Operational Efficiency through Resource Planning Optimization and Work Process Improvement

by

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Abstract

This thesis covers work done at National Grid to improve resource planning and the execution of pipeline construction and maintenance work carried out at the yards. Resource Planning, the art of picking the right jobs for the right days and assigning the right crews to them while meeting constraints of regulation, customer service, and safety at the minimum cost is an extremely difficult problem. This is exacerbated by the fact that there needs to be enough slack in the system to deal with one or more pipeline leaks that may be called in. At the execution stage, when the jobs are carried out by crews, the lack of standardization in work processes dealing with granting and approval of overtime, productivity tracking, data collection, and imperfect alignment of incentives make it difficult to get the best work from the crews. These issues lead to high levels of overtime at yards, which are the major source of costs for gas operations for the company.

We propose the Resource Allocation and Planning Tool (RAPT) accompanied by yard level process management to improve operations performance. To automate short term planning, RAPT includes a two stage stochastic optimization model to perform job scheduling and crew assignment in the presence of a variable number of emergency leaks, thus creating optimal daily and weekly plans with minimal overtime costs. The tool also serves as a business intelligence platform, providing a companywide view of gas operations efficiency and as a decision aid, enabling management to predict the impact of management policies on field operations.

The execution of work was improved by the creation of new processes for scheduling, crew data entry, overtime approval, incorporating accountability and oversight at multiple levels. This work has enabled more consistent processes, better overtime and productivity management, and the ability to understand and track deviations.

These changes are currently being piloted at yards across the company and the initial results are very encouraging. As a direct result of this work, National Grid has the potential to achieve up to 65% reduction in overtime, saving the company a substantial amount of money.

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1 Introduction

1.1 Overview of National Grid

National Grid, one of the largest investor backed energy companies in the world, is a British multinational with operations in the United Kingdom, Wales and northeastern United States. The company is a utility focusing on electricity and natural gas transmission and distribution, operating 4,300 miles of gas transmission pipelines, 93,800 miles of gas utilities infrastructure, and 71,000 circuit miles of electric utilities infrastructure.

Figure 1: National Grid's UK Electricity Transmission Infrastructure (National Grid Plc, 2011)

1.2 Overview of Electricity Grids

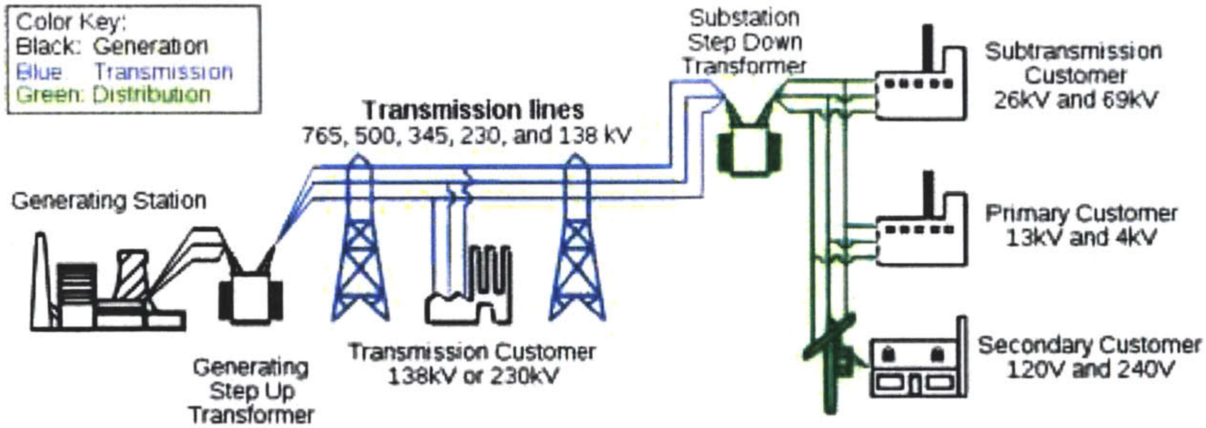

Figure 2: Diagram of Electric Power Generation, Transmission and Distribution

To understand National Grid's business better, we present a brief introduction to the system used for electricity generation and transportation. Figure 2 above illustrates an electricity grid, with its three principal components (Wikipedia, 2012). These are:

1. **Electricity Generation:** Electricity is generated at plants through a variety of means using non-renewable fuels such as coal and natural gas and renewable sources such as wind and solar. These plants are typically large, in order to take advantage of economies of scale and are typically also situated away from densely populated areas. The electric power that is generated is stepped up to a higher voltage (110KV or above) at which it connects to the transmission network. This is done to reduce energy loss in long distance transportation to the end-consumer. A key limitation in the distribution of electricity is that, with minor exceptions, electrical energy cannot

be stored, and therefore must be generated as needed. A sophisticated system of control is therefore required to ensure electricity generation very closely matches the demand

2. **Transmission:** The transmission network is comprised of high voltage lines that move power long distances, sometimes over international boundaries, to the point it reaches the whole sale customer (usually another company that handles electricity distribution to the end consumer). Transmission lines are typically overhead high voltage lines, although in certain areas underground lines are used as well.

3. **Distribution:** Electricity distribution is the final stage in the delivery of electricity to end consumers. Upon arrival at the substation, the power is stepped down in voltage- from a transmission level voltage to a distribution level voltage (less than 50 KV). As it exits the substation, it enters the distribution network. Only large industrial or commercial end-consumers are fed directly from distribution voltages; most utility customers are connected to a transformer, which reduces the distribution voltage to the relatively low voltage (120V, 240V) used by lighting and interior wiring systems.

1.3 Overview of Natural Gas Grids

As in the case of electricity, often natural gas produced at a particular source will have to travel a great distance to reach its point of use. The transportation system for natural gas is analogous to that of electricity, consisting of a complex network of pipelines, designed to quickly and efficiently transport natural gas from its origin, to areas of high demand. There are three major types of pipelines along the transportation route: the gathering system, the interstate pipeline system, and the distribution system (NaturalGas.org, 2011). The gathering system consists of low pressure, small diameter pipelines to transport raw natural gas from the wellhead to the processing plant. The interstate pipeline system (in the US) consists of high pressure pipelines used to transmit the processed gas to the point of distribution. The distribution system, analagous to the distribution network in the electric grid, is where the pressure of natural gas is lowered so that it can be delivered to the end residential, industrial and commercial consumers.

1.4 National Grid's US Gas Distribution

National Grid owns and operates the Transmission and Distribution of electricity and natural gas in various parts of the United Kingdom and the US. This section, like the thesis, focuses on the US Gas Distribution network.

