worker absence causes the actual staffing to be lower than the forecasted demand for staff and studied the impact on expected profit based on the absence recovery mechanism employed. Among other things, their simulations showed that holdover overtime generally outperforms call-ins or external temporary workers because it allows

managers to apply precise amounts (increments as small as one worker-hour) of overtime labor.

Hur et al. [45] introduce the Real-Time Work Schedule Adjustment (RTWSA), which is defined as the modification of the planned work schedule on a real-time basis to cope with unexpected demand changes and/or disruptions of labor supply. The scenario they consider is a fast-food restaurant with three workstations to be staffed according to the predicted demand. The parameters that can be changed as a result of a change in demand include modifications to station assignments, break times, worker start or end times, shift lengths and shift assignments. They proposed a mathematical formulation of the real-time adjustment decision, developed efficient heuristic solution approaches, and evaluated the relative effectiveness of the heuristics versus experienced service managers. Their studies showed that experienced managers' decisions were effective, but computer-based heuristic approaches could provide further improvements in profitability, particularly when the difference in actual workload is very different from the estimated workload before the day. The RTWSA has been further studied in other service industries including agent staffing in call centers [46], nurse scheduling in hospital inpatient units [47], [48].

Apart from literature that has looked at the RTWSA as an optimization problem, there have also been some interfaces designed for dynamic workforce management, particularly in the service industry. Lesaint et al. [49] developed a dynamic workforce management tool for British Telecommunications (BT) that manages field operations of technicians who have to serve customers and repair network faults. The system attempts to schedule tasks, assign technicians to each task, dispatch work by informing a technician of his/her next assignment, and then finally monitor the work using feedback information on the progress of tasks. The problem inherently is very uncertain since real-time events such as new jobs in the system, job cancellation, variable

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task execution times and modified worker availability necessitate periodic re-planning. The dynamic scheduler in the system employs a predictive-reactive approach to scheduling using constraint propagation, local search and simulated annealing to solve the optimization problem, with a new schedule is generated every 20-30 minutes. Moreover, supervisors can also visualize the tasks both geographically and temporally. This tool, known as TASKFORCE, enabled BT to reduce operational costs, improve customer satisfaction and enhance employee productivity.

Another decision support interface for dynamic workforce scheduling is one designed by Mirrazavi and Beringer [50] who developed a web-based workforce management system for labor scheduling in a supermarket. Their work discusses all the business requirements presented to them by Sainsbury's Supermarkets Ltd. and then details their workforce management system. The core of the system is to first predict staff demand for each department in the store and then consider factors such as employee contractual details (days off, wages etc.), worker preferences, and employee skills to decide the schedule for each employee. The scheduling determines not only details about shifts including length and breaks but also which department the employee should staff. While the focus of the tool is to enable planners to develop long term (monthly) staff planning and allocation plans it does have component that permits flexible scheduling for daily and weekly operations to periodically cope with unplanned events such as worker absences.

A limitation of the systems that have tried to solve the dynamic workforce scheduling problem is the lack of human-automation collaboration in this domain. While the works that have studied the RTWSA have focused solely on the optimization algorithms that can be used to solve dynamic workforce scheduling problems, the decision support tools simply use algorithms to construct new schedules and display it to the human planner without involving the planner in the scheduling process. Recent studies have shown that systems that allow high-level interaction

between human operators and automated planning systems have seen increases in overall system performance than both humans performing the planning manually and purely automated systems. An example of such a study is one by Cummings et al. [51] that looked at human-automation collaboration in the problem of controlling a network of unmanned vehicles. They compared the overall mission performance of a human guiding a set of decentralized automated planners to that of a perfectly compliant human who simply accepts the schedule proposed by the automated planners, and observed that the performance of the human-on-the-loop system was significantly better.

While automated planning algorithms are a critical component of planning and resource allocation systems since they can solve complex multivariate scheduling problems much faster than humans, they can only take into account quantifiable variables that were identified by developers in the design stage [52]. In a dynamic production or service environment, new events and variables come up regularly that the automated planners do not account for and as a result systems that only leverage automation are inherently brittle and unable to respond to uncertainties in these dynamic environments. In such environments, more important than trying to find an optimal solution based on a pre-defined objective function, it is critical that the system work with the human to try and find a 'satisficing'[53] assignment based on the preferences of the human planner and the real-time events in the environment. The key in this collaboration is the appropriate allocation of tasks between human and automation; human operators are given high-level planning tasks and the ability to set goals, while the automation handles the creation of the detailed planning and scheduling assignments.

2.3 CHAPTER SUMMARY

In this chapter, I discussed prior work that has been undertaken in the fields of ergonomics in manufacturing and dynamic workforce scheduling. While there has been extensive work done to consider ergonomics in manufacturing settings, most of the work in ergonomic scheduling has been confined to job rotation scheduling and assembly line re-balancing. In dynamic workforce scheduling, there have been several attempts to model and solve the planning problem as an optimization problem and there have also been a few decision support tools to aid human planners in the process. However, in both ergonomic scheduling and dynamic workforce scheduling approaches, little research has explored human-automation collaboration. Furthermore, no previous work has combined dynamic workforce scheduling and worker absence recovery with ergonomics planning. This research identifies a unique opportunity to work at the intersection of ergonomics and worker absence recovery by leveraging collaborative techniques between a human operator and an automated planning algorithm.

In this thesis, I attempt to develop a decision support tool that will aid human operators who have to schedule jobs in a large-scale manufacturing environment to manage their workforce in real-time. More specifically, I will be dealing with predictive-reactive scheduling of workers; that is, starting from a pre-generated schedule, the worker schedule must be updated in real-time as a response to events such as worker absences and other dynamic events. Based on the supervisor's preferences and domain expertise, the scheduling can be robust to minimize changes to the existing worker-task assignments or a new assignment altogether can also be generated. The goal of the system is to staff as many tasks as possible while also managing worker ergonomic risk exposure. Also, the tool leverages both the expertise of a human operator and the computational power of an automated algorithm. While the scenario considered focuses

on a manufacturing-related application, the tool is generic enough to be easily adaptable to any

environment that has similar characteristics: a set of workers, a set of tasks to be staffed and a set

of constraints and objectives that can change based on the real-time events in the environment.

CHAPTER 3: PLANNING AND ANALYSIS

This chapter details the process undertaken to develop the decision support tool. The development process includes three main phases: planning, analysis and design. Figure 3.1 illustrates the different phases in the conceptualization of an initial design for the system interface. After the initial design is developed, it is tested and evaluated using various techniques discussed in Chapter 6.
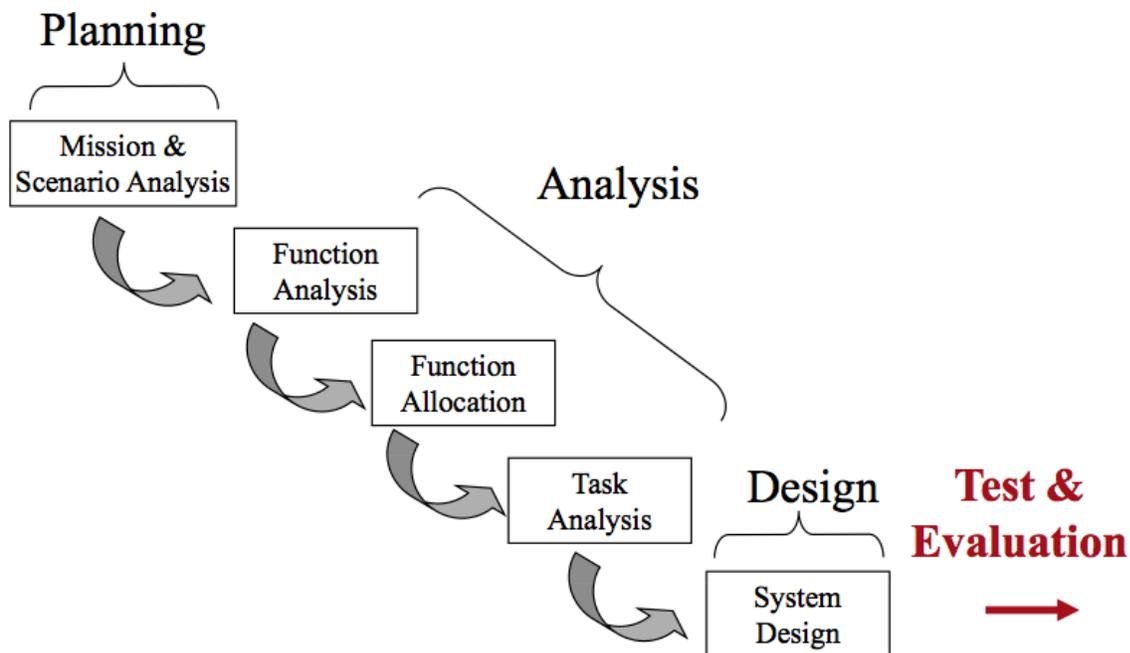
Figure 3.1: Phases in the Design Process [54]

3.1   PLANNING

This research began with a planning phase, which included initial conversations with researchers from Boeing. Through these conversations, I gauged that in most manufacturing environments, there are existing systems to solve the complex optimization problems behind planning production, which include the identification of tasks required to be performed, organization of tasks into shifts, and the initial assignment of workers to tasks. However, once the shift begins and the dynamic component of scheduling begins, the re-planning component is mostly done by humans using paper charts and best judgment. Hence, shift supervisors who make these complex decisions of how to re-assign tasks to workers in a constantly changing production environment would benefit from a decision support tool. Further, in most manufacturing plants, ergonomic risk is not incorporated either in the planning or the re-planning decisions. To mitigate injuries to workers, incorporation of ergonomic constraints is essential for worker-task re-assignments. The observations from the planning phase were confirmed during the pluralistic walkthrough in the testing phase described in Chapter 6.

3.2   HYBRID COGNITIVE TASK ANALYSIS

For the analysis phase of the design process, which includes Function Analysis, Function Allocation and Task Analysis, the Hybrid Cognitive Task Analysis (hCTA) method was used. The goal of the hCTA process is to generate the information and functional for the design of the interface of a complex system starting from a high level task description. The hCTA consists of the following components: 1) Scenario Task Overview, 2) Event Flow Diagrams, 3) Situational Awareness Requirements, 4) Decision Ladders (and jointly, display requirements and levels of

automation), and finally, 5) Information and Functional Requirements [10]. The hCTA process attempts to define the cognitive workflow of an operator in a complex environment, deriving a complete set of requirements necessary to meet system goals from operational tasks. The process is illustrated in Figure 3.2.
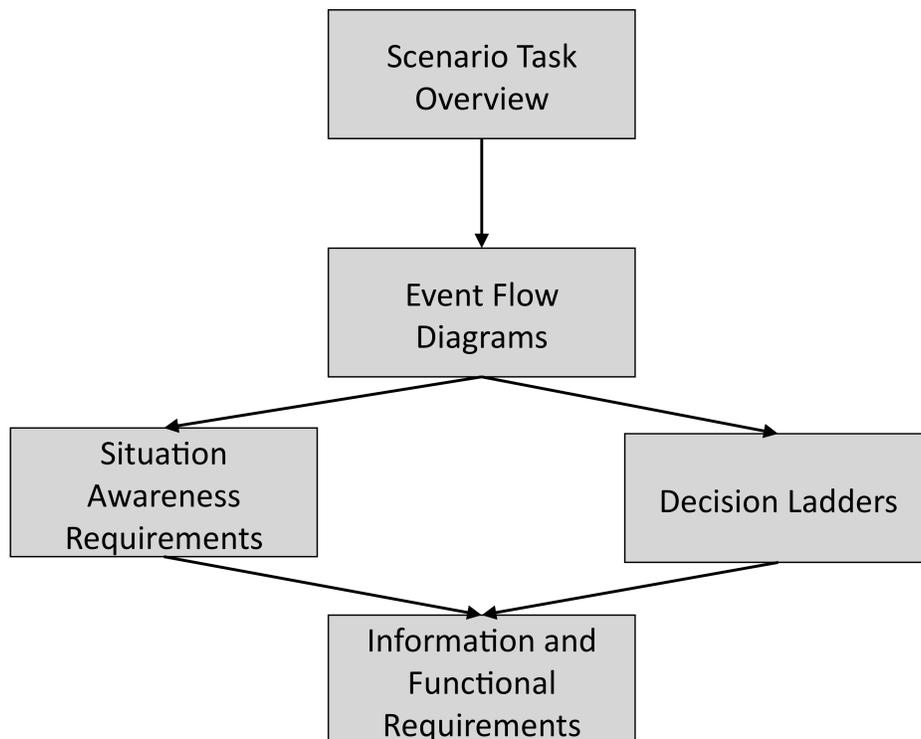
Figure 3.2: A Description of the hCTA Process [55]

3.2.1 SCENARIO TASK OVERVIEW

A scenario task overview attempts to formalize the overall system functionality into a set of distinct tasks and phases. Tasks are grouped together into phases either temporally or functionally; each phase represents an independent process step to be performed by the operator. Moreover, each phase usually has a set of sub-goals that the operator attempts to achieve.

In the situation of allocating workers to tasks in real-time, there are two main phases: Monitoring and Re-planning. In the Monitoring phase, the shift supervisor is continuously monitoring the status of tasks and workers; this phase is meant to support the shift supervisor's decision to re-plan. Once the supervisor initiates a re-plan, the re-planning phase begins. The tasks involved in these two phases are outlined in Tables 3.1 and 3.2

Table 3.1: Tasks for Monitoring Phase

Phase	Task no.	Tasks
Monitoring	1.	Monitor status for all tasks.
	2.	If any change in task status (e.g. held up, in progress, completed, tested for quality), document.
	3.	Monitor worker availabilities.
	4.	If any change in worker availabilities, document and re-calculate task staffing.
	5.	If any tasks understaffed, judge need to re-plan.
	6.	If re-plan need arises, initiate re-plan.

Table 3.2: Tasks for Re-Planning Phase

Phase	Task no.	Tasks
Re-planning	1.	Identify task workability to understand which tasks are delayed and cannot be staffed.
	2.	Identify task sequence dependencies.
	3.	Identify task priorities.
	4.	Identify ergonomic risk of each task.
	5.	Identify which workers cannot perform certain tasks due to medical restrictions.
	6.	Identify which workers are suited for which tasks (based on certifications and skills).
	7.	Determine if re-plan with existing workers possible.
	8.	If instead additional workers are required, determine how many spare workers are available.
	9.	Determine how many workers to bring in.
	10.	Determine which workers to bring in.
	11.	Re-compute assignments with existing workers (and additional workers if required).

Since the inclusion of an automated planning algorithm serves to offload operator re-planning tasks, it changes the how an operator performs the tasks and subtasks during the re-planning process. Thus, I describe another phase, known as Automated Re-plan to augment the Re-plan phase. In this new phase, rather than creating specific assignments for the shift, the human operator manages inputs to and guides the performance of an automated algorithm that help him/her to find feasible solutions. The scenario task overview for the automated re-plan phase is described in Table 3.3.