National Grid's Gas Distribution US segment services 3.5 million consumers across the northeastern US in upstate New York, New York City, Long Island, Massachusetts, New Hampshire and Rhode Island (National Grid Plc, 2011). This distribution network is comprised of approximately 58,000 kilometers of gas pipelines and covers an area of approximately 26,400 square kilometers. In the US, with a few exceptions, customers may purchase their supply from independent gas providers, with the option of billing for those purchases to be provided by National Grid. In this case, the independent gas providers buy the gas from the gas producers, and then transport companies transfer the gas over the inter-state pipeline system and deliver it to the local National Grid gas distribution networks.

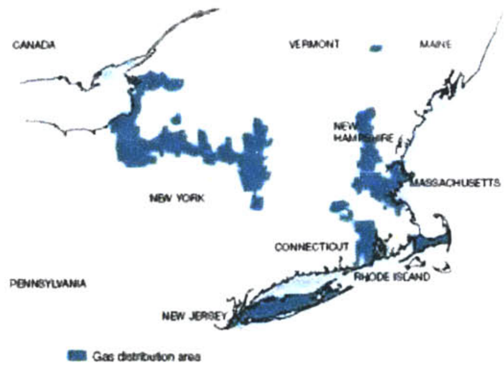

Figure 3: US Gas Distribution Coverage Area

1.5 History of US Operations

National Grid has grown in the US through a series of acquisitions beginning with New England Electric System and Eastern Utilities Associates in 2000, and ending with the latest acquisition of KeySpan Corporation in 2007. There has been effort at the corporate level over the last few years to integrate these different acquisitions under a "One company, one way" strategy, this message as will be shown later does not necessarily percolate down to the different sites where the day-to-day operations of the company are performed. The following is a brief history of the highlights of National Grid's growth in the US (National Grid Plc, 2011).

- 31 March 1990 – **UK:** Electricity industry privatized (National Grid owned by 12 Regional Electricity Companies)
- December 1998 / January 99 - Acquisitions of NEES and EUA announced
- 23 March 2000 - NEES and EUA acquisitions completed
- September 2000 - Acquisition of Niagara Mohawk announced
- 31 January 2002 - Acquisition of Niagara Mohawk completed

- July 2005 - Adoption of National Grid as single name for principal businesses
- February 2006 - Agreements to acquire KeySpan Corporation and Southern Union Company's gas distribution network in Rhode Island
- August 2007 - Acquisition of KeySpan

1.6 Brief Overview of US Gas Operations

This thesis focuses on the US Gas Distribution operations of National Grid. The day to day operations for the US Gas Distribution involves the construction and maintenance of pipelines comprising the distribution grid. It is critical for the company to carry these two operations efficiently, as they are the source of a majority of the expenditures for this division.

National Grid carries out the construction and maintenance of the distribution pipelines at fifty sites, also referred to as yards, across New England and New York. The work done at these yards is driven by the certain key factors- growth, regulatory compliance, maintenance, and emergencies requiring immediate pipeline repairs. Every day at each yard, Resource Planners plan what tasks need to be carried out for the day to fulfill these directives. These tasks are then carried out by the union crews assigned to each yard. The planning and execution of these tasks follow different processes at each yard, and aren't necessarily done efficiently or at the lowest cost. Please see Chapter 3 for a detailed explanation of the processes followed.

In general, in the last few years, utilities have seen a rapid rise in the workload and in the cost of field service activities (Bain & Company, 2011) due to increasing capacity utilization and aging networks, growing demand from customers and regulators for wider range and greater reliability of services, lowered expectations for employee efficiency or engagement, skillset gaps in the workforce in adapting to new technologies and lack of a strong emphasis on measuring and managing productivity.

1.7 Problem Addressed

This thesis covers work done at National Grid to improve resource planning and the execution of pipeline construction and maintenance work carried out at the yards. Resource Planning, the art of picking the right jobs for the right days and assigning the right crews to them while meeting constraints of regulation, customer service, and safety at the minimum cost is an extremely difficult problem. This is exacerbated by the fact that there needs to be enough slack in the system to deal with one or more pipeline leaks that may be called in. At the execution stage, when the jobs are carried out by crews, the lack of standardization in work processes dealing with granting and approval of overtime, productivity tracking, data collection, and imperfect alignment of incentives make it difficult to get the best work from the crews. The major component of the cost of yard operations is the level of overtime, defined as any hours over eight hours a shift worked by a crew member. Overtime is paid at 1.5-2x the regular rate.

Using sophisticated models and standardized processes with accountability, this project improved these sources of inefficiencies at the yards.

1.8 Contribution of the Thesis

One major outcome of this thesis is the optimization of short term resource planning. We automate the complex task of resource planning by the means of a sophisticated tool, the Resource Allocation and Planning Tool. RAPT includes a two stage stochastic optimization model, and powerful analytics tool. It serves three primary functions:

a. Automates short term planning and performs the task of job selection, crew assembly and assignment, to minimize cost in the presence of uncertain resource availability and in the presence of a variable number of pipeline leaks.
b. As an analytics tool, providing a companywide view of US gas operations efficiency, allowing management to ask sophisticated questions about yard operations and gain a deep understanding of operations at a yard, allowing management to perform companywide comparisons for metrics they prefer.
c. As a decision aid, enabling management to predict the impact of management policies on field operations.

The effort to improve the execution of yard operations focused on improving the data collection, realigning incentives and standardizing work processes. New processes were created for scheduling, crew data entry, overtime approval, adding accountability and oversight at various levels. Our work has enabled better overtime and productivity management, and has provided the company the structure for continuous improvement allowing management the ability to understand and track unexpected deviations in their work going forward.

These changes are currently being piloted at a number of yards around the company, and the initial results are very encouraging. As a direct result of work done in this thesis, National Grid has the potential to achieve up to 65% reduction in overtime, saving the company a substantial amount of money.

1.9 Thesis Outline

In the next chapter, we review prior research in the lean operations space, focusing on work done in scheduling under uncertainty, lean processes, and cultural change in the context of a utility.

Chapter 3 provides an organizational assessment of the company, conducted using the three lens analysis as presented by (Carroll, 2002).

Chapter 4 deals with understanding the processes as they were before the work done in this thesis. The processes described cover resource planning, work execution, long term planning and how these processes interact with each other.

Chapter 5 describes the RAPT model, explaining its function and structure in detail. It covers in depth the optimization model and analytic components of the tool. It also describes the process changes made, and the rationale for those changes.

Chapter 6 provides the results obtained by running RAPT, and provides a comparison with the performance of schedules created by a live resource planner. It also describes the pilot in progress and the future of this work at the company.