Table 3.3: Tasks for Automated Re-Plan

Phase	Task no.	Tasks
Automated Re-plan	1.	Decide permissibility of high-risk task assignments for each category.
	2.	Decide the number of workers to call in or the maximum allowed number of workers to call in.
	3.	Identify any preferred workers to be called in from the list of spare workers available.
	4.	Determine which workers are suited for which tasks (based on certifications and skills).
	5.	Determine which workers are not suited for certain tasks.
	6.	Invoke automation to re-compute worker task assignments.
	7.	Identify suggested worker-task assignments.
	8.	Determine task staffing in suggested assignments (including number of workers to call in if not specified while planning).
	9.	Determine ergonomic risks in suggested assignments.
	10.	Determine whether suggested assignment is acceptable (in terms of task staffing, possible delays, ergonomic risk and workers called in).
	11.	If suggested schedule is unacceptable, determine whether manual overrides can lead to an acceptable schedule.
	12.	If new schedule is unacceptable, initiate re-plan again.

3.2.2 EVENT FLOW DIAGRAMS

An Event Flow Diagram (EFD) provides a finer level of specification of operator tasks that eventually produce a set of informational requirements for the user interface. It represents the temporal constraints of events and tasks that occur within a specific phase. The elements of EFD's used in this work include:

- Processes – normal interactions between the human and the system.

- Loops – processes that occur iteratively till a pre-determined event occurs.

- Phase blocks – other event-flow diagrams accessible from the current diagram.

- Decisions – simple rule-based decisions or complex knowledge-based judgments with many dynamic variables.

- Transitions – transitions between various components of the EFD.

Elements in the EFD are depicted using different shapes illustrated in Figure 3.3. Process, decision and loop blocks are labeled with alphanumeric codes so that they can be cross-referenced throughout the rest of the hCTA process. The labels consist of a single letter (P for processes, D for decisions, L for loops) and a number.

I constructed Event Flow Diagrams for the two phases: Monitoring (Figure 3.4), and Automated Re-plan (Figure 3.5).
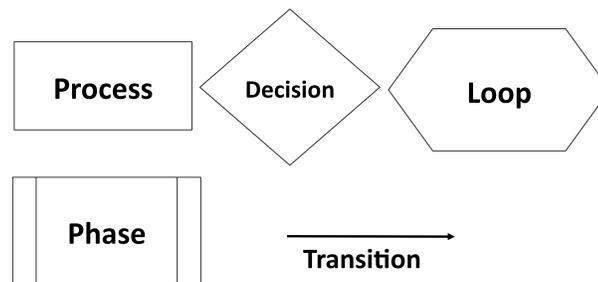

**Figure 3.3: Elements Used in the Event Flow Diagram. [65]**
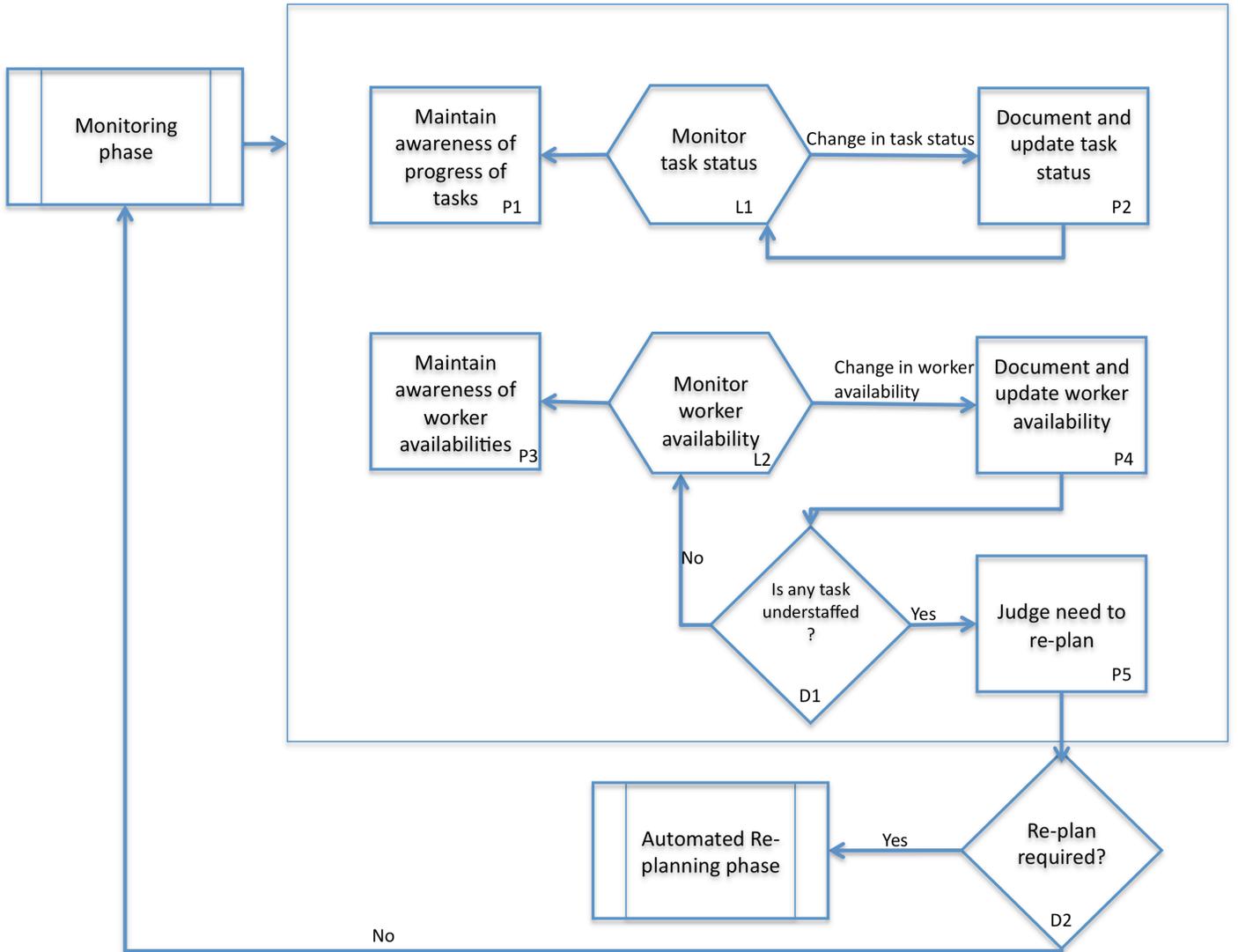
Figure 3.4: Event Flow Diagram for the Monitoring Phase
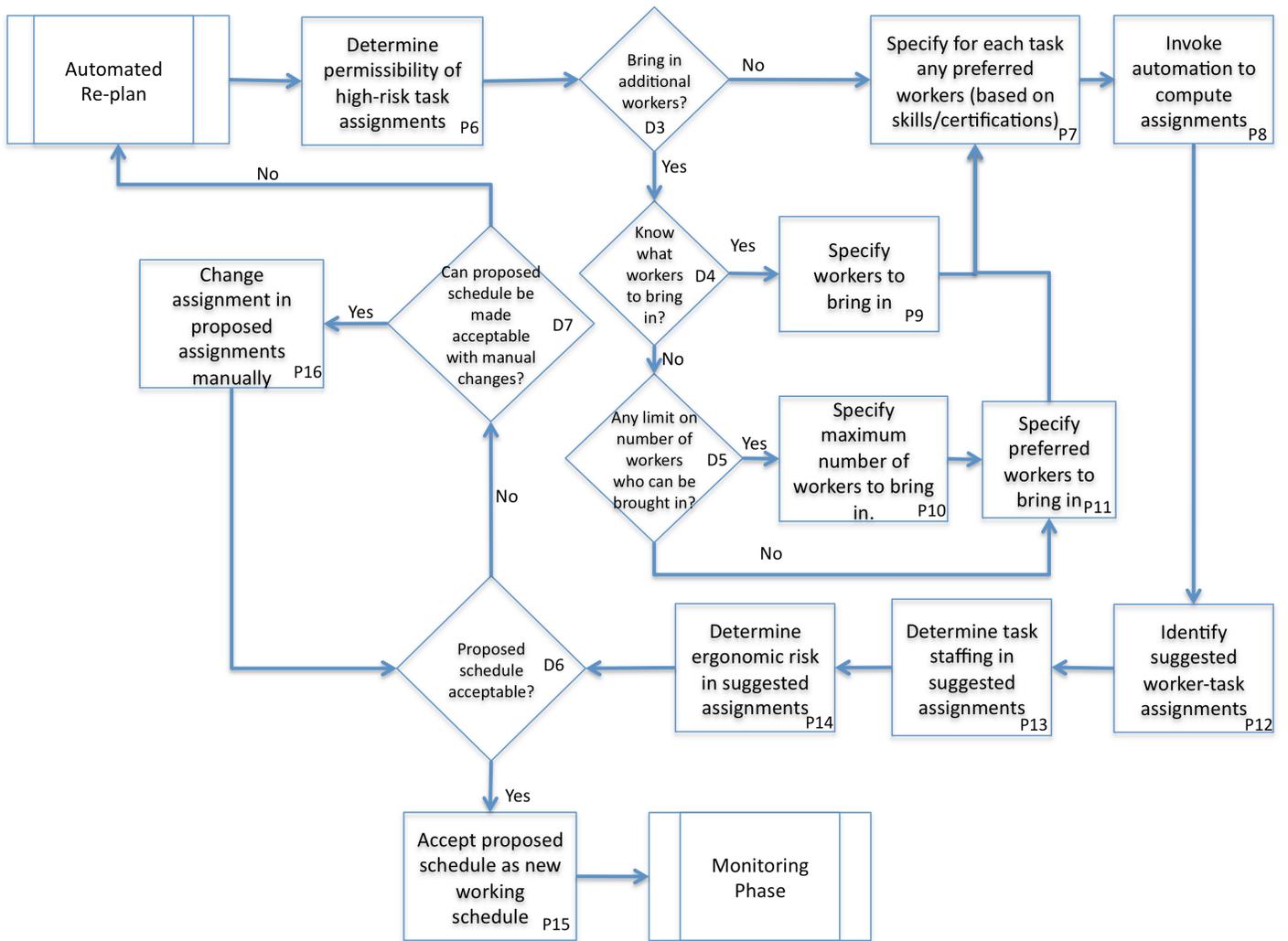
Figure 3.5: Event Flow Diagram for the Automated Re-Plan Phase

3.2.3 DECISION LADDERS

Decision Ladders are tools that aid in capturing the states of knowledge and information-processing activities that are necessary to reach a decision. In the hCTA process, Decision ladders are created for complex decisions identified in the Event Flow Diagram. The aim of the Decision Ladder is to understand the information required to best support the human decision-maker [56]. Each Decision Ladder depicts the entire decision-making process, starting from the observation and identification of an anomalous state to interpretation and evaluation of the ultimate goal in addressing the decision and finally, determination and execution of the correct response.

In a Decision Ladder, the decision-making process is categorized using three levels of human behavior: skill-based behavior, rule-based behavior and knowledge-based behavior [57]. Skill-based behavior includes unconscious control, rule-based behavior utilizes rules that a human decision-maker has learned from previous experience and knowledge-based behavior involves using environment cues and individual goals to make decisions.

A Decision Ladder traditionally includes two different shapes: boxes and ovals. While boxes illustrate the information-processing activities, ovals signify the knowledge produced by those activities. In the original hCTA process, two iterations of a Decision Ladder are constructed: one is a ladder annotated with display requirements for various components in the decision-making process and the other is a ladder incorporating annotations about potential levels of automation from the levels of automation defined by Sheridan and Verplank [58]. These levels of automation range from the human being in complete control of the system to the automation being entirely in charge, and are summarized in Table 3.5.

In a system where it is known in advance that the human will have to work in conjunction

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with the automation, only a single the Decision Ladder is created that is slightly different from

traditional Decision Ladders [59]. In this ladder, apart from the traditional symbols representing

information processing (boxes) and the knowledge produced by them (ovals), the levels of

automation are also displayed. Additionally, information-processing activities that must be

performed with the help of automation are displayed separately from regular information-

processing activities. These activities represent situations in which the human operator processes

a complex multivariate optimization problem that is hard for humans to solve and thus would

require some sort of automation assistance. The symbols used in the modified Decision Ladders

are illustrated in Figure 3.6.

Table 3.4: Levels of Automation [60]

Level	Description
1.	The computer offers no assistance; human must take all decisions and actions.
2.	The computer offers a complete set of decision/action alternatives, or
3.	Narrows the selection down to a few
4.	Suggests one alternative, and
5.	Executes that suggestion if the human approves, or
6.	Allows the human a restricted time to veto before automation execution, or
7.	Executes automatically, then necessarily informs the human, or
8.	Informs the human only if asked, or
9.	Informs the human only if it, the computer, decides to, or
10.	The computer decides everything, acts autonomously, ignoring the human.

Information-processing activity   Knowledge produced by information-processing activity   Information-processing activity with automation   Automation levels
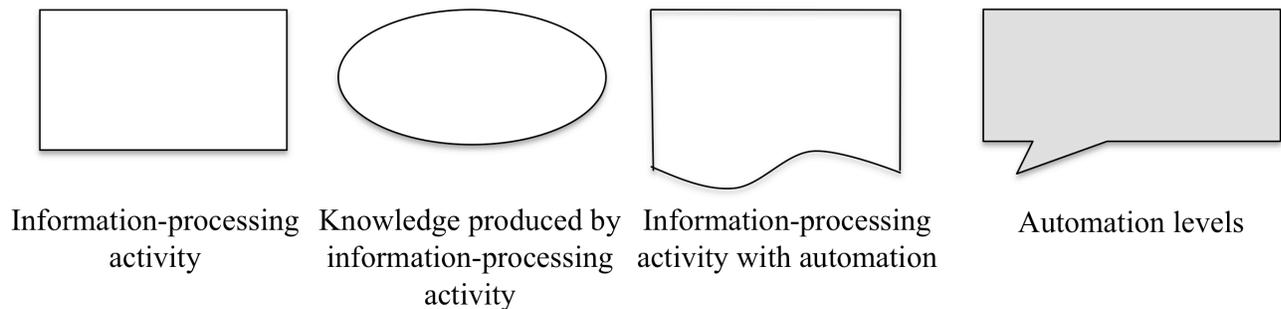
Figure 3.6: Symbols Used for the Modified Decision Ladder [59]

The Decision Ladder developed for this project was for one complex decision that supervisors have to make while interacting with the system. The decision is to determine whether the system proposed schedule is acceptable or not (decision labeled D6 in the EFD for the Automated Re-Plan phase). The ladder is illustrated in Figure 3.7.

3.2.4 SITUATION AWARENESS REQUIREMENTS

In the hCTA process, after developing the event flow diagrams and in conjunction with constructing decision ladders, Situation Awareness Requirements (SARs) are generated. Many interactions of operators with a system cannot be clearly mapped to a specific known decision process but instead include monitoring of a situation, detection of anomalies and need for intervention; SARs are generated for these processes.

Situation awareness consists of three cognitive levels: Level I (Perception), Level II (Comprehension) and Level III (Projection) [61]. During Level I, the human operator perceives any available information from the system. During Level II, he/she integrates the acquired data to guide his/her mental model of the state of the environment. Finally, during Level III, he/she forecasts future events based on his/her current mental model for timely and accurate decision-making. Table 3.6 lists the SARs identified for this project.

3.2.5 INFORMATION AND FUNCTIONAL REQUIREMENTS

The resulting situation awareness requirements, along with the display requirements from the decision ladders, are used to generate the final set of Information Requirements (IRs), which form the framework of information content required for the resulting application; these

requirements are placed into functional groupings. For this project, 34 IRs were generated and were separated into requirements related information about workers, tasks, details of original worker-task assignments, quality of original assignments, details of proposed worker-task assignments and quality of the proposed assignments. Table 3.7 lists these IRs in their respective functional groups.
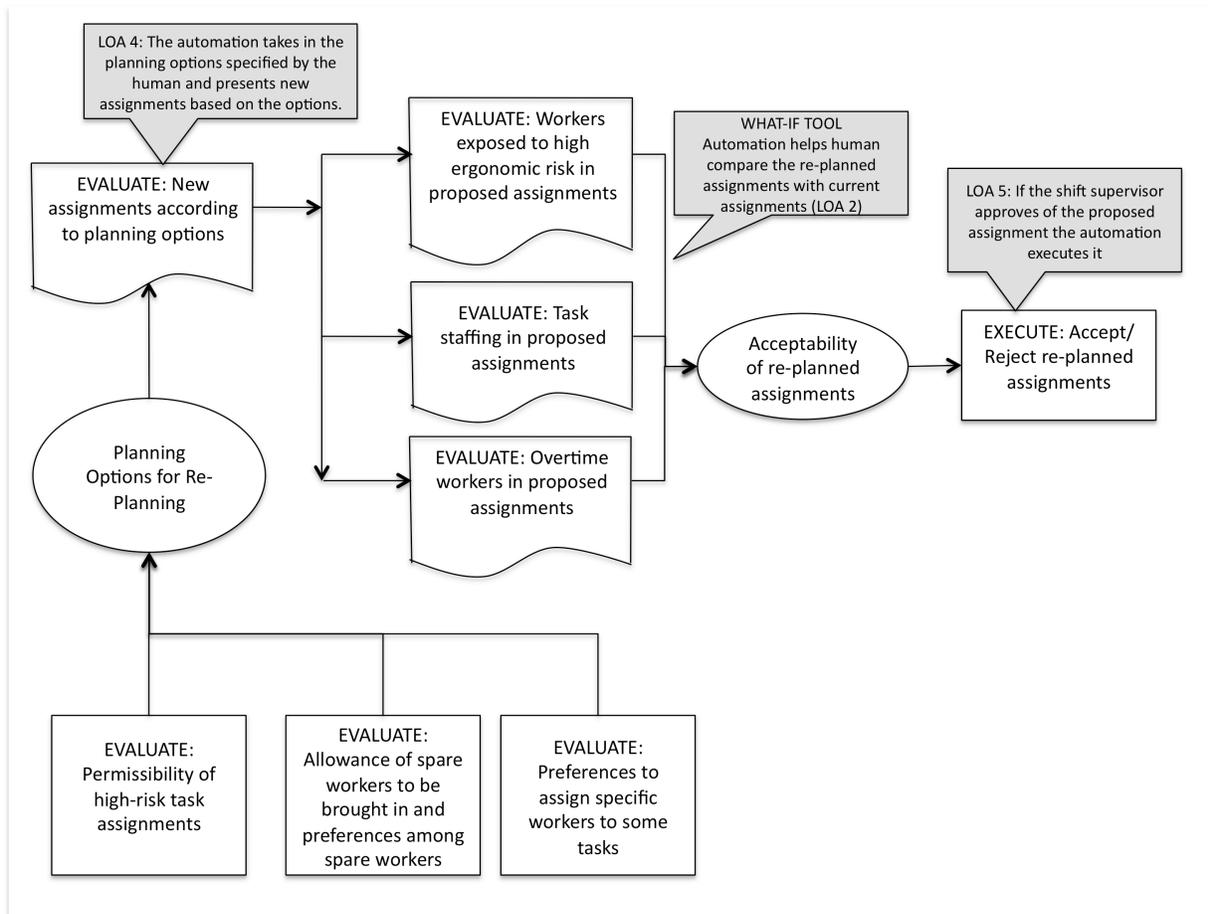

Figure 3.7: Decision ladder with Display Elements for Decision of Whether System Proposed Schedule is Acceptable or Not

Table 3.5: Situation Awareness Requirements

SAR	Level I (Perception)	Level II (Comprehension)	Level III (Projection)
1.	Worker availability indicator (partial/full/none)	Details of worker availability	Suitability of a worker to be assigned to specific tasks (depending on worker availability and task timeframe)
2.	Visual alert if worker has history of light duty/work-related compensation/medical restrictions	Alert clarification with details of medical restrictions	Suitability of workers for high-risk task assignments
3.	Worker certifications and skills	Clarification of certifications and skills	Suitability of a worker to be assigned to specific tasks (depending on worker skills and certifications)
4.	Visual indicator of task status (not started/in progress/completed)	Details of task status	Whether each task can be staffed, whether it is already completed/in progress or still needs attention
5.	Visual indicator if task is held up	Details of hold up reason	Task workability and whether task should be staffed
6.	Task dependencies	Tasks that must be completed before a given task can be started	Task workability and whether task should be staffed Other tasks that may be held up if one task is not staffed
7.	Visual indicator of any miscellaneous information that may affect task staffing (e.g. if a task has been carried over from a previous day)	Details of miscellaneous information that may affect task staffing. Reason why a task may have been assigned a high priority.	Feasibility of current or proposed assignments in terms of task staffing.
8.	Worker requirement for each task	Number of workers required for each task	
9.	Visual depiction of workers assigned to each task	Workers assigned to each task. Number of workers assigned to task	
10	Visual alert if a task is understaffed	Number of workers more that task requires	Whether re-planning is required. Additional number of workers required
11	Visual indicator of ergonomic risk of worker as a result of performing each task in	The amount of ergonomic risk each worker is subject to in each category as a result of performing each	

	current assignment	task	
12	Worker ergonomic risk after performing all assigned tasks in the shift	The amount of ergonomic risk each worker is subject to in each category after performing all assigned tasks in the shift.	
13	Visual indicator of number of high risk workers as a result of performing their currently assigned tasks	Number of workers at high risk as a result of performing their currently assigned tasks	Possible increase in ergonomic risk workers in the schedule might be able to handle
14	Additional workers called for current assignment	Number of additional workers called for current assignment	
15	Visual depiction of workers assigned to each task in proposed assignment	Number of workers assigned to each task in proposed assignment	
16	Visual alert if a task is understaffed in proposed assignments	Number of workers more that task requires in proposed assignment

Whether proposed assignment accomplishes more tasks than current assignment

Whether proposed assignment reduces the amount of possible delays due to understaffing | Feasibility of proposed assignment in terms of task staffing

Whether proposed assignment requires manual overrides |
| 17 | Worker ergonomic risk after performing all assigned tasks in the shift according to proposed assignments | The amount of ergonomic risk each worker is subject to in each category after performing all assigned tasks in the shift according to proposed assignments | Whether proposed assignment requires manual overrides |
| 18 | Visual indicator of number of high risk workers as a result of performing their tasks in proposed assignment | Number of workers at high risk as a result of performing their assigned tasks in proposed assignments

Whether the proposed assignments pose less ergonomic risk to workers | Feasibility of proposed assignment in terms of ergonomic risk |

		than current assignments	
19	Spare workers available to call in for overtime	Number of spare workers available, their availabilities	
20	Overtime workers called for proposed assignment (if any)	Number of overtime workers called for proposed assignment Whether the proposed assignment utilizes fewer overtime workers than current assignment	Feasibility of proposed assignment in terms of number of overtime workers

Table 3.6: Information and Functional Requirements for the Display

Requirement No.	Group	Information Requirement
1.	Workers	List of workers originally in shift
2.		List of spare workers available for overtime
3.		A visual indicator indicating the worker has medical restrictions
4.		Availabilities for each worker during the shift
5.		Certifications and skills of workers for tasks in the shift
6.	Tasks	List of tasks to be accomplished in the shift
7.		Task times
8.		Task priorities
9.		Task sequencing information
10.		Ergonomic risk scores of a task according to each category
11.		Task status (in progress/completed/not started.)
12.		Task workability indicator (whether task is held up). For non-workable tasks, reason for non-workability
13.		Miscellaneous information that may affect task staffing (such as information about a task being carried over from a previous day)
14.		Number of workers required for each task.
15.	Original Worker-Task Assignments	Workers assigned to each task in original assignment
16.		A visual indicator indicating a task is understaffed in the original assignment.
17.		For each worker, the amount of ergonomic risk he/she has accumulated as a result of performing an assigned task (according to original assignments)
18.		For each worker, the amount of ergonomic risk he/she has accumulated as a result of performing all assigned

		tasks (according to original assignments)
19.		A visual indicator indicating the worker is at high risk as a result of performing an assigned task (according to original assignments)
20.		A visual indicator indicating the worker is at high risk as a result of performing all assigned tasks (according to original assignments)
21.	Quality of Original Worker-Task Assignments	Number of overtime workers in original assignment
22.		Number of tasks understaffed in the original assignment
23.		Delay caused by understaffing in original assignments
24.		Number of high risk workers in the original assignments
25.	Proposed Worker-Task Assignments	Workers assigned to given task in proposed assignment
26.		A visual indicator indicating a task is understaffed in the proposed assignment.
27.		For each worker, the amount of ergonomic risk he/she has accumulated as a result of performing an assigned task (according to proposed assignments)
28.		A visual indicator indicating the worker is at high risk as a result of performing an assigned task (according to proposed assignments)
29.		For each worker, the amount of ergonomic risk he/she has accumulated as a result of performing all assigned tasks (according to proposed assignments)
30.		A visual indicator indicating the worker is at high risk as a result of performing all assigned tasks (according to proposed assignments)
31.	Quality of Proposed Worker-Task Assignments	Number of overtime workers in proposed assignment
32.		Number of high risk workers in the original assignments
33.		Number of tasks understaffed in the proposed assignment
34.		Delay caused by understaffing in proposed assignments

3.3   CHAPTER SUMMARY

This chapter details the process undertaken to conceptualize the initial design for this project.

The planning phase consisted of initial conversations with Boeing staff and the analysis phase

consisted of the Hybrid Cognitive Task Analysis (hCTA) process for identifying the display

requirements. In the next chapter, the visualization that resulted from these initial phases of the

design process is presented.

CHAPTER 4: INTERFACE DESIGN

In this chapter, I describe the interface that was designed as a result of the requirements analysis from the previous chapter. Along with details of the function of each interface element, this chapter also describes the interaction of the human supervisor with the automated planning algorithm (explained in the next chapter).

While designing the interface, I paid special attention to the following user interface design principles [62]:

- Learnability – it should be easy for users to learn to use the system. Users should not have to use recall (having to remember specific functionality) but should be able to use recognition (using visible cues to be guided through functionalities).

- Efficiency- once users have learned the system, it should be fast and efficient to use.

- Visibility- the system state as well as the actions available to the user should be visible. In addition, the system should give adequate feedback for user actions.

- Error Prevention- the interface should help prevent user errors.

- Satisfiability- this is a subjective measure related to how satisfied the users are with the look and feel of the interface. The interface should feel smooth and be aesthetically designed.

The design description is divided into three configurations: Information Display Configuration, Re-plan Configuration and Schedule Review Configuration. In this chapter, I discuss the various elements in each of these configurations.

4.1 INFORMATION DISPLAY CONFIGURATION

The information display configuration is meant to support the shift supervisor's decision to re-plan. It allows the supervisor to view the current workers in the shift, any on-call workers he/she can bring in, the tasks in the shift, as well as visualizations of metrics associated with the current schedule.

This configuration includes three major elements: the Worker Display, the Master Schedule and the Schedule Statistics. The Worker Display represents the functional group 'Workers' from the Information Requirements (IRs) (Table 3.7). The IRs from the functional groups 'Tasks' and 'Original Worker-Task Assignments' were grouped together to form the Master Schedule. Finally, the IRs from the functional group 'Quality of Original Worker-Task Assignments' are incorporated into the Schedule Statistics. Figure 4.1 illustrates this configuration along with labels of each element.

4.1.1 WORKER DISPLAY

The Worker Display shows two tables with information about workers. The first table (Figure 4.2) includes the workers scheduled for the shift while the second incorporates information about spare workers who may be called in if required.

For each table, four columns with information are displayed, which are described below along with details of the IRs each column satisfies:

1. The 'Worker' column displays the name of the worker (IR1, IR2).

2. The 'Available' column has an icon with a checkmark if the worker is available for the entire shift, a cross if the worker is unavailable for the entire shift and a check with a cross if the worker is available for part of the shift. Clicking on this icon displays a dialog

to toggle the worker's availability (Figure 4.3) (IR4). If workers are unavailable for all or part of the shift, they are greyed out with dark grey denoting unavailability for the entire shift and light grey indicating unavailability for a part of the shift.
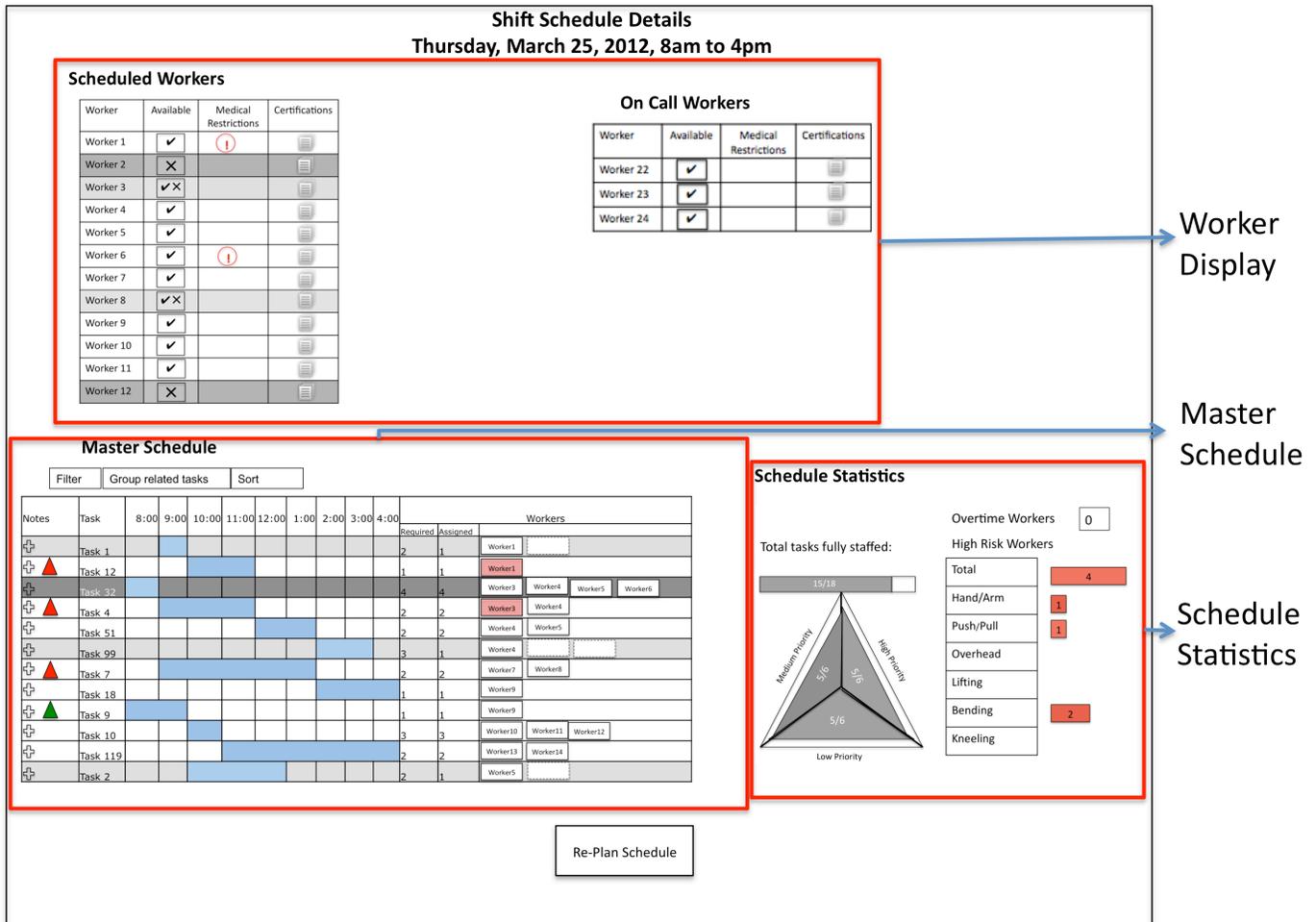

Figure 4.1: Elements of the Information Display Configuration

3. The 'Medical Restrictions' column shows a visual alert (a red circle with an exclamation symbol) if the worker has any medical restrictions for the type of tasks he/she can perform (IR3). Clicking on this alert shows a description of the worker's medical

restriction to the shift supervisor; this information is useful for the supervisor to understand what kind of tasks a worker should not be assigned.