1.10 Chapter Summary

This chapter provided an introduction to National Grid. We saw that the company, being one of the largest utilities in the US, owns and operates both electric and gas infrastructure. We explored the gas distribution operations of the company in the US, and understood field operations carried out at the fifty independent yards in the company. We also took high level look at the inefficiencies in these processes and examined the impact that the work in this thesis has on mitigating these inefficiencies. The contributions of this thesis are the analytical models and process improvements that lead to a 65% reduction in the majority cost of operations at a yard, i.e. overtime, offering the company substantial cost reductions.

2 Literature Review

There are two critical aspects to the work in this thesis. As explained above- we want to create efficient schedules in the presence of uncertainty, and implement process changes to add accountability and apply these changes in a way acceptable to the current workforce in the company. We examine research in these two principal areas in the sections that follow.

2.1 Efficient Scheduling under Uncertainty

Herroelen (Herroelen, 2005) recognizes a key aspect of the issue that we address in this thesis- creating a schedule under uncertainty. He identifies five approaches to dealing with this problem:

a. **Reactive Scheduling:** Reactive scheduling does not try cope with uncertainty while creating the baseline schedule. Instead it re-optimizes the schedule when an unexpected event occurs. This could be potentially computationally expensive if it requires a full re-scheduling with every new unexpected event.

b. **Stochastic Scheduling:** Herroelen describes a stochastic resource-constrained problem, specifically in the instance of a scheduling problem that aims at scheduling project activities with uncertain durations in order to minimize the expected project duration subject to renewable resource constraints.

c. **Scheduling under Fuzziness:** This approach also looks at a scheduling problem dealing with project activities with an uncertain duration. It takes an interesting approach; the advocates of the fuzzy activity duration approach argue that probability distributions for the activity durations are unknown due to the lack of historical data. While this is not true in our case, we can see that if activity durations have to be estimated by human experts, often in a non-repetitive or even unique setting, management would be confronted with judgmental statements that are vague and imprecise. In those situations, which involve imprecision rather than uncertainty in the occurrence of an event, the fuzzy set scheduling literature recommends the use of fuzzy numbers for modeling activity durations, rather than stochastic variables. Instead of probability distributions, these quantities make use of membership functions, based on possibility theory. In our case, we have sufficient historical data to make reasonable assumptions about the time taken by a job (service time), dealing with uncertain events is the issue that impacts us.

d. **Proactive (Robust) Scheduling:** For project based scheduling, Leus and Herroelen (Leus, 2004) have studied the problem of generating a robust resource allocation under the assumption that a feasible baseline schedule exists and that some advance knowledge about the probability distribution of the activity durations is available. The authors explore the fact that checking the feasibility of a resource allocation can easily be done using maximal flow computations in the resource flow network. As such, the search for an optimal allocation is reduced to the search for an associated resource flow network with desirable robustness characteristics. The authors propose a branch-and-bound algorithm that solves the robust resource allocation problem in exact and approximate formulations and report on promising results obtained on a set of problem instances generated using the problem generator RanGen.

e. **Sensitivity Analysis:** This problem appears to have been generally studied with a specific application towards machine scheduling.

Our work creates a fast and efficient scheduling system that uses stochastic mixed IP multi-period model and with an approximation that had a minimal impact on model performance, we were able to significantly reduce computational complexity. In our case the primary issue not with the length of the jobs being performed but with the random occurrence of jobs (that followed certain distribution derivable from historical data).

Schaefer et al.'s work (A. Schaefer, 2005) examines airline crew scheduling. Airline crew scheduling algorithms widely used in practice assume no disruptions. Because disruptions often occur, the actual cost of the resulting crew schedules is often greater. Schaefer considers algorithms for finding crew schedules that perform well in practice, seeking better approximate solution methods for crew scheduling under uncertainty that still remain tractable. Schaefer introduces a measure for evaluating the performance of crew schedules in practice and shows that, in terms of this measure, solutions produced by an expected cost procedure perform better than solutions produced by a procedure based on a deterministic model.

Keller et al. (Keller, 2009) look at scheduling under conditions where each job being scheduled requires multiple classes of resources. They refer to this problem as the Multiple-Resource-Constrained Scheduling Problem (MRCSP).Instances of MRCSP are found in various places, one example is an operation theatre, where multiple tasks and resources are required to complete one job, i.e. the operation. They develop a two-stage stochastic integer program to determine the optimal schedule for jobs requiring multiple classes of resources under uncertain processing times, due dates, resource consumption and availabilities, and embed Benders decomposition within a sampling-based solution method to solve problems with a large number of scenarios. Our work differs from Keller's in that we aren't interested in solving a large number of scenarios. The major component of uncertainty in our case is Grade 1 Leaks, and for a given yard, the standard deviation and mean of the distribution of these leaks is not very unmanageable given the number of crews and resources available at the yard.

2.2 Process and Culture Change in a Utility

To understand the impact of introducing process and cultural changes to a utility, we look at the case of SembaCorp (Martin-King, 2009) that undertook a transformational two year operational and cultural program to greatly increase its asset utilization. The authors' describe how the company took a two pronged approach to change:

a. A bottom up approach to engaging first line supervisors and the union representatives to encourage engagement and cross-functional collaboration
b. A top down approach to identifying operational improvements that needed to be made

By using this approach the company was able to, within six months, improve their asset utilization as well as availability

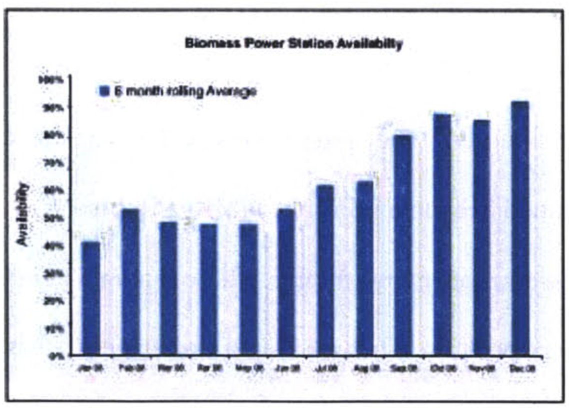

Figure 4: In less than 6 months from starting the project, the availability of the biomass plant almost doubled

We also look at the case of New Jersey's principal utility Public Service Electric and Gas company (PSEG) (Simon, 2009). Through this initiative, this organization with 6,500 employees and a record of 32 fatalities in the previous 27 years achieved an OSHA recordable rate of

1.41 and a lost-workday case rate of 0.33 by 2007. PSEG was a company, with electric and gas operations, where site-specific subcultures had been in place for generations. They undertook a 9-year culture change project to improve their safety record impacting the organization "village by village" tailoring interventions to fit each individual subculture. The second phase focused on issues that needed to be addressed system-wide—leadership, trust, measurements, learning and communications. They felt that their key to a successful culture change, besides the points mentioned, was engaging and empowering union employees in the process and ensuring that their voice was heard.