4. Finally, the 'Certifications' column displays an indicator icon when the worker has certifications associated with the tasks scheduled in the current shift (IR5). Clicking on this icon displays a table listing the worker's certifications along with the tasks associated with each certification. Since a worker can only be assigned to a task for which he/she has the required certifications, a worker's certifications (or lack thereof) can help the shift supervisor understand why a worker was (or was not) assigned to particular tasks. Hence, these certifications effectively become a hard constraint that the planning algorithm (described in Chapter 5) uses to assign tasks to workers.

Figure 4.2: Table of Scheduled Workers in Worker Display

Figure 4.3: Pop-up to Toggle Worker Availability

4.1.2 MASTER SCHEDULE

The Master Schedule (Figure 4.4) displays all the information required by the shift supervisor to monitor the state of tasks including task status, staffing requirements and worker assignments. A task is color coded according to its status with white denoting a task that has not begun, light grey represents a task currently in progress, and dark grey is used for a task that has finished (IR11).

The Master Schedule includes the following pieces of information:

1. An ID number or name used to identify the task listed in the first column titled 'Task' (IR6). Clicking on the task identification shows details of the task including its priority, current status as well as its ergonomic risk profile by category (IR8, IR10, IR11).

2. Free text notes that the supervisor can use to annotate tasks. The added notes are displayed with a color-coded triangle (with red being notes indicating task delays and holdups and green being other general notes) (IR12, IR13). Clicking on the triangle displays the note.

3. The time for which the task is scheduled displayed by shading the relevant timeslots in the timeline (IR7).

4. The number of workers required by the task, number currently assigned and the workers currently assigned to the task listed in the 'Workers' column (IR14, IR15). If the task needs additional workers scheduled, empty boxes are displayed in this column after the list of workers assigned to the task already (IR16). Clicking on an assigned worker's name displays his/her ergonomic risk profile for each risk category separated into 3 different types: cumulative risk for the entire shift, risk before the given task was performed and risk as a result of performing the task (IR17, IR18). This profile is color-

coded according cumulative risk (red for high risk and no color otherwise). Also, the background of the worker name is colored the same color as the ergonomic risk category in which he/she is the highest at risk cumulatively (IR19, IR20).

The supervisor has options to filter, sort and group the tasks in various ways to retrieve the information that he/she might need during re-plan.

- Filtering- tasks can be filtered by priority or by task status (IR8, IR11).
- Sorting- tasks can be sorted by start time, end time, priority or worker requirement (IR7, IR8, IR14).
- Grouping- related tasks can be grouped together and the dependency relations between tasks are depicted using a tree-like structure (IR9).

Notes	Task	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	Required	Assigned	Workers
✚	Task 1										2	1	Worker1
✚ 🔺	Task 12										1	1	Worker1
✚	Task 32										4	4	Worker3 Worker4 Worker5 Worker6
✚ 🔺	Task 4										2	2	Worker3 Worker4
✚	Task 51										2	2	Worker4 Worker5
✚	Task 99										3	1	Worker4
✚ 🔺	Task 7										2	2	Worker7 Worker8
✚	Task 18										1	1	Worker9
✚ 🔺	Task 9										1	1	Worker9
✚	Task 10										3	3	Worker10 Worker11 Worker12
✚	Task 119										2	2	Worker13 Worker14
✚	Task 2										2	1	Worker5

Filter | **Group related tasks** | **Sort**

Figure 4.4: The Master Schedule

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4.1.3 SCHEDULE STATISTICS

To visualize the IRs in the functional group 'Quality of the Original Worker-Task Assignments', I use two configural displays (Figure 4.5): one to represent the tasks staffing (IR23 and IR24) and another to represent the workers at high ergonomic risk in the current schedule (IR25). Configural displays were chosen for their ability to support efficient perceptual processes as these displays reduce the contemplation required to understand the information and make decisions [63]. The two displays are described as follows:

1. Task Staffing Statistics - shows the fraction of tasks that are fully staffed, both overall and also split by priority.

2. Ergonomic Risk Statistics - represents for each category, the number of workers who as a result of the schedule, are at high ergonomic risk.

Above the configural displays, the number of overtime workers in the current assignments (IR 21) is shown.
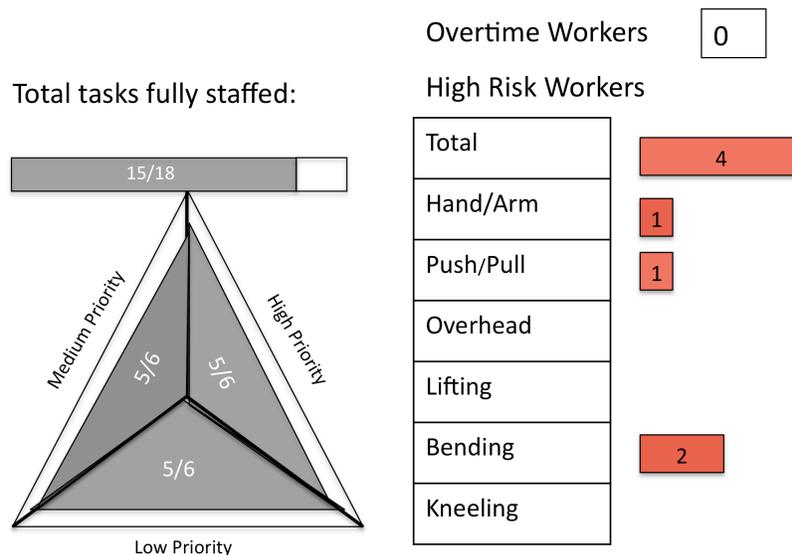
Figure 4.5: Configural Displays to View Shift Statistics

4.2   RE-PLAN CONFIGURATION

The Re-Plan Configuration is the first component of the collaborative framework between the human operator and the automated scheduling algorithm. In this configuration, the shift supervisor identifies high-level goals for the planning process, and communicates them to the automation.

Once the supervisor decides that a re-plan is required, he/she can begin a collaboration session with the automated planner by clicking on the 'Re-Plan' button. Clicking on the button opens a dialog that provides three different planning options to the user: 'Plan with existing shift workers', 'Plan with selected additional workers', and 'Suggest workers to call in' (Figure 4.6). In all three planning options, the supervisor has to specify the permissibility of high-risk assignments, which indicates whether or not it is acceptable to put high-risk workers in the schedule for each ergonomic risk category. Also in all three options, the supervisor can view for all tasks that have not yet started, the workers who are certified to perform the tasks. For all such tasks, he/she can specify the list of workers who he/she prefers to be selected for the task along with a list of workers that he/she does not want the task to be assigned to.

The three planning options are described as follows:

1. Plan with existing shift workers (Figure 4.6): In this option, re-planning is done with only the existing shift workers. No additional inputs apart from the permissibility of high-risk assignments and worker preferences are required from the supervisor.

2. Plan with selected additional workers (Figure 4.7): If the supervisor also knows how many and which workers he wishes to bring in, he/she can use this option. In this option, the supervisor must also specify the set of workers he/she wishes to bring in to help cover the tasks.

3. Suggest workers to call in (Figure 4.8): In the third planning option, the number of workers to call in as well as the workers that should be called is suggested by the automation. The supervisor can mention a maximum number of workers to call in (if fixed) as well as a pool of workers he/she prefers workers be brought in from.

4.3   SCHEDULE REVIEW CONFIGURATION

The Schedule Review Configuration is the second step in the human-automation collaboration framework, wherein the algorithm computes the new schedule using the information provided by the human, and then displays the new assignments to the human operator. The human operator reviews these assignments and decides whether they are feasible in the current shift scenario.

Clicking on the 'Create Schedule' button in the Planning Options pop-up closes the dialog and displays another copy of the schedule that is suggested by the automation along with statistics of tasks completed and worker ergonomic risk associated with the suggested schedule (Figure 4.9). The task times in the suggested schedule are the same as that of the original schedule but the worker-task assignments are different. The new copy of the schedule includes the IRs from the functional group 'Proposed Worker-Task Assignments' (IR25, IR26, IR27, IR28, IR29, IR30). The schedule statistics display of the new schedule is derived from the IRs of the functional group 'Quality of Proposed Worker-Task Assignments' (IR31, IR32, IR33, IR34). Similar to the original schedule, the statistics of the proposed schedule are also visualized using configural displays. For the planning options in which additional workers can be called in ('Plan with selected additional workers' and 'Suggest workers to call in'), the number of workers to bring in as well as the set of workers to call is also displayed (IR31).

The format and color-coding of the proposed schedule is the same as that of the Master

Schedule (Figure 4.4). If the planning algorithm (Chapter 5) is not able to find an assignment that staffs all tasks, the tasks that are understaffed have empty boxes displayed in the 'Workers' column after the list of workers assigned to the task by the automation (IR26). Similarly, workers who are at high cumulative ergonomic risk as a result of the proposed assignments are color-coded red in the new assignments (IR30).

The purpose of the Schedule Review Configuration is to allow the supervisor to compare and contrast the schedule proposed by the automated planner with the current schedule, both according to the metrics displayed, as well as their own preferences. The use of configural displays in the Schedule Statistics display serves to facilitate this comparison process.

If the supervisor decides this schedule is acceptable, he/she can accept this schedule as the master schedule using the 'Save' button. If he/she believes the schedule is close to acceptable, he/she is allowed manual overrides; he/she can drag and drop workers from one task to another. After a manual override, the schedule statistics are immediately updated to reflect the change so the effect of the override on the schedule can be observed instantaneously. After making an override, the supervisor can undo the action using the 'Undo' button. If the supervisor wants to revert to the schedule suggested by the automation, he/she can utilize the 'Revert button. Finally, if the supervisor wants to stick to the current working schedule, he/she can click on the 'Cancel' button and cancel the re-plan.

Figure 4.6: Pop-up Dialog for Planning Options to Invoke the Automated Planner

Plan with existing shift workers

Plan with selected additional workers

Suggest workers to call in

Category	High Risk Assignments Allowed
Hand/Arm	☐
Push/Pull	☐
Overhead	☐
Lifting	☐
Bending	☐
Kneeling	☐

Workers to bring in:

Select Worker ▼

Worker 9 ⊠

Task	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	Workers				
										Required	Assigned	Skilled	Preferred	Not Preferred
Task 12										2	1	Worker1 Worker2	Worker10 ⊠ Worker11 ⊠ ⊕	Worker12 ⊠ ⊕
Task 4														
Task 51														
Task 7														
Task 18														
Task 9														
Task 10														
Task 119														

Create Schedule   Cancel

Figure 4.7: Second Planning Option (Plan with Selected Additional Workers)

Plan with existing shift workers
Plan with selected additional workers
Suggest workers to call in

Category	High Risk Assignments Allowed
Hand/Arm	☐
Push/Pull	☐
Overhead	☐
Lifting	☐
Bending	☐
Kneeling	☐

Maximum Number of Workers to call in : [2 ▼]   Preferred Workers: [Select Worker ▼]

Task	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	Workers				
										Required	Assigned	Skilled	Preferred	Not Preferred
Task 12										2	1	Worker1 Worker2	Worker10 ⊗ Worker11 ⊗ ➕	Worker12 ⊗ ➕
Task 4														
Task 51														
Task 7														
Task 18														
Task 9														
Task 10														
Task 119														

[Create Schedule]   [Cancel]

Figure 4.8: Third Planning Option (Suggest Workers to Call In)

Figure 4.9: Schedule Review Configuration

4.4 CHAPTER SUMMARY

In this chapter, I illustrated the design of the decision support tool for dynamic workforce scheduling that was derived as a result of the requirements analysis from the last chapter. Table 4.1 lists the IRs from Chapter 3 that each element in the display corresponds to. In the next chapter, I describe the details of the automated planner that the system uses to suggest new worker-task assignments to the shift supervisor.

Table 4.1: IR's Satisfied by Various Components of the Display

Display Configuration	Configuration Element	IR's Satisfied
Information Display Configuration	Worker Display	1,2,3,4,5
	Master Schedule	6,7,8,9,10,11,12,13,14,15,16,17,18,19,20
	Schedule Statistics (Master Schedule)	21,22,23,24
Schedule Review Configuration	Proposed Schedule	25,26,27,28,29,30
Schedule Review Configuration	Schedule Statistics (Proposed Schedule)	31,32,33,34

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CHAPTER 5: THE AUTOMATED PLANNER

This chapter describes the planning algorithm that re-plans worker-task assignments in the decision support tool. First, the problem that the planning algorithm must solve is defined. Next, a description of the details of the algorithm is presented followed by an explanation of how the algorithm interacts with the interface illustrated in the previous chapter. The chapter ends with a discussion of the results produced by the algorithm.

5.1 PROBLEM DEFINITION

At the simplest level, the planner tries to solve a problem of resource allocation; the problem consists of a set of workers scheduled to work in the shift, a set of overtime workers and a set of tasks that need to be staffed. The goal of the planner is to allocate workers to tasks such that all tasks are staffed without violating any constraints. This section lists the attributes of each component of the planner, including workers and tasks, and then describes the objective the planner must achieve as well as the constraints the resulting assignment must satisfy.

5.1.1 WORKERS

The system consists of two sets of workers: those who are scheduled for the shift, and those who are on-call (aka 'spares'). For the purposes of the automated planner, each worker in the system, regardless of whether the worker is scheduled or spare, has the following set of attributes:

1. Worker Availability- for the purpose of the visualization (described in the previous chapter), each worker can be available for the entire shift, available for a part of the shift or not be available for the shift at all. However, the planner considers only the workers that are available for at least a part of the shift. Each of these workers has a known start time and end time during the shift, which are both represented as Date/Time variables. For example, one worker may be available between 8am and 4pm (an entire 8 hour shift) while another may only be available between 8am and 12pm (half of the same 8 hour shift).

2. Worker Certifications- each worker has a set of certifications that he/she has completed that indicate the tasks he/she is skilled to perform. In the planner, each certification is represented using an integer.

5.1.2 TASKS

The system consists of a set of tasks that need to be staffed. Each task in the shift has the following set of properties:

1. Task Time- each task has a fixed start time and end time. Similar to worker availability, both the start time and end time are Date/Time variables.

2. Worker Requirement- the number of workers required by the task.

3. Task Priority- a priority number between 1 and 5, with 5 being the highest priority and 1 being the lowest.

4. Dependencies - each task has a set of other tasks that it depends on. These dependencies should be completed before the task can be started.

5. Ergonomic Risk Score – a floating-point number for each ergonomic risk category. The ergonomic risk score for a task in a given risk category is interpreted as the ergonomic risk performing this task adds to a worker's cumulative risk in that particular category (Appendix A).

6. Required Certifications- each task may require the assigned workers to possess one or more certifications.

5.1.3 OBJECTIVE AND CONSTRAINTS

The objective of the automated planner is to staff all tasks while ensuring that the resulting worker-task assignment satisfies the following constraints:

1. Task Overlap Constraint- a worker cannot work on two tasks that overlap.

2. Worker Availability Constraint- a worker can only work on a task if he/she is available for the entire duration of the task.

3. Certification Constraint- a worker can only be assigned to tasks if he/she has completed all certifications that the task requires.

4. Ergonomic Risk Constraint- the worker's cumulative ergonomic risk in each category as a result of performing all tasks in the shift should not exceed a pre-determined threshold. The shift supervisor can override this constraint for one or more categories if he/she decides that it is acceptable to place high-risk assignments in the given category(s); details of this interaction are explained in Section 5.4. Also, some very high-risk tasks can have their own individual ergonomic risk exceeding the threshold in one or more categories. In this case, any worker assigned to the task will have to violate this constraint. In this situation, the constraint is relaxed to allow the task to be staffed but still

needs to ensure that the worker(s) assigned to this task may not be assigned to any other task that has ergonomic risk in the categories for which the given task's risk exceeds the threshold.

If a complete satisfying assignment is not present, the planner strives to maximize the number of tasks that are completely staffed, and returns the assignment that staffs the largest number of tasks without violating any of the above constraints.

5.2 SOLUTION IMPLEMENTATION

In general, any Constraint Satisfaction Problem (CSP), including the one this planner is trying to solve, consists of variables, a domain of possible values for each variable and a set of constraints that an assignment of values to variables must satisfy. The two most commonly used methods to solve CSP's are backtracking search and local search. Backtracking search searches the solution space through a depth-first search (DFS) assigning a value to one variable at a time and backtracking when a variable no longer has any remaining values it can be assigned to [64]. On the other hand, local search begins by assigning a value to every variable and then changing the value of one variable at a time to search for a satisfying assignment [64]. For this planner, backtracking search works better than local search because in case no complete satisfying assignment is found, the algorithm should return a partial assignment that staffs as many tasks as possible without violating any constraints. Local search considers only complete assignments and in case no feasible complete assignment is present, would have only encountered complete but inconsistent assignments in its search.

The function BACKTRACK-SEARCH (Figure 5.1) illustrates how to take an instance of

a CSP (referred to as *csp* in Figure 5.1) and solve it using a backtracking search algorithm; this algorithm searches the possible set of solutions recursively in a depth-first search traversal to find a satisfying assignment [64]. In CSP's, a factor that can considerably speed up the execution of the backtracking search is the order in which variables are selected to be assigned (specified by the SELECT-UNASSIGNED-VARIABLE function in Figure 5.1). The most common heuristic used to select the variable to be assigned is the "minimum remaining values" (MRV) heuristic, which selects the variable that has the fewest values remaining in its domain; by assigning the most-constrained variables first, the probability that variables assigned later, with larger domains, will still have values available to them is increased.

I use the framework provided by BACKTRACK-SEARCH to develop the PLAN-TASK-ASSIGNMENTS algorithm (Figure 5.2) that takes in this planner's constraint satisfaction problem (*csp* in Figure 5.2) and an initial assignment, and attempts to find a complete satisfying assignment. In the input *csp*, the variables to be assigned are the tasks in the shift and each task's domain is defined by the set of workers who are both certified to perform the task and available for the entire duration of the task. The constraints that are checked for each assignment include the Task Overlap Constraint and the Ergonomic Risk Constraint from the previous section.

There are a few areas in which PLAN-TASK-ASSIGNMENTS differs from BACKTRACK-SEARCH. First, BACKTRACK-SEARCH begins with an empty initial assignment and must consider all variables in the search tree; PLAN-TASK-ASSIGNMENT, on the other hand, may have an initial assignment given to it by the interface (described in Section 5.4) and has to assign only tasks that are understaffed. Second, BACKTRACK-SEARCH assumes that each variable requires one value; however in PLAN-TASK-ASSIGNMENTS, a task (variable) needs workers (values) assigned to it according to its worker requirement. Hence,

each task is used as many times in a node in the search tree as the number of workers it requires more from the initial assignment provided. Finally, BACKTRACK-SEARCH returns failure if no complete satisfying assignment is present. Here, however, if no satisfying assignment is present, the best solution (which is the assignment that staffs maximum number of tasks completely without violating any constraints) that is encountered in the solution space traversal before realizing infeasibility is returned.

In the PLAN-TASK-ASSIGNMENTS algorithm described in Figure 5.2, the *current-assignment* is complete if all tasks are fully staffed. The function SELECT-UNDERSTAFFED-TASK returns the next understaffed task that should be assigned a worker. The ALLOWED-WORKERS function returns the set of workers that are in the selected task's domain and the IS-CONSISTENT function checks for consistency in terms of task overlaps and ergonomic risk. To select the ordering of tasks to be assigned (the task returned by the function SELECT-UNASSIGNED-TASK), I order the tasks based on three criteria:

1. Tasks that depend on other tasks must be assigned after their dependencies.

2. Higher priority tasks must be staffed before lower priority tasks.

3. Among tasks that are not related by a dependency relation and are of the same priority, the task with the least number of workers remaining in its domain is assigned first according to the MRV heuristic.

The first criteria ensures that in case no complete feasible assignment is present, the partial assignment returned ensures that a task is only staffed after its dependencies have been staffed since before completing dependencies, the task cannot begin. The second criterion ensures that a partial assignment always strives to staff higher priority tasks first. Finally, the third criterion helps speed up the execution of the program.

function BACKTRACK-SEARCH(*csp*) returns a solution or failure
      return BACKTRACK({}, *csp*)

function BACKTRACK(*assignment, csp*) returns a solution or failure
      if *assignment* is complete **then return** *assignment*
      var ← SELECT-UNASSIGNED-VARIABLE(*csp*)
      for each value in ORDER-DOMAIN-VALUES(*var, assignment, csp*) **do**
            if *value* is consistent with *assignment* **then**
                  add {*var = value*} to *assignment*
                     result ← BACKTRACK(*assignment, csp*)
                     if *result* $\neq$ *failure* **then**
                          return result
                remove {*var = value*} from *assignment*
      return failure

Figure 5.1: Description of Generic Backtrack Search to Solve CSP's.

function PLAN-TASK-ASSIGNMENTS(*initial-assignment, csp*) returns a solution
      current-assignment ← *initial-assignment*
      best-assignment ← *initial-assignment*
      result ← BACKTRACK-PLAN(*current-assignment, best-assignment, csp*)
      if *result* $\neq$ *failure* **then return** *result*
      else return *best-assignment*

function BACKTRACK-PLAN(*current-assignment, best-assignment, csp*)
      if *current-assignment* is complete **then** *return current-assignment*
      task ← SELECT-UNDERSTAFFED-TASK(*csp*)
      for each *worker* in ALLOWED-WORKERS(*task, current-assignment, csp*) **do**
            if IS-CONSISTENT(*worker, current-assignment*) **then**
                 assign *worker* to *task* in *current-assignment*
                 if IS-CURRENT-BEST(*current-assignment*) **then**
                     best-assignment ←*current-assignment*
                 result ← BACKTRACK-PLAN(*current-assignment,*
                                  best-assignment, csp)
                 if *result* $\neq$ *failure* **then**
                     return *result*
                 remove *worker* from *task* in *current-assignment*
      return *failure*

Figure 5.2: Description of Planning Algorithm that Uses Backtrack Search to Assign Workers to Tasks

5.3 COMMUNICATING WITH THE INTERFACE

The planning algorithm must interface with the visualization described in the previous chapter to build a human-automation collaboration framework. As was described, the shift supervisor has three different planning options with which he/she can invoke the automation: planning with existing shift workers, planning with pre-selected additional workers and planning with workers suggested by the automation. In all three planning options, the supervisor has to specify the permissibility of high-risk assignments, which indicates whether or not it is acceptable to put high-risk people in the schedule for each ergonomic risk category. This option dictates the categories for which the ergonomic risk constraint must be checked in the automated planner. Also in all three options, the supervisor can specify for all tasks that have not yet started, the workers who he/she prefers to be assigned to the task; these assignments are taken in as part of the initial assignment that the PLAN-TASK-ASSIGNMENTS algorithm then builds upon.

Each of the three planning options differs slightly in its execution of the planning algorithm; these differences are described as follows:

1. Plan with existing shift workers (Figure 4.6): In this option, the automated planner must solve a CSP where variables are the tasks that have not yet started and values come from the set of workers scheduled for the shift.

2. Plan with selected additional workers (Figure 4.7): Since in this option, the shift supervisor has specified exactly who he/she wants to bring in, the planner solves a CSP where variables are tasks that have not yet started and values come from both the set of workers scheduled for the shift and the set of workers that the supervisor has specified should be brought in.

3.   Suggest workers to call in (Figure 4.8): In the third planning option, the automation is allowed to bring in spare workers but must figure out the number of workers to call in as well as the workers who should be called in. In this option, the supervisor has the option to specify the maximum number of workers who should be brought in. If no maximum is specified, the algorithm solves a CSP with tasks as variables and all workers (scheduled as well as spare) as the value set. The spare workers are always the last variables returned by ALLOWED-WORKERS to ensure that these workers are only used for tasks when all other choices in a particular branch of the search tree are inconsistent; the spare workers employed in the returned assignment are identified by the automation for overtime. However, if the maximum number of workers that can be brought in is specified, the planner must first identify the subset of spare workers to include with the scheduled workers for the value set in the CSP; the size of this subset is the maximum number of workers specified by the supervisor. To identify the workers to be selected in this subset, the planner sorts the spare workers on the basis of the number of tasks each worker is certified for and then selects the subset of workers certified to perform the maximum number of tasks.

As described in Chapter 4, after the algorithm calculates the new worker-task assignments, it displays a new copy of the schedule with the proposed assignments below the current schedule (Schedule Review Configuration - Figure 4.9). Next to the proposed schedule, visualizations of statistics related to task staffing and ergonomic risk are depicted using configural displays. If a complete feasible assignment is found, the task staffing statistics of the proposed schedule conveys that all tasks are staffed in the suggested schedule. On the other hand, if the planning

algorithm returns an incomplete assignment, the task staffing statistics display communicates the number of tasks that the algorithm was able to completely staff (both cumulative and split by priority) (similar to Figure 4.5). Also, each task that is understaffed in the proposed schedule has empty boxes equal in number to the number of more workers it requires in the 'Workers' column of the schedule (similar to the Master Schedule in Figure 4.4).

5.4 ALGORITHM PERFORMANCE

5.4.1 DATA GENERATION

For the purpose of testing the system and creating realistic simulations of the production processes during manufacturing, representative data (using typical numbers from a large aircraft manufacturing plant) was first generated. I considered an eight-hour shift with ten tasks to be accomplished. Of these ten tasks, four were full day tasks (eight hours), four were half day tasks (four hours), one six hours long and one two hours long. The start time for non-full day tasks was randomly selected to be any time after the start of the shift that allowed the task to be completed by the end of the shift. Using the generated start times, three tasks were selected to be dependent on another task that was scheduled later in the shift. In terms of task priority, three tasks were randomly selected to be high priority, four were medium priority and three tasks had high priority values. With regards to worker requirement distribution, six of these tasks required one worker, three required two workers and one required three workers. Finally, in terms of certifications, six tasks required three certifications and two tasks each required two and four certifications respectively. There were no overlaps between certifications required by tasks.

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To generate values for ergonomic risk for tasks, I used data supplied by Boeing. Boeing's ergonomic risk assessment generated an ergonomic risk score for six different categories, namely Hand/Arm, Push/Pull, Bending, Kneeling, Lifting and Overhead stress. Using this data, I learned the distributions of value for each category (more details in Appendix A).

There were fifteen workers originally scheduled for the shift. An additional three workers (twenty percent of the number of workers scheduled for the shift) were spares that could be called in for overtime if required. Of the fifteen workers, there were five workers (one-third), who were available for part of the shift; of these, three were available for four hours and two for six hours. Worker certifications were generated to guarantee that each worker has certifications for five tasks (fifty percent of total number of tasks in the shift).

Original worker-task assignments using the fifteen workers in the shift were constructed manually by considering task overlaps, worker availability constraints and certifications (without considering ergonomic risk). In the original schedule, all tasks were completely staffed. There were thirteen workers who had tasks assigned to them in the original assignment. In some manufacturing environments, there are one or two workers apart from those assigned to tasks in the shift that are also scheduled for the shift. Hence, the assignments caused two workers who were originally scheduled in the shift to not be assigned to any tasks.

5.4.2 ALGORITHM TESTING

The algorithm was tested in several example scenarios. All tests were run on a MacBook Pro running the OS X Operating System Version 10.6.8; the system had 4GB of RAM and a 2.53 GHz Intel Core 2 Duo Processor. The planner was implemented in Java[TM] using the Eclipse IDE, which was also used to run the simulations. All reported runtimes measure the execution

time of the implemented PLAN-TASK-ASSIGNMENTS algorithm; the algorithm was run five times for each scenario and the average runtime is mentioned.

As mentioned in the previous section, I manually constructed, from scratch, a complete feasible assignment that satisfies the task overlap constraint, certification constraint and worker availability constraint. The ergonomic risk constraints were not incorporated in this schedule. Therefore, to first test the performance of the algorithm, I decided to run the planner with an empty initial assignment, and no ergonomic risk constraints to measure the time it took to find a complete feasible assignment using just the scheduled workers in the shift (which I was sure existed). The planner was able to find a complete feasible assignment in about a tenth of a second (on average it took 96 milliseconds). Furthermore, since in the manually constructed assignment, there were two workers who were not assigned to any tasks, despite removing these workers, a complete feasible assignment was guaranteed. After removing these two workers, the planner was again able to find a complete feasible assignment in about a tenth of a second (average runtime was 112 milliseconds).

To further assess the performance of the algorithm, I ran several example scenarios that affected the original worker-task assignment and used the planner to re-plan the task assignments. For each scenario, all three planning options were considered. Since the second planning option ('Plan with selected additional workers') works almost identically to the first ('Plan with existing shift workers'), its performance is very close to that of the first option. Hence, I report results only for the first and third scenario ('Suggest Workers to Call In'). The scenarios are described as follows:

1. One scheduled worker, who was originally assigned to one high priority and one medium priority task, is reported absent.