Bain & Company provide a high level report that looked at dealing with the improvement of field operations at a utility (Bain & Company, 2011) They provide a diagnostic to better understand costs in field operations that span six categories:

1. Volume of jobs, which can be classified as good (e.g., good plans or job designs), potentially avoidable (e.g., modified by field or scheduling) or bad (e.g., rejected by field or scheduling). Job design and work process changes were outside the scope of what we considered in this work.
2. Utilization, which measures a crew's productive hours as a percentage of the total (i.e., actual time spent working contrasted with nonscheduled time, idle time, sick time and holidays). Bain indicated that in a diagnostic conducted by one US utility, an analysis of how crews spent their time revealed that less than 50 percent was spent on actual maintenance or construction work.
3. Work rate, which measures the rate at which employees can complete jobs due to optimization of jobs designs and scheduling.

4. Hourly cost, which analyzes the total cost of labor, including overtime (for in-house work vs. contractors);
5. "Overhead and other," which addresses the costs of supporting non-field activities (e.g., resource planning, dispatch) and non-labor costs (e.g., fleet).

Bain propose six categories of initiatives, highlighted in **Figure 5**. The work in this thesis primarily focuses on crew utilization, work rate, and to a certain extent hourly cost using an integrated approach of sophisticated models and process improvements. In Bain's classification system our work falls into categories 1,4,5,6.

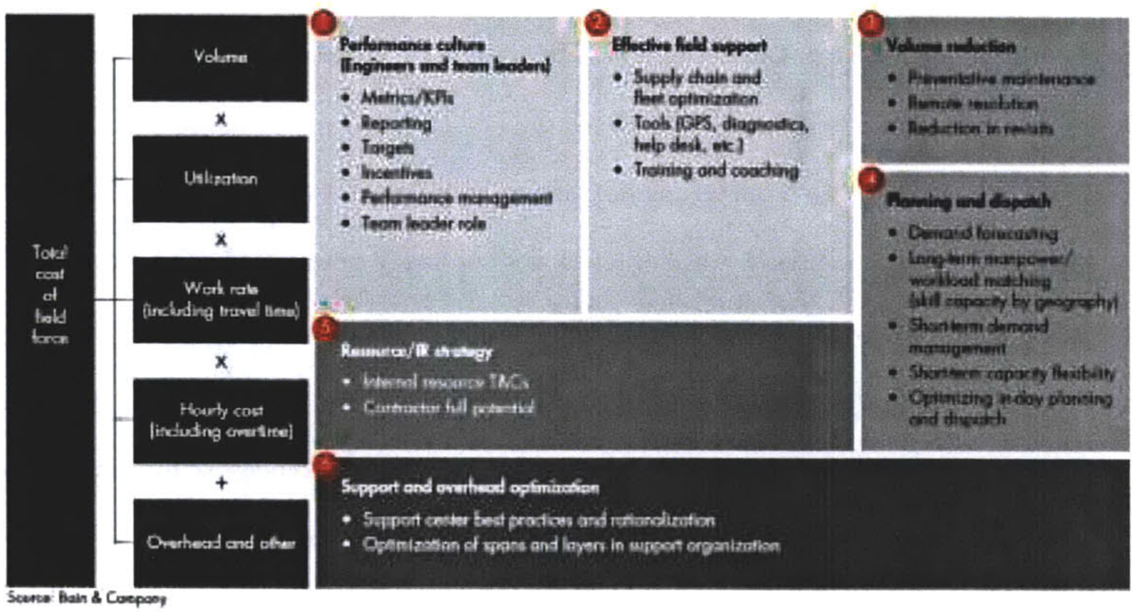

Figure 5: Six categories of high value intiatives to manage yard costs

2.3 Chapter Summary

In this chapter, we look at literature that deals with efficient scheduling under uncertainty and the process of bringing about operational improvements and culture change in a utility. We compare our work with the papers cited, and discuss how our work contributed to the body literature in these fields.

3 Organizational Analysis

3.1 Three Perspectives on Organizational Processes

According to (Carroll, 2002), organizations can be viewed through three lenses: strategic, political and cultural. The strategic design lens is used to analyze the formal structure and organization of the teams in a company, and their goals and purpose. The political lens examines the incentives of the different groups, and their struggles for power. The cultural lens focuses on how the backdrop, i.e. the unstated experiences and artifacts that shape an organization's culture. Using these lenses enables us to better understand the appropriate process to introduce change in a company. The following sections examine National Grid's US Gas Operations through these lenses.

3.2 Strategic Design Lens

The work for this internship was done under the aegis of the Operations Performance Group at National Grid. The charter of this group is quite broad. Projects in this group may be based anywhere in gas operations and are usually initiated based on ideas for operational improvements provided by senior management. Operations Performance group members assigned to a project work closely with the groups in the company where the operational improvement is desired. Their approach to the issue resolution and operational improvements are typically very analytical and involve the introduction of sophisticated models and process improvements. To implement their proposed changes, the operations performance team relies on management and affected group buy-in gained through persuasion and a deep understanding of the operational issues at hand.

This thesis involves changes that affected the Resource Planning group, Resource Management group and the Field Operations. The organization of these groups is in depicted in Figure 6 below.

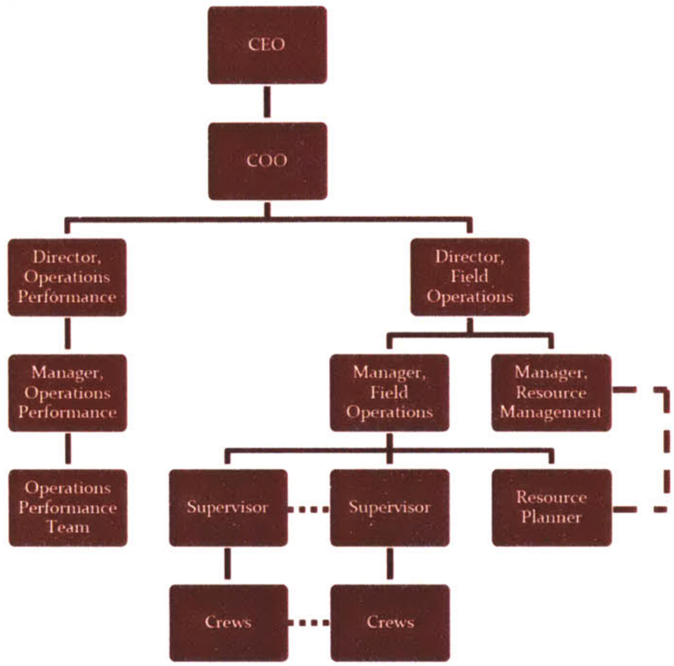

Figure 6: Select depiction of Management Hierarchy

We briefly describe the function of these groups here, for further information, please refer to Chapter 4:

a. **Resource Management:** Resource Management is responsible for the long term planning for the company's gas operations and infrastructure development- it lays out the yearly plans for growth, regulatory compliance, pipeline maintenance and determines the number of workers required. This is a very small group with a single manager who, along with his team, is responsible for creating long-term plans and working with the Resource Planners at the various yards to ensure that they are on target to meet monthly and yearly targets.

b. **Resource Planning:** Resource Planning, unlike Resource Management, handles the daily, and weekly job planning and crew allocation. As previously explained, this process entails deciding which jobs should be done, creating crews out of the workers at a yard, and assigning jobs to those crews. This process is usually carried out on a daily basis, although certain jobs that require customer interaction have to be scheduled much further in advance. Resource Planners are typically allocated to a single yard and directly report to the Field Manager for that yard. They also have a dotted line reporting to the manager in the Resource Management group. The Resource Planners at the company do not directly manage the supervisors or the crews, but provide them with the daily plans, and guide them through any changes to these plans that may occur during the day.

c. **Field Operations:** The Field Operations group is responsible for implementing the plans created by Resource Management. This group comprises of a number of Field Managers, where each Field Manager is responsible for a single yard and all workers in that yard report to him or her. The Field Manager has the ultimate responsibility for the yard.

d. **Supervisors:** Supervisors report to the field manager, and are responsible for managing multiple crews. They allocate overtime to the crews and ensure that the work is completed according to specifications while following the appropriate safety measures.

e. **Crews:** The crewmembers at a yard belong to the union chapter of that yard. The number of crews at a yard depends on the size of the yard, and the region covered by it. Each crew comprises of about 2 or 3 people, who are typically picked by the Resource Planner and Supervisors to work together for that day. The crews actually carry out the execution of the jobs, which involve pipeline construction, maintenance or metering tasks.

During the course of the work done for this thesis, the firm went through rounds of layoffs that affected all levels of the company with the exception of the union workers. As can be expected, this caused a lot of uncertainty at the company and as of the date of writing this thesis, the current management structure differs a little from that depicted in Figure 6. This however, has had no impact on the work done in this thesis and there has been tremendous support from senior management at National Grid to implement the changes described in this thesis.

3.3 Cultural Lens

This is the first project borne out of the collaboration of National Grid and MIT. The company has been extremely supportive and encouraging all throughout the process. From a cultural perspective, different groups affected in the company almost universally believe the project to be useful and that it adheres to the analytical rigor and process improvement principles advocated by the Operations Performance group.

From a general company standpoint, we have seen in Chapter 1 that the company has grown through an acquisition strategy in the US. While management has been very consistent in promoting the principle of "One company, One way", to ensure that employees felt a part of National Grid rather than their original constituent company, this message sometimes is not fully embraced at the yard level. We visited several yards in the New England area, and met a number of people at each yard to better understand both the processes at these yards and the context in which they existed. We observed that a number of people, especially those who had been at the yard for a number of years, still referred to their employer by the name it was known before National Grid acquired it. We also noticed that often the processes followed at certain yards were identical to those followed prior to the National Grid acquisition, down to the previous company's logo on the paperwork created. This does indicate that any changes made to yard level operations, needs to be informed by local variations and a strategy need to be developed to manage this regional variability.

The importance of unions at the yard is another key aspect of work at a yard. As previously mentioned, all crewmembers are members of the local chapter of a union. There are multiple union's chapters across National Grid, each with their own rules, regulations and culture. The members of a union chapter identify very strongly with that chapter; we noticed that at times this association was stronger than the association with the company. However, National Grid largely has a good working relationship with their union. This was corroborated through a number of interviews we conducted of both crewmembers and management throughout the company.

3.4 Political Lens

The Political Lens is very useful tool to formulate a strategy to pilot and roll out the work done in this thesis across the company. It enables us to understand the motivations of the various groups in the company, and helps us foresee and respond to potential objections that they may have.

We experienced the utility of this tool firsthand when, during our initial yard visits, we encountered Resource Planners who did not appear very keen to help us and openly stated that they felt that any tool that resulted from our work would not be interesting to them. After looking at the issue through the political lens, we realized that there was a very real and natural fear among the Resource Planners that the tools created for this thesis were intended to replace them. This problem was exacerbated by the fact that the company had just announced a round of layoffs. In conjunction with the company management, we presented project formally to the Resource Planners company wide and solicited their feedback. We emphasized that the work we were doing was intended to help them, and any tool or processes created required their expertise to be effective. We also pointed out several painful issues with the current resource planning process, such as the necessity for repeatedly modifying the daily plans in response to new job or crew information. Tasks that Resource Planners spent hours on could easily be automated and completed in seconds, allowing the Resource Planners time to focus on other tasks that added more value to yard operations. This strategy paid off and we received a lot of cooperation from the same Resource Planners when we revisited their yards. They were much more eager to help out, and we were able to job shadow them, as well as learn what the major pain points of their roles were.

As previously mentioned, we do believe that when this work is to be rolled out across the company it will be vitally important to understand the incentives of various groups and actors. For instance, one of the major operational efficiencies of this work is the reduction of overtime at the yards. While this is overall very beneficial for the company, crews that are affected may be unhappy with this work and this may lead to a lack of cooperation on their part. We expect that in this case, and to eliminate any other potential issues that may arise, the company should follow a strategy of engaging the key stakeholders identified above, and ensuring that while they company goals are being met, the various stakeholders are heard and their concerns alleviated.

3.5 Chapter Summary

We discuss National Grid through the three lens perspective as proposed by (Carroll, 2002). We examine the company structure and the relevant parties to this project namely Resource Management, Resource Planning, Field Operations, Supervisors and Crews through the Strategic lens and understand how they fit together. We use the cultural lens to explain the enthusiastic response of the company to the internship, the unionized workforce and management interactions, and the reasons for yards following different processes. We finally look at incentive alignment and understand potential issues that may crop up in rolling out the operational changes across the company.

4 A Deep Dive into Yard Operations

4.1 Overview

In this chapter we look at generalized processes for Resource Management, and Resource Planning and Work Execution across yards at National Grid. We understand the variation between yards, and discuss the main issues that prevent high operational performance at yards at the company.