2. Two scheduled workers, who were both originally assigned to one high priority and one medium priority task, are reported absent.

3. Four scheduled workers, all of who were assigned to at least one high priority task, are reported absent.

4. Eight scheduled workers are reported absent; of these four were assigned to at least one high priority task (same as the previous scenario) and four others were chosen randomly.

The results of planning with existing shift workers in the various scenarios are summarized in Table 5.1 and those of planning with suggested spare workers are listed in Table 5.2.

Table 5.1: Results of Algorithm for Planning Option 1 (Planning with Existing Shift Workers)

Scenario	Tasks Staffed	Time (ms)
One scheduled worker absent	10/10	929
Two scheduled workers absent	9/10	1470
Four scheduled workers absent	7/10	197
Eight scheduled workers absent	3/10	8

Table 5.2: Results of Algorithm for Planning Option 3 (Suggest Workers to Call In)

Scenario	Number of Spare Workers Brought In	Tasks Staffed	Time (ms)
One scheduled worker absent	2/3	Complete	<5
Two scheduled workers absent	2/3	Complete	<5
Four scheduled workers absent	3/3	Complete	<5
Eight scheduled workers absent	3/3	6/10	23

Both the number of tasks that the algorithm is able to fully staff and the running time are mentioned. For the case where the algorithm suggests spare workers to bring in, the number of

spare workers recommended by the algorithm to be called in is also specified.

As can be seen from the results in Tables 5.1 and 5.2, for the example scenario I consider (which is representative of a typical shift environment), the algorithm's runtime never exceeds a few seconds, regardless of whether a complete assignment exists. However, in the cases where no complete feasible assignment exists, the assignment returned is not optimal since the algorithm simply returns the best feasible assignment (that staffs the most number of tasks) it encountered during the search before realizing infeasibility. More sophisticated algorithms would possibly be able to find assignments that are able to staff more tasks in these scenarios.

Another brittleness the testing brought out is that in the 'Suggest workers to call in' planning option, the algorithm does not globally minimize the number of spare workers who should be brought in. Although in each node of the solution tree the ALLOWED-WORKERS function (Figure 5.2) ensures that spare workers are considered only after all scheduled workers do not yield a complete feasible assignment (Section 5.3), if the algorithm takes a branch early in the search that contains a complete solution featuring spare workers at a node, the algorithm returns that solution. As can be seen in Table 5.2, in the scenario where one worker was reported absent, the algorithm returned a solution that recommended that two spare workers be brought in even though another complete assignment that staffs all tasks using no spare workers had been found when planning with the only the existing shift workers (Table 5.1). In an attempt to overcome this shortcoming, I modified the algorithm to only return a solution if the assignment it found not only staffed all tasks but also did not include any spare workers. If the complete feasible assignment that was found incorporated spare workers, the algorithm continued the search to try and find another complete feasible assignment that utilized fewer spare workers. However, this modification meant that a much larger solution space had to be traversed in an

attempt to find a solution that features fewer spares. Table 5.3 summarizes the results of this

change. As can be seen from the table, when possible, a fewer number of spare workers were

included in the suggested assignments. However, the algorithm runtime increased from a couple

of seconds to more than twenty seconds in some cases. Therefore, this change was reversed. It is

likely that more sophisticated scheduling techniques would be able to efficiently find an

assignment that optimizes the multi-criteria objective function of staffing the maximum number

of tasks and minimizing the number of spare workers.

Table 5.3: Results of Traversing More of the Solution Space to Find Solutions that Require Fewer Spare Workers

Scenario	Number of Spare Workers Brought In	Tasks Staffed	Time (ms)
One scheduled worker absent	0/3	Complete	12325
Two scheduled workers absent	1/3	Complete	20886
Four scheduled workers absent	3/3	Complete	2273

The final measure was the effect of problem size on running time. As the problem size increases,

the algorithm's runtime expands as factorial in time. To evaluate this near-exponential increase

in runtime with problem size, I created a new dataset that was double in size by considering two

copies of the original problem. The new problem included twenty tasks, thirty workers, with

each worker certified for fifty percent of the tasks. For problems this size, the algorithm can take

up to a few hours to search the solution space. Thus, for shift environments with a large number

of tasks and workers, a more sophisticated algorithm would be required. To ensure that the

current implementation of the tool can still handle large problem sizes, while interfacing the

algorithm with the display, I included a timeout that returned the best assignment found after

about 10 seconds. Since acceptable performance is more important for usability than the

optimality of the result, the tool is still functional in all scenarios. Also, a new dialog was added to the interface (discussed in Chapter 4) that is displayed while the algorithm is running to inform the operator that the results are loading (Figure 5.3).
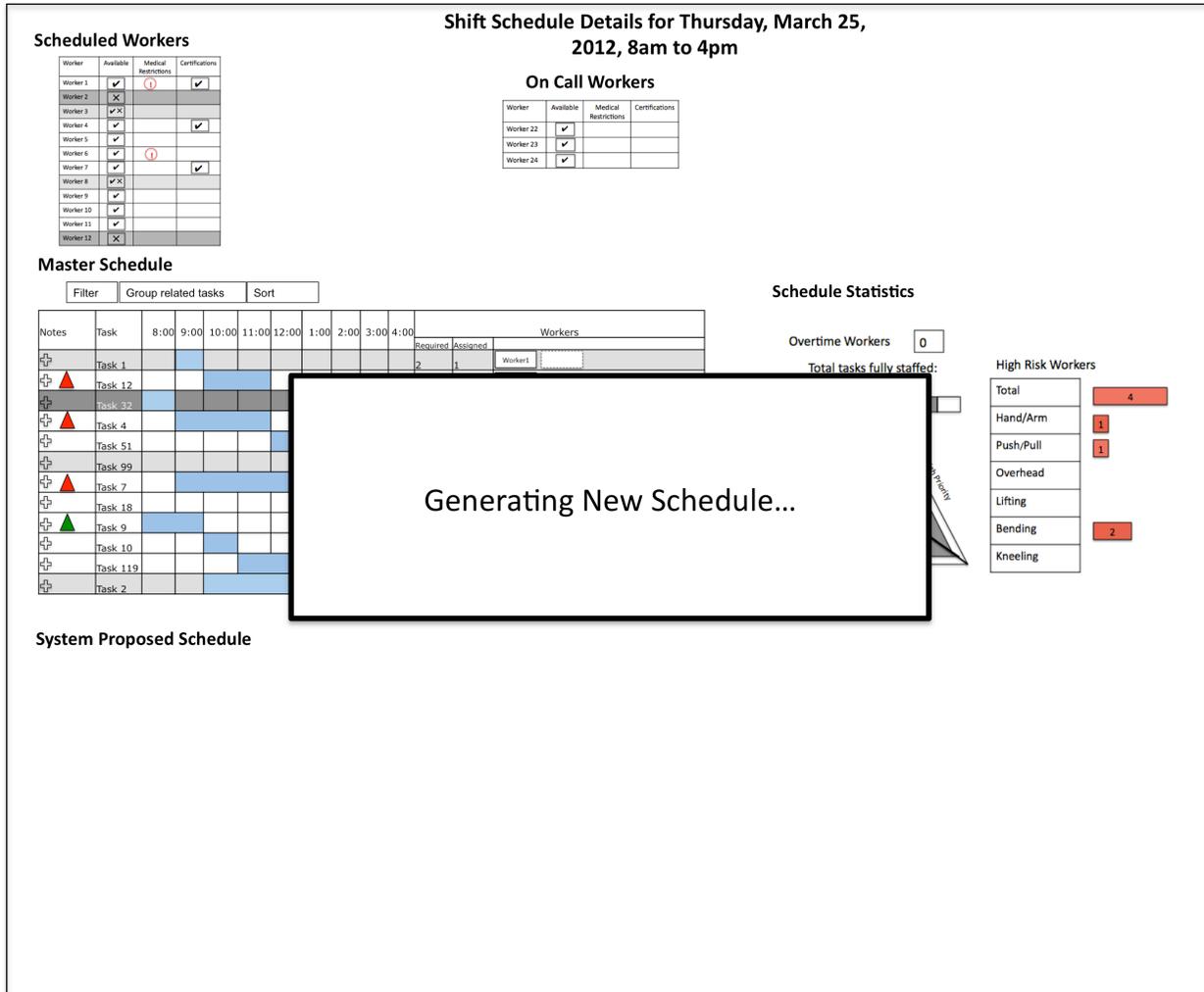
Figure 5.3: Dialog Displayed While Planning Algorithm is Executing

5.5   CHAPTER SUMMARY

The automated planner is an essential component of the decision support tool developed in this thesis. The planner in the tool currently searches through the solution space to try and find a satisfying assignment, and in case of no satisfying assignment, returns the best solution found before failure was detected. To traverse through the solution space, heuristics are employed for ordering variable selection. Although the algorithm performs well for a problem size of a typical shift (many scenarios take less than one second, some need a few seconds), it takes too long for larger problem sizes. In addition, in situations when a complete feasible assignment is not present, assignments that staff more tasks are likely to be found if more of the solution space is traversed. Furthermore, in the planning option where the automation suggests spare workers to be brought in, solutions that bring fewer spare workers can also be found with improved search space traversal. As the tool matures, the planning algorithm would also be developed further to find better solutions in a short span of time. In the next chapter, I describe the methods used to evaluate the entire system as well as the results of those evaluations.

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CHAPTER 6: SYSTEM EVALUATION

This chapter describes the process of evaluating the system described in Chapter 4. While developing the tool, the focus was to employ an iterative design process, which consists of several stages of cycling between prototyping and usability testing. In this process, feedback from the evaluation of a stage informs the prototype design of the next stage, and with each stage, the fidelity of the prototype increases.

After the requirements analysis (described in Chapter 3), several low-fidelity paper prototypes were generated. The paper designs were analyzed using usability heuristics and then combined into a single PowerPoint prototype. After a heuristic evaluation of the PowerPoint prototype by human factors researchers at the MIT Humans and Automation Laboratory (HAL), I conducted pluralistic walkthroughs [65] at Boeing's manufacturing operations. The feedback from these pluralistic walkthroughs was used to further refine the design. Finally, the tool was developed into a prototype on an Android tablet and cognitive walkthroughs were conducted to evaluate this prototype and develop it further. Figure 6.2 illustrates the complete development process. In the next sections, I explain the pluralistic walkthrough and cognitive walkthrough techniques, and also detail how I used these techniques to evaluate this tool.

6.1 PLURALISTIC WALKTHROUGHS

The pluralistic usability walkthrough is a focus group that consists of representative users, members of the product team and human factors experts to analyze each element of an interface.

In a pluralistic walkthrough, product developers go through an example scenario, presenting the interface screens in the same order as they would appear to users; the team discusses each screen element [65]. Pluralistic walkthroughs are widely used, particularly during early phases of the design process. Including users, developers and human factors professionals brings a lot of different perspectives and yields useful feedback.

Several pluralistic walkthroughs were conducted during a visit to Boeing Commercial Airplanes (BCA) operations and Boeing military operations in Everett, Washington and Seattle, Washington respectively. The walkthroughs all consisted of a product developer (the author of this thesis), a representative from the human factors and ergonomics division of Boeing Research and Technology (BR&T), and various representatives of the user population.

Currently, shift supervisors at Boeing (and many other manufacturing plants) only use paper charts and best judgment to re-plan worker-task assignments in case of last-minute unexpected worker absences. The purpose of the walkthroughs was to understand whether the decision support tool would effectively serve as an aid to shift supervisors who had never used technology in the decision-making process, and if there was any missing functionality in the tool. PowerPoint prototypes of the design were presented to the participants of the walkthrough in order to understand whether the tool captured all functionality required in a real production environment.

The participants together went through a complete absence recovery scenario in which the shift supervisor discovers a worker is unavailable, invokes the automation to re-plan worker-task assignments, and then finally reviews the results of the planner. I discuss the results obtained from pluralistic walkthroughs featuring various user representatives.
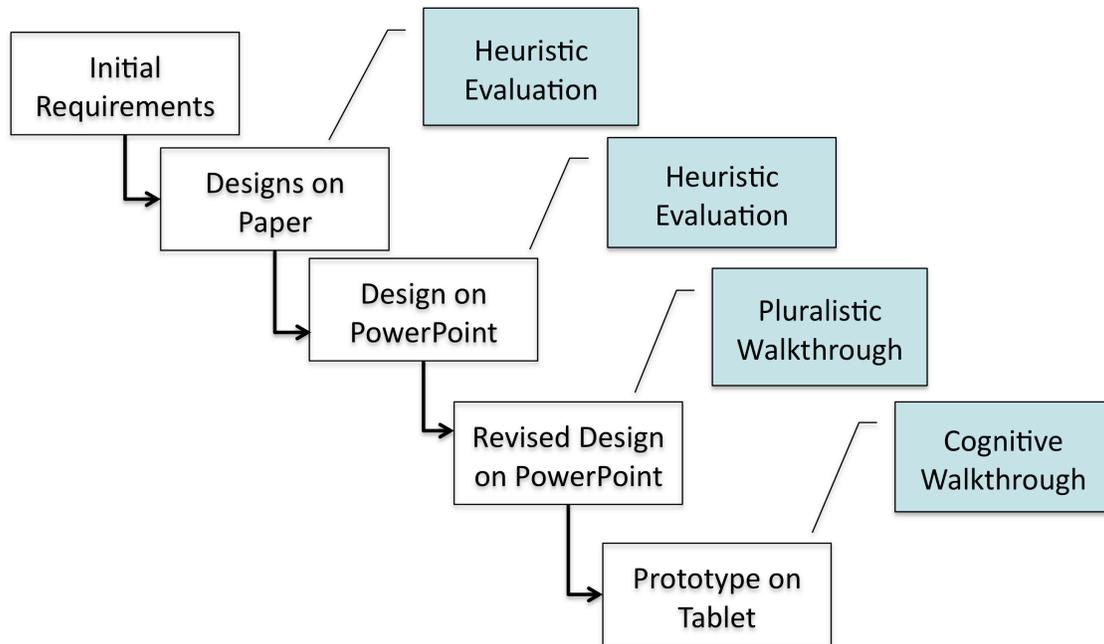
Figure 6.1: The Design Process Used in the Development of this Tool

6.1.1 INDUSTRIAL ENGINEERS FOR 787 OPERATIONS

The first walkthrough included two senior members of the Industrial Engineering (IE) department in the 787 aircraft division that is responsible for the final assembly of the Boeing 787 Dreamliner, a long-range, mid-size wide body jet airline. The primary responsibility of these individuals is to generate the original worker-task assignments that are then executed on the assembly line floor. They have interacted extensively with production personnel including supervisors on the shop floor and thus understand the complex decisions that have to be made in the dynamic shop environment. The Industrial Engineers (IEs) helped me sensitize some verbiage I had used in initial designs to be more acceptable to workers on the shop floor. For example, to describe that a worker had medical restrictions due to injury related compensation or light duty history, in the first few iterations, I had simply decided to display details of this

compensation or light duty history. After this walkthrough, I changed it to instead be represented as generic medical restrictions (such as "no lifting") without disclosing sensitive information such as compensation filing (Figure 4.2).