4.2 Data Gathering Methodology

The data for the process descriptions presented in this thesis was gathered in multiple ways. We visited several yards around the New England area and interviewed a number of Resource Planners, Supervisors and Crew Leaders as well as members of the Resource Management group. We also did extensive job shadowing of crews from multiple yards performing different types of jobs, and documented the range of processes followed. The sections that follow describe our findings and provide a generalized process map for the different functional areas.

4.3 Job Classification and Overview of Relevant Concepts

This section provides a brief overview of the different kinds of work carried out at yards and briefly explains the terms and issues that the reader will encounter in the following sections.

There are two kinds of work done at a yard- planned and unplanned work. Planned work is the kind of work that may be predicted well in advance (and is certainly very well known at the point a Resource Planner at a yard is preparing the daily schedule). This work category includes:

a. Construction work: These are the jobs that involve construction of the new high pressure pipes that form the arteries of the gas distribution network.

b. Maintenance work: These jobs involve the repair of existing pipelines, and carrying out scheduled, often government mandated work to enhance the infrastructure connecting homes to the grid

c. Customer Metering Services: These are jobs that involve installing, relocating, reading or removing gas meters.

Unplanned work involves work that can arrive suddenly such as leaks in a pipeline, or less frequently, sudden reports that another utility has accidently breached the gas lines owned by National Grid (known as encroachment jobs). Leaks are graded on severity of the leak, i.e. the amount of gas leaking out from the pipe into the environment, and the proximity of the leak to a populated area. Leaks are either rated as Grade 1 (emergency leaks that must be addressed immediately), Grade 2 or 2As(less severe leaks, that must be taken care of within 12 months of the first report), or Grade 3s (leaks that are low severity or far away from habitable areas that must only be watched over.)

All jobs are also divided into Capital work and Operational and Maintenance Work (O&M Work). The construction jobs fall in the former category and most of the other kinds of jobs fall in the latter. National Grid presents its capital expenditure to the States each year as a part of its Rate Case. A Rate Case is the case presented to the State, where the State determines the gas prices that may be charged to the end consumer. The gas rate is typically set by the State so that all capital expenses borne by National Grid are reimbursed with a certain percentage of profit. This leads to an interesting situation for the company where it is less incentivized to control costs for jobs classified as Capital work as opposed to those classified as O&M work.

Another point to keep in mind while reading the following sections, is that at each yard, there are three shifts. The first shift typically starts at 7am, the second starts at 3pm and the third at 11pm. This isn't necessarily the same for every yard however. The first shift across the company has the maximum number of crews, with a smaller number of crews in the second shift, and a skeleton crew for the third shift, who generally take care of any emergency leaks that occur during the night.

4.4 Resource Management Processes

As previously mentioned, the function of Resource Management is primarily to set yearly targets for the work to be performed in the field (the Work Plan) and monitor the progress relative to these targets through the year. All targets are yearly and companywide. These targets are then allocated to each yard based on the size of the yard and the characteristics of the regions that each yard served.

4.4.1 Creating the Work Plan

At a high level, the method used by the Manager in this group to create the Work Plan consists of the following steps:

4.4.1.1 Work Estimation

1. **Construction work:** (This is Capital Work, as it counts as a Capital Expenditure and can be included by National Grid in their case to the regulatory body that oversees the setting of gas prices to the end-customer.) Based on expected growth rates of natural gas end-customers,

and the regions that National Grid wishes to expand in the year, the number of feet of main pipeline required is calculated. Most construction work on the gas distribution side is done by contractors not directly employed by the company. Therefore work done on most of these jobs are not taken into account while trying to calculate overtime limits and number of workers required for the year.

2. **Maintenance Work:** (This is Operations and Maintenance Work, as it is counted under that line item on the income statement. The money spent to carry out this work cannot be recovered via future gas price increases) These jobs include planned work mandated by the government through regulations, pipeline replacement work that National Grid undertakes, and unplanned pipeline leaks that spring up unexpectedly. For some of this work, such as the mandated jobs, the exact number of these to be done next year is known beforehand. For the unplanned work that occurs (i.e. pipeline leaks), Resource Management uses historical data to estimate the work that will need to be done over the year for which the Work Plan is being created.
3. **Customer Meter Services (CMS):** This work pertains specifically to meters installed at the end-customer locations. These jobs mainly involve installing, removing, or relocating these meters. This work is also typically estimated from historical data and the expected number of end-customers to be added by the new construction work done over the year.

4.4.1.2 Work Plan Generation

1. Once the work for the year has been estimated, it is allocated across each yard based on the yard size, number of workers available and other characteristics of the region the yard serves.
2. Monthly targets are then derived from the yearly targets for each yard
3. Resource Management is also charged with estimating the manpower required to complete

the yearly plan created. To accomplish this, the team figures out the number of manpower hours required for every job type for the year, using historical information and expert knowledge. Once they have the total number of productive manpower hours required to complete the yearly work, they look at the number of employees required to accomplish the work. The group knows the total number of workers that will be available across all yards in the coming year, and estimates the total productive hours achievable with the work force working a regular workweek (i.e. not all hours worked are put into doing a job, there is a certain percentage of overhead for tasks such as driving). If the number of available manpower hours is less than the number of manpower hours required to do the jobs for the year, the resource management team assumes that those hours will be worked on overtime. The total number of overtime hours estimated for the year is all the productive hours needed on overtime in addition to the expected number of non-productive hours on overtime.

It is interesting to note that towards the end of our work at National Grid, there were plans to replace the above process with a linear optimization model developed by the Operations Performance group that would create optimal yearly plans for a number of yards.

4.4.1.3 Tracking Progress

1. Every week each yard's Resource Planner updates the Manager of the Resource Management team with the weekly progress of that yard, which includes the number of jobs of each type completed, the progress compared to the yearly forecast, and the total number of overtime and non-overtime hours worked as compared with the forecast.
2. At the weekly meeting, the manager of the Resource Management team discuss the week's overall figures, and tries to understand the issues at any yard which seems to be deviating too

much from the forecasted plan. Corrective measures taken range from reallocating crews from different yards to the underperforming yard or focusing the yard to work on jobs of a single job type that are required to be finished by a certain date (for instance, in the winter towns prohibit certain types of pipeline work in New England, yards in these regions often carry out a higher than average number of those kinds of jobs just before the deadline.)

4.5 Yard work: Resource Planning and Work Execution

4.5.1 Overview

A recap of the high level view of Resource Planning and Work Execution processes would be beneficial in understanding this section. Resource Planning, as the reader no doubt recalls, is a manual short-term planning process carried out at each individual yard at National Grid. A Resource Planner at a yard decides, based on the monthly targets that they are required to meet, the daily and weekly jobs (construction, maintenance or service) to be carried out. She then assembles the yard workers into crews and allocates crews to the jobs scheduled for that particular day. Following this, the crews carry out the jobs allocated to them for that particular day, sometimes utilizing overtime to accomplish these. These processes are not standardized across National Grid's US Gas operations and both vary greatly between yards causing inefficiencies in the company's operations.

4.5.2 Resource Planning Processes

In this section, we first present an overview of Resource Planning that is an amalgamation of the processes undertaken at several yards surveyed. We also highlight where some yards differ in the processes followed and how these differences impact the operations performance of the yard.

4.5.2.1 Start of the day: The Current Day's Schedule is updated

At the start of the day, the Resource Planner has in front of her the plan made the afternoon of the previous day. This plan lists the jobs to be done for current day, which crews are to perform them, and the composition of these crews. The Resource Planner then goes through the run-sheet of the night before. This tells her what jobs were outstanding from the night before, and where the night crew needs to be replaced by the day crew. She also looks through the newly arrived vacation sheets, and absence notifications and checks whether anyone allocated to a crew today will not be at work. The new leak reports are also examined, and she checks if any leak is an emergency one (a Grade 1 leak) that requires a crew assigned to it immediately. All the above information is collected and the day's plan is adjusted. Unfortunately, since some of this information (such as absence reports) aren't available at the start of the day, but trickle in instead, the Resource Planner remakes the plan several times. In some cases certain jobs for the day are pushed out to the next day because the crew originally assigned to the job does not have a sufficient number of people to complete the job. The final plan created is then printed and handed over to the supervisors, who hand a copy to their crews.

4.5.2.2 Mid-day: Status Check

The Resource Planner and the Field Manager of the yard hold a call with the supervisors and their crew leaders in the field close to the second shift coming on. The goal is to determine the number of jobs that are still being worked on, and whether they are expected to continue through the second shift. If the crew indicates that the job will take over two hours, the Resource Planner may make the decision to replace the crew that would have been on overtime, with a new crew from the second shift. Doing so eliminates the need for the replaced crew to work on overtime, which is more expensive than regular or straight time. Crews that indicate that their jobs would take less than two hours extra after the shift's end are typically allowed to work for the two hours on overtime. The idea in this case is that it is more inefficient to get a crew to replace them or stop the work midway and return to it the next day.

Besides the number of jobs still pending, the Resource Planner also looks at the incoming Grade 1 Leaks to determine if crews need to be allocated and the actual shift those crews should be from.

4.5.2.3 Mid-day: The Next Day's Schedule is created

The Resource Planner looks at the jobs to be scheduled. She has previously received work packages from the corporate office that let the Resource Planner know what jobs she has to schedule and provide the required city permits for them. At the beginning of the internship, the number of work packages at each yard varied greatly ranging from 2-3 days to 2 weeks' worth of work. The Resource Planner begins the process of creating the next day's schedule. This process varies greatly between yards, but good Resource Planners generally go about this by picking towns with the most pending jobs, and try to assign all the jobs for those towns. The idea is that it is more efficient for a supervisor that manages multiple crews to visit them if they are located close to each other. It is also more efficient for crews that have to do multiple jobs in a day, to not drive too far to get from one job to the next. The Resource Planner also has to keep in mind the progress being made thus far on the weekly targets that need to be reported to Resource Management, and adjust the job mix to be scheduled accordingly. After deciding what jobs to schedule, the Resource Planner and Supervisors together determine crew composition. There are a few rules that they have to follow. These rules are set by the union contracts under which the workers operate and govern issues such as the number of people on a crew, the jobs that a crewmember is allowed to do, the number of sick days, and the policy for overtime allocation. The Resource Planner and Supervisor then compose the crews based on the people expected to be at work the next day for the two shifts. Each crew is allocated between one to three jobs, not all of which are expected to be completed the next day. The crews are handed these extra jobs as backups to complete if they get done with their first job early. Some crews receive light short-duration jobs, so that they can be easily moved in the event that a Grade 1 Leak is called in to the yard. For certain kinds of jobs, the crews doing them are fixed for the season; other jobs can be picked up by any crew. Some of the yards we observed had a policy of dividing all crews such that a crew only got jobs of a certain job type.

4.5.3 Work Execution Overview

4.5.3.1 Start of Day

The crews at the yard are given their crew composition for the day and the list of jobs with locations that they are supposed to do. They head out from the yard to the location for the first job, and proceed down the list once that is complete. Each job roughly involves digging through to the pipeline, pipeline construction or maintenance, subsequent filling of the hole, using a dump truck to dispose of any large rocks dug up and then calling in a paver to repave the street. Supervisors are generally allocated to regions, and any crews working in those regions fall under the supervisor's management. The supervisor may visit the crews during the day to determine the crew's progress on that day's tasks and check if they need anything to complete their work.

It is important to note here that the time taken to do any single job by a crew is uncertain. Supervisors indicated that the length of time worked on a job may depend on the busy-ness of the street being worked in, the width of the pipe, the length of the pipe replaced, the quality of the soil. However, a regression analysis found very little statistical correlation between the length of time being billed to the company by crews and the factors described above. We believe that there may be factors such as crew experience, supervisor management practices, as well as general data entry errors that may be responsible for the discrepancy.

4.5.3.2 During the day: New Leaks called in

Leaks are uncovered through two ways – either a leak survey team discovers a gas leak while surveying the state of the pipelines in a region or members of the general public call National Grid when they smell gas in their neighborhood. The company's policy is to respond to a leak within one hour of it being reported, since unattended gas leaks are a safety hazard. When a leak is called in, a Customer Metering Services team is immediately dispatched and it makes the determination of the severity of the leak (i.e. Grade 1, 2 or 3 in decreasing severity). Supervisors of the regions in which the leak occurs are notified by dispatchers, who monitor the Grade 1 leaks being called in (the Resource Planner isn't typically involved). As Grade 1 Leaks need to be addressed immediately, the supervisor makes a determination which one of their crews needs to be dispatched to address the leak. The crew assigned is usually among those assigned light work at the beginning of that day, but depending on the number of leaks that occur during the day and the number of crews in a region, this may not be a possibility.