6.1.2 SENIOR IT LEADERSHIP FOR BOEING COMMERCIAL APPLICATIONS

The user representatives for the second pluralistic walkthrough were two senior managers from Boeing's IT department responsible for designing systems and technology for all of BCA. These managers have significant experience developing a wide range of systems for production scheduling. During the walkthrough, the managers highlighted some of the challenges of implementing systems for the shop floor including an inherent distrust of technology. This insight led me to push further for ways to increase the shift supervisors' trust in the system for the next design iteration. To convince the supervisor that he/she was in complete control of the system, I made the decision to only suggest a new schedule to the shift supervisor with schedule metrics and leave it up to him/her to accept or reject the automation's suggestion (Figure 4.9).

6.1.3 SENIOR MANAGER (AND FORMER SHOP LEAD) OF WORK SCHEDULING FOR 777 OPERATIONS

In the third walkthrough, I interacted with a senior manager in charge of work scheduling who had also previously worked as a lead on the production floor of Boeing's 777 manufacturing operations; the 777 is the world's largest twinjet. This walkthrough was the most insightful in understanding the large number decisions shop managers have to make on the floor. Before this walkthrough, I had not included any notion of skills in our system, neither in the initial task

analysis (Chapter 3), nor in any prior design. However, skills and certifications are important pieces of information, which must both be displayed to the user and be taken into account in the planning algorithm (Chapter 5). Further, this walkthrough also informed us of the importance of allowing the shift supervisor to input the list of workers he/she prefers and does not prefer for each task (Figure 4.6). Taking such input while executing the re-plan allows for increased collaboration between the human and the automation and also ensures that the shift supervisor still feels in control.

During this walkthrough, another important functionality that was suggested was the inclusion of task workability indicators and general free text notes associated with tasks. There are often situations during shifts in which certain tasks may not be workable the day of the shift due to uncontrollable factors such as missing parts or an incomplete preceding task from a previous shift so it's important for managers to see what tasks are not workable and why. Apart from the workability indicators, shift supervisors also want to know the reason behind a task being high priority. For example, a task from a previous shift that did not meet quality standards may be a high priority in the present shift. As a result of these requirements, I incorporated a generic color-coded notes associated with each task that could give the shift supervisor the required information on demand (Figure 4.4).

As ergonomic risk is not incorporated currently in any of Boeing's planning or re-planning activities, the manager felt very optimistic about the potential of the tool. He firmly agreed with the idea that it was essential to include ergonomic risk in any tool that assigns workers to tasks and this inclusion would be an important step in increasing worker safety in manufacturing environments.

6.1.4 INDUSTRIAL ENGINEERS IN 777 BODY STRUCTURES DIVISION

The 777 is one of the oldest production lines in BCA and is one of the programs that has sustained a large number of worker injuries over the years especially in the body structures division. The final walkthrough at BCA consisted of IEs from the 777 body structures division. These IEs were also especially pleased to see that I had recognized that ergonomic risk should be an important component of the decision to assign workers to tasks on the shop floor.

6.1.5 INDUSTRIAL ENGINEER FOR P-8 MILITARY OPERATIONS

Apart from gaining considerable feedback from management in the commercial operations, I was also able to conduct a pluralistic walkthrough where the user representative was an Industrial Engineer from Boeing's military division. The pluralistic walkthrough included an Industrial Engineer responsible for generating initial task schedules for the manufacturing of the Boeing P-8 Poseidon, a military aircraft being developed for the United States Navy. This particular IE is not only responsible for task scheduling for the P-8 production line, but is also leading initiatives in the Boeing military division to utilize technology for building dynamic visualization tools to view the state of each aircraft as it is being built, as well as comprehend the status of task staffing during shifts in real-time at any point during the production process. The IE is also conducting a new pilot program to incorporate some of these technologies in the production.

Although this tool being piloted does not include any provisions for worker absence recovery and schedule re-planning, the IE has a thorough understanding of the production environment and the important pieces of information that are required by the leads on the shop floor. The feedback received from this walkthrough was that the tool captured most of the major information required to make decisions on the floor. While the IE was not sure how useful the

tool would be in shifts with only ten or fewer workers, he was certain that the tool would be beneficial in control stations that had twenty to thirty people per shift such as stations in the final body join divisions of various aircrafts since the re-planning problem is especially complex in these scenarios. The IE also expressed interest in incorporating components of the display and planning algorithm from this system in the visualizations he had been developing.

6.2 COGNITIVE WALKTHROUGHS

The cognitive walkthrough is a widely used method for evaluating the usability of a system. Cognitive walkthroughs focus on the ease of learning by exploration in an interface rather than by formal training [66]. A cognitive walkthrough consists of a representative user being guided through a test scenario that covers the main capabilities of the system. The user is asked to perform several tasks as a part of the scenario and to gather information from the interface. Observing the interactions of a user with the interface identifies potential flaws in the design. Since the user has never worked with the interface before, the method is useful to test the learnability of the interface. Moreover, by selecting the tasks carefully, a cognitive walkthrough can help assess how well the interface was able to comply with the generated functional and information requirements (generated using the hCTA process described in Chapter 3).

6.2.1 WALKTHROUGH PROCESS

For the purpose of the cognitive walkthroughs, an interactive prototype was developed on a Google Nexus 10 Tablet, a 10.1-inch touch-screen device running the Android operating system. The device had 16 GB internal memory and 2 GB RAM, and utilizes a dual-core ARM Cortex-

A15 processor. A tablet device was selected since smaller mobile devices are more useful in a shop floor environment than laptop or desktop computers. In addition, 10-inch tablets are particularly suited for this problem since they are big enough to be able to display all the required information, which smaller tablets would not be able to achieve. Lastly, the Android OS is an open source system leveraging a large amount of open source code freely available.

The prototype included all the elements of the interface described in Chapter 4 with a subset of IRs implemented. Table 6.1 lists what IRs each element of the display incorporated. Cognitive walkthroughs were conducted during a visit to BCA operations in Charleston, South Carolina. These walkthroughs consisted of interactions with ten representative users, all of who were leads and managers on the production floor. Since we were only able to get 15-20 minutes with every individual (or in some cases a group of two individuals), complete cognitive walkthroughs were infeasible. Instead, I demonstrated the tool to each user by walking them through a small worker absence recovery scenario and showcased each element of the interface (interactions related to IRs that were not implemented (Table 6.1) were explained qualitatively in the context of the scenario). During the demonstration, I asked them questions about the various elements of the display to gather feedback about the tool. Some users, who had a few more minutes to spare after the demonstration interacted with the tool while I observed their interactions.

After the demonstration, I requested the users to fill a short questionnaire about the interface. The questionnaire consisted of three main parts, two of which included questions with quantitative responses on a 7-point scale and one that included fields for written qualitative feedback. The first part of the questionnaire included ten questions about the usefulness of the tool in production for re-planning tasks and managing ergonomic risk, as well as the perceived

ease of use and training required to learn the software. The second part consisted of four

questions about the quality of the display elements. Finally, the third part tried to gather

qualitative feedback that may have been missed during the interactive demo. The usability

questionnaire used for the process is included in Appendix B.

Table 6.1: IRs Implemented in Prototype for Cognitive Walkthrough

Display Configuration	Configuration Element	IR's Satisfied
Information Display Configuration	Worker Display	1,2,3,4,5
	Master Schedule	6,7,8,10,11,14,15,17,19,20
	Schedule Statistics (Master Schedule)	21,22,23,24
Schedule Review Configuration	Proposed Schedule	25,28,29,30
Schedule Review Configuration	Schedule Statistics (Proposed Schedule)	31,32,33,34

6.2.2 QUANTITATIVE RESULTS

All ten subjects I interviewed believed the tool has high potential to be useful in production

scheduling. The average rating to the prompt, "This software can be useful in production

scheduling." was 6.4 (on a 7-point scale). The questions that required appraising the ability of the

tool to manage ergonomic risk and prevent worker injuries also mostly received high scores

(average 5.7 and 5.8 respectively).

In terms of gauging the tool's simplicity and ease of use, the rating for the prompt to

assess the software's complexity was low (average 2.7), the rating for the prompts related to its

ease of understanding and simplicity was high (average 5.7 and 5.3 respectively). These results

are illustrated in Figure 6.2. The questions about the requirement of formal training and technical

help to operate this software on the shop floor received average ratings of 4.8 and 4.6 respectively.
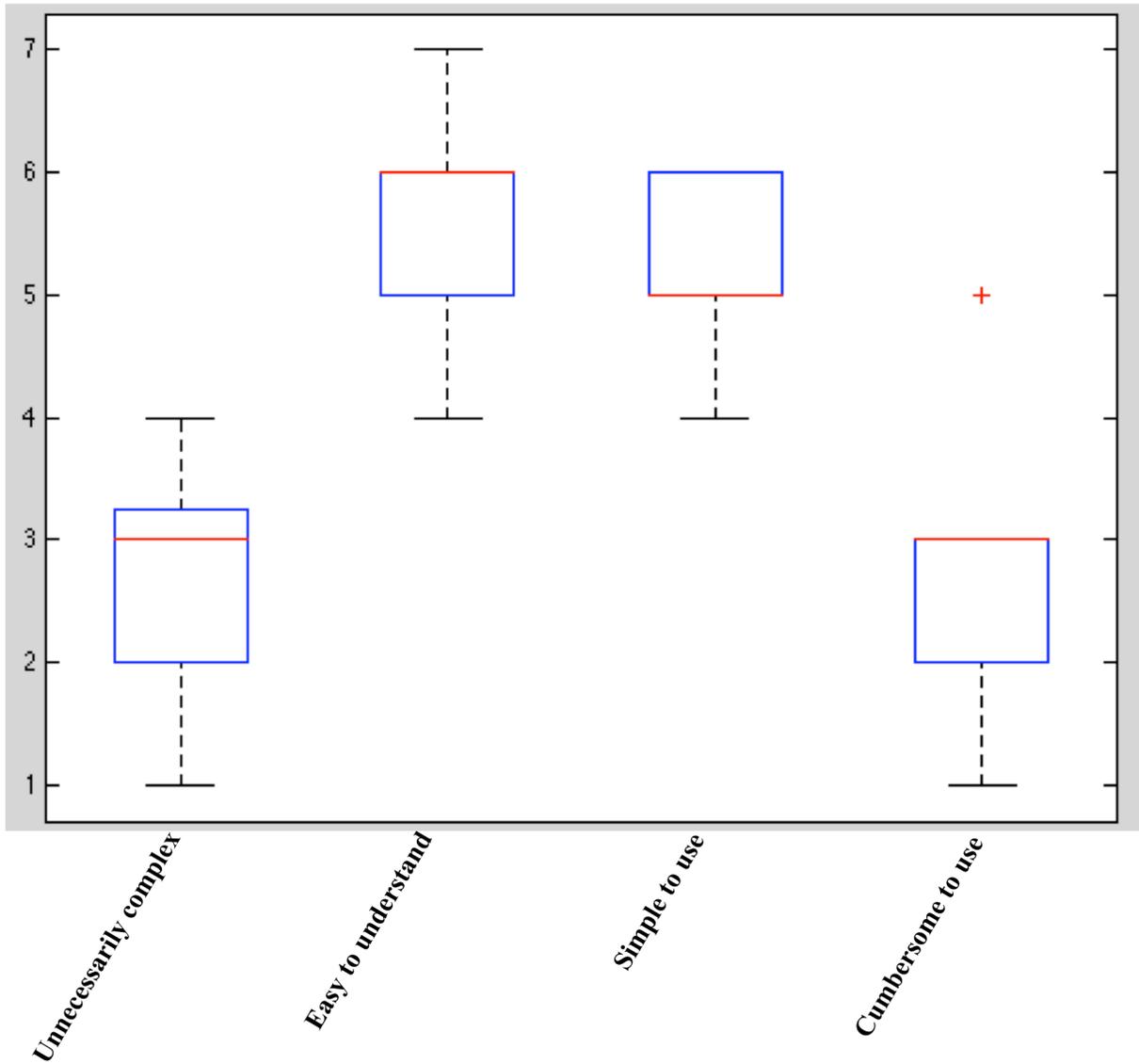
Figure 6.2: Box Plots of Questionnaire Responses Related to Perceived Simplicity and Ease of Use

All prompts from part II of the questionnaire that appraised the quality of the display

elements received a high to very high rating. On average, the colors of the screen were rated very simple (6.2), the sequence of screens logical (5.5), the flow of information clear (5.6) and recognizing functions of the display very easy (6). Box-plots of responses from these questions are illustrated in Figure 6.3.
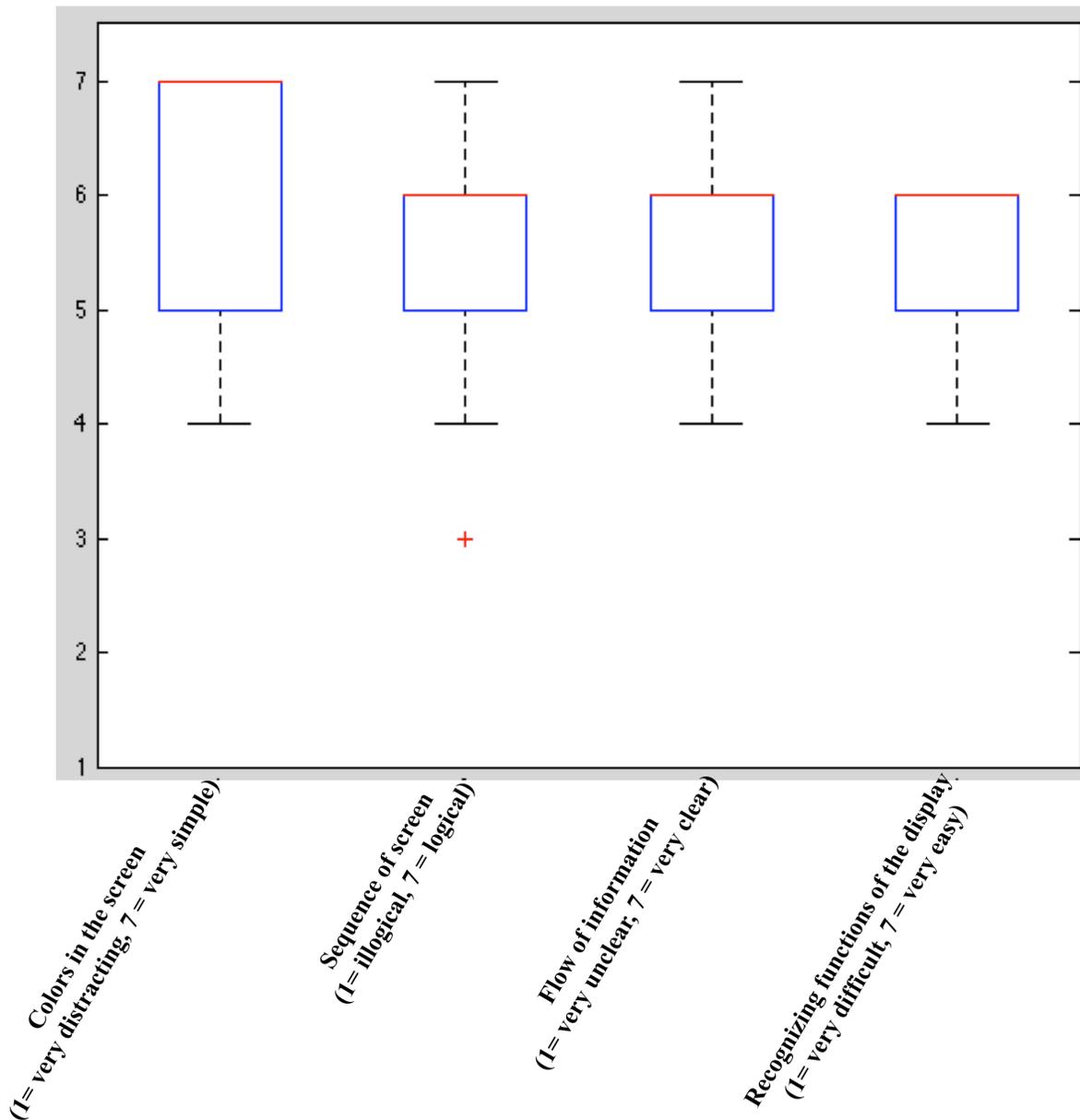
Figure 6.3: Box Plots of Questionnaire Responses Related to Quality of Display Elements

6.2.3 QUALITATIVE FEEDBACK

Through the cognitive walkthrough, qualitative feedback was also received, which can be used to further enhance the tool. Many shift supervisors voiced that a closely tied issue with scheduling is worker certification management, and, they suggested that along with offering the ability to view a worker's certifications, the tool should also include alerts and indicators to indicate when a worker's certifications are about to expire or have already expired.

Another piece of qualitative feedback that was received recurrently was that along with the ability to view certified workers for each task and the capability to specify preferred workers for each task while re-planning, an option should be included to view workers who are not only certified but also skilled in a particular task (e.g. if they have performed a task before). To populate this list of skilled workers, a suggestion received was to incorporate the ability to store feedback of how well a worker performed the task after the task had been completed; this feedback could then be used in future to assess which workers are particularly skilled in each task.

One shift supervisor requested the inclusion of abilities to plan two or three days ahead and not just during the shift since often times supervisors are aware of workers' unplanned absences a couple of days in advance. Moreover, the paper schedule provided to them is based on an aircraft specific timeline; some control stations received planned schedules for three days while some for seven days. Hence, a feature requested was the ability to view all the shifts in the planned schedule to facilitate re-planning further in advance.

Another supervisor suggested that apart from just providing the capability to view details of worker medical restrictions, the tool should include the restrictions as part of the planning algorithm to ensure that workers who have restrictions in any of the predefined ergonomic risk

categories are not assigned to tasks with any element of risk in the restricted category.

Two pieces of qualitative feedback about the re-plan flow were received. The first was an affirmation of the part of the flow that allowed supervisors to manually override the assignments suggested by the automation. The supervisor was able to identify that the feature is particularly useful in situations when the proposed assignment is close to acceptable as instead of re-planning entirely, the supervisor could make manual changes and view results instantaneously. The second piece of feedback suggested that for each task, there should be an option to collectively enter all the currently scheduled workers as preferred workers instead of having to manually add them individually. This would aid in situations where the supervisor wants the currently assigned workers to stay with the original assignments.

With regards to the quality of the display, most supervisors liked the use of colors and the information flow. Two supervisors commented that they would like either the font on the screen to be increased or have the ability to zoom into the screen. Another suggestion received was that the ergonomic risk numbers themselves were not very informative. More useful than the numbers would be a graphical visualization depicting the progression of a worker's risk exposure as a result of performing various tasks in the shift.

Overall, all users felt quite optimistic about the tool. The shift supervisors I spoke with belonged to different control stations of the assembly line. Stations that had a lot of repetitive movements and awkward postures are concerned more with ergonomic risk exposure. Stations that are perpetually short on workers focus on ensuring adequate task staffing. While the former saw more applicability of the tool to manage ergonomic risk and less to reduce task delays, the latter focused more on the benefits related to re-planning during worker absences.

6.3   CHAPTER SUMMARY

In this chapter, I described the steps undertaken to evaluate the tool. The major evaluations

consisted of pluralistic walkthroughs and cognitive walkthroughs through extended

conversations with individuals at Boeing. Through these evaluations, I was able to accumulate

feedback about the display, gauge missing functionalities and further refine the interface

elements. Both the pluralistic walkthroughs and the cognitive walkthroughs yielded positive

results about the usefulness and applicability of the tool in real-time production environments.

CHAPTER 7: CONCLUSION

7.1 THESIS SUMMARY

The focus of this thesis was to develop a decision support tool to manage worker absences in a dynamic production environment, while also mitigating cumulative ergonomic risk exposure to workers.

The problem of worker absence recovery is important because worker absences cause a significant disruption to production schedules. How to manage absences, right before or during shifts, is a complex decision that is currently almost exclusively handled by human judgment without leveraging technology. Since the desired outcome of worker absence recovery is highly dependent on the dynamic situations on the shop floor and the preferences of shift supervisors, there is no single solution that can work for all situations. Thus, the objective of the tool developed through this thesis was to serve as an aid to the shift supervisor considering both objective constraints and subjective supervisor preferences to produce a work schedule that can staff the maximum number of tasks.

An important component of this tool is the inclusion of ergonomic risk, both in the display as well as the planning algorithm. There is a growing concern in the manufacturing industry regarding Work-related Musculoskeletal Disorders (WMSDs). Worker-task assignments that do not take into account ergonomics risk exposure can lead to these repetitive stress injuries over time. As a result, any system that plans or re-plans worker-task assignments, including systems that are used for dynamic workforce scheduling, must take into account the ergonomic

risk that workers are subjected to due to the tasks they perform in the given shift. The decision support tool's visualization includes clear indicators of each task's ergonomic risk, each worker's cumulative ergonomic risk as a result of performing tasks in the shift, and a configural display showing the high-risk workers in a schedule. While re-planning, shift supervisors have the option to constrain the ergonomic exposure such that each worker's cumulative exposure does not exceed a given threshold, which results in additional constraints being added to the planning algorithm.

Through the various chapters, I described the process of designing the tool starting from the requirements analysis to details of each component of the visualization, as well as the planning algorithm that powers the display. Evaluations of the system were conducted through pluralistic walkthroughs and cognitive walkthroughs.

The requirements analysis was conducted using the hybrid Cognitive Task Analysis method (hCTA), a technique useful for generating information and functional requirements for novel displays. The result of this process led to the design of the decision tool visualization. The resource allocation algorithm that generates new worker-task assignments given the input parameters was implemented as a Constraint Satisfaction Problem (CSP). The resulting system (interface plus algorithm) was built iteratively starting from low fidelity paper prototypes to higher fidelity PowerPoint designs and then finally a tablet-based display. At every iteration, comprehensive evaluations including heuristic evaluations, pluralistic walkthroughs and cognitive walkthroughs were conducted to ensure that the system would be usable in real production scenarios.

The results thus far have been optimistic. During the pluralistic walkthroughs, all representative users agreed with both overarching themes of this tool, that is, dynamic worker-

task assignments and ergonomic risk management. Through interactions with subject matter experts, these walkthroughs also helped in identifying certain usability concerns and missing functionalities. The cognitive walkthroughs involved discussions with representative users who make re-planning decisions everyday. Everyone agreed that the tool would be useful for production scheduling. Through conversations and a usability questionnaire, both qualitative and quantitative feedback was gathered.

7.3   FUTURE WORK

7.2.1 SYSTEM EVALUATION

Since the system was primarily evaluated using heuristic evaluations, pluralistic walkthroughs and cognitive walkthroughs, the system is yet to be formally evaluated in real production environments. In the short term, the next step in this research would be to initiate a pilot study to compare the system with the current methods used to create schedules (manual construction using paper and best judgment). Comparison could be using objective criteria such as production rates and task delays, as well as subjective evaluations by shift supervisors. Since ergonomic risk is not incorporated in current scheduling, no immediate impact on cumulative risk exposure can be measured. However, a longitudinal study could measure the impact of using the tool on both production efficiency, as well as worker injuries.

7.2.2 INTERFACE DESIGN

During the cognitive walkthrough (Chapter 6), several suggestions were made about the interface and its various elements. Possible future work would be to investigate each suggestion and assess

the utility of incorporating the suggestion into the interface design.

7.2.3 PLANNING ALGORITHM

The planning algorithm used in the tool right now (Chapter 5) is a CSP, which searches through the solution space to find a complete satisfying assignment, and when no complete assignment is present, returns the best assignment it encountered before realizing infeasibility. The algorithm was tested by first generating data for a typical production shift, and then simulating several scenarios. In terms of running time, the algorithm's performance was acceptable for the problem size of a typical shift. However, for large problem sizes, the algorithm takes too long to terminate. Thus, for shift environments that have a large number of tasks and workers, more efficient algorithms would be required. Furthermore, since, in cases when no complete feasible assignment is present, the algorithm simply returns the best solution it encountered before realizing failure, the resulting assignment in these cases is often not optimal. Also, in the planning option where the automation suggests spare workers to bring in, the algorithm does not effectively minimize the number of spare workers brought in. Hence, more sophisticated algorithms should be considered to efficiently find more optimal assignments.

Similar to many scheduling problems, the resource allocation problem considered by the planner has a structure that could be modeled as an Integer Linear Program (ILP) [67]. There are several optimized solvers available for ILP's such as ILOG CPLEX Optimizer [68], which are usually able to search through the solution space faster and produce better results. While CSP's and ILP's are deterministic algorithms, some other solutions to such constrained scheduling problems include heuristic based solutions such as tabu search [69], or probabilistic methods such as Rapidly exploring Random Trees (RRT) [70].

7.2.4 EXTENSIONS TO OTHER DOMAINS

We designed this tool to be generic enough to be easily customized and extended for other domains apart from manufacturing. Although one requirement was to mitigate ergonomic risk in manufacturing environments, the tool is amenable to situations where ergonomics is not a primary consideration and other types of constraints could be incorporated. Essentially, in any situation where there is a shift consisting of workers, tasks and the possibility of dynamic events occurring during the shift, the tool can be used to aid a shift supervisor quickly determine the way to get the most number of tasks accomplished under a set of complex constraints. While there is a proliferation of scheduling technology in various domains, all of it focuses on the initial planning problem of deciding staffing of shifts and allotting workers to tasks before the shift starts. A significant advantage of this tool is that it is simple to understand and features a low cognitive overhead. Thus, shift supervisors would be able to adapt to it without management investing a lot of resources to transition to the software.

To understand the applicability of the tool to other domains, I spoke with the manager and assistant manager of MIT's custodial service department. The custodial service staff in public buildings has very similar problems of assigning workers to tasks related to cleaning building spaces. In general, the managers held the opinion that the tool would be applicable to their domain. They were also able to identify ways to customize the tool for their application. For example, one of their suggestions was that their shift supervisors actually liked few options and small problem sizes while re-planning. Hence, instead of having three different options to re-plan, they recommended that the software plan with existing workers first and then allow re-planning to staff the remaining tasks.

Some other domains that the research in this thesis could be extended to include:

- Healthcare- Hospitals require nurses and doctors to be assigned to tasks across shifts, with constantly varying staff availability so this contingency management tool could be useful for that purpose.

- Transport and logistics- Logistics companies often face the real-time worker scheduling problem when drivers do not show up and they need to re-assign the affected routes.

- Food Services- Restaurants and other similar dining service companies need to staff their employees to tasks in shifts, and worker absences are very common in this industry.

- Event Management- Event planning and management requires many tasks and staff to accomplish those tasks. Real-time re-allocation of workers to tasks is often required in these situations.

APPENDIX A: ERGONOMIC RISK SCORE CALCULATIONS

For the purpose of quantifying ergonomic risk to workers in this tool, Boeing Research and Technology (BR&T) developed and patented a method using data from their manufacturing plants [19]. In this method six main categories that account for 90 percent of injuries in aircraft production are identified, namely Hand/Arm, Push/Pull, Bending, Kneeling, Lifting and Overhead stress. For each category the following pieces of information are used to is calculate the ergonomic risk scores:

1. Hand/Arm- grip type, force and count.

2. Push/Pull- type of push/pull, force and count.

3. Bending- number of times the torso is bent forward greater than 45° and the total amount of time for which the torso is bent forward greater than 45°.

4. Kneeling- the total amount of time kneeling is required.

5. Lifting- lifting zone (primary/ modified primary/ modified secondary), amount of weight lifted each time and number of times weight lifted.

6. Overhead- number of times the hands are raised above the head and the total amount of time for which the hands are raised above the head.

BR&T analyzed the tasks performed in the production of the 787 Dreamliner in two manufacturing plants from two separate locations: Everett, Washington and Charleston, South Carolina. The data from the two locations was blended to mitigate potential bias due to location,

and then the distribution for each category was learned using a software known as EasyFit [71].

For most tasks, the ergonomic risk value in each category is a number between 0 and 1.

However, in some extremely high-risk tasks, the numbers can be as high as 67. Using this data,

the probability distributions of ergonomic risk scores were generated for each category; these

distributions are listed in Table A.1.

A worker's cumulative risk for a given shift is determined by the tasks he/she performs in

the shift; for each category, the worker's risk exposure is the sum of the risk values of the tasks

he/she is assigned to. A worker is considered to be at high risk during a shift if his/her

cumulative risk in the shift exceeds 1 in any category.

Table A.1: Distributions for Ergonomic Risk of Tasks in Each Category

Ergonomic Metric	Distribution	Mean	Standard Deviation	Other Parameters
Overhead	Weibull	0.341	0.701	a = 0.531, b = 0.189
Hand/Arm	Weibull	0.050	0.072	a = 0.711, b = 0.040
Lifting	Weibull	0.179	0.580	a = 0.392, b = 0.051
Push/Pull	Weibull	0.130	0.384	a =0.416, b = 0.043
Bending	Weibull	0.176	0.348	a =0.548, b = 0.103
Kneeling	Gamma	0.109	0.150	a =0.524, b = 0.207

APPENDIX B: USABILITY QUESTIONNAIRE

Part I

	Question	Circle One Answer (1 = strongly disagree, 7= strongly agree)
1.	This software can be useful in production scheduling.	1 2 3 4 5 6 7
2.	This software is unnecessarily complex.	1 2 3 4 5 6 7
3.	This software is easy to understand.	1 2 3 4 5 6 7
4.	This software is simple to use.	1 2 3 4 5 6 7
5.	This software would require technical help to be used on the shop floor.	1 2 3 4 5 6 7
6.	This software can help reduce worker injuries.	1 2 3 4 5 6 7
7.	The software can help manage ergonomic risk to workers.	1 2 3 4 5 6 7
8.	This software will require a lot of formal training before it can be used on the shop floor.	1 2 3 4 5 6 7
9.	This software can help make scheduling on the shop floor easier.	1 2 3 4 5 6 7
10	The software is cumbersome to use.	1 2 3 4 5 6 7

Part II

	Question	Circle One Answer (1 = strongly disagree, 7= strongly agree)
1.	The colors in the screen are (1 = Very distracting, 7= Very simple)	1 2 3 4 5 6 7
2.	The sequence of screens is (1 = Illogical, 7= Logical)	1 2 3 4 5 6 7
3.	The flow of information is (1 = Very unclear, 7 = Very clear)	1 2 3 4 5 6 7
4.	Recognizing the functions of the display is (1 = Very difficult, 7 = Very easy).	1 2 3 4 5 6 7

Part III

What are some aspects of the display that you liked? _____

_____

What are some aspects of the display that need improvement? _____

_____

Other Comments? _____

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