4.5.3.3 End of Shift: Overtime Granting Process

At the end of the shift, the Field Manager, Supervisors and the Resource Planner determine what jobs will not be complete by the shift end. They ask each Crew Leader, how many hours they estimate that each job will take beyond the scheduled shift end. Typically, if the jobs are estimated to take between 0-2 hours of overtime, the crew is allowed to continue. If the job is estimated to take over 2 hours of overtime, the Resource Planner and the Supervisors make the determination if the crew should be replaced. This is based on whether sufficient crews in the next shift have a light load, or if the jobs for some of the crews in the next shift can be pushed out to the next day. In some yards however, the Supervisors have the sole discretion in granting overtime to their crews.

4.5.3.4 Time sheets and Overtime Approval Process

Time sheets are typically filled out by the Crew Leads at the end of the day. These list the people working for that crew, the jobs that they worked on, and the time worked on each job. The timesheets are required to be approved by the Supervisors before the workers can be paid. This is meant to provide another layer of accountability to the overtime number and crew productivity. Quite often, the supervisors approve time sheets for all days and all crews managed by them, just once every two weeks, thereby reducing the effectiveness of this layer of accountability. Following the supervisor approval, the workers are paid.

The generalized processes for Resource Planning and Work Execution can be seen in Figure 7 below. In the figure, an additional role we see is the work coordinator. She is responsible for obtaining permits for new work and ensuring that the Resource Planner has a sufficient number of jobs to schedule.

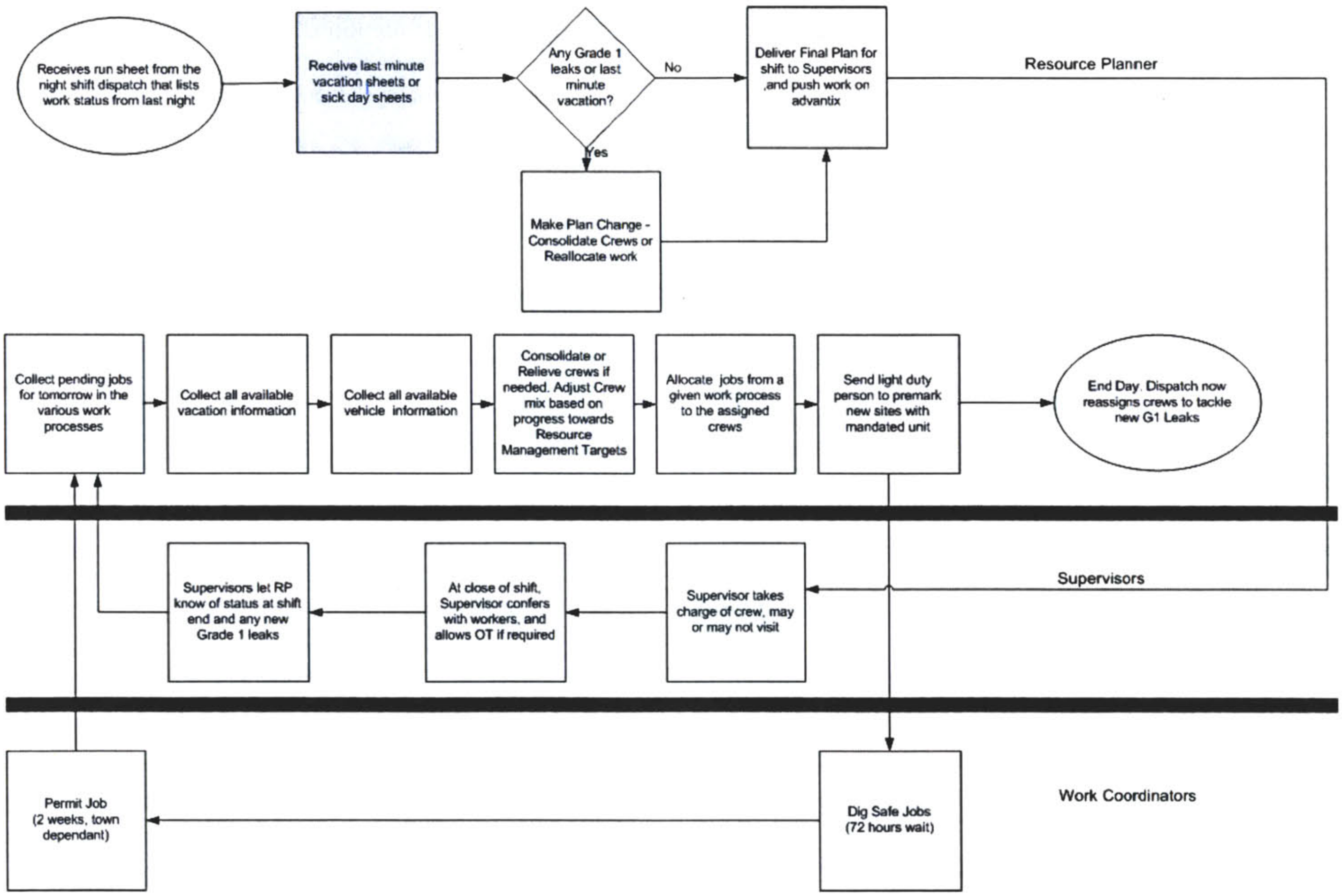

Figure 7: Resource Planning and Work Execution High Level Process Map

4.6 Issues with Resource Planning and Work Execution Processes

After visiting several yards and observing the processes described above, a few key factors jumped out as being roadblocks to high operational performance. For the purposes of this thesis, we define high operational performance as the completion of the yearly job targets with a high degree of safety within an acceptable level of cost. We observed that while the safety levels at National Grid's US Gas operations were laudable, the operational efficiency could still be improved. At a yard, labor cost is the majority component of overall operational cost and the largest component of labor cost is overtime. 25-40% of all hours worked are overtime hours at the average yard. National Grid, like most other companies pays overtime at a 1.5x regular pay- implying that at a level where overtime forms 40% of the total hours worked, the yard's labor cost is twice as much as in the case with no overtime. Based on the processes described above, and our interviews with yard and management employees, we delve into the causes of the high levels of overtime.

4.6.1 Drivers of Overtime

Some of the key causes of overtime have been detailed below:

1. **Focus of yard operations**: The primary focus of yard operations and the emphasis of management have been on hitting yearly targets, and safety. Traditionally, productivity or overtime management has been something that is not focused on, the primary goal at a yard being to "get the job done".
2. **Resource Planning is very difficult problem to get right**: Optimal resource planning even for a short period of two weeks requires the analysis of thousands of variables of job, resource and schedule availability. This is further compounded by the uncertainty in the occurrence of jobs such as Grade 1 Leaks, and crewmember availability.
3. **Insufficient accountability and oversight:** Supervisors are often responsible for granting overtime to crews that request it to complete their day's jobs and always responsible for

approving time sheets and thus overtime. There is no management of individual worker overtime or productivity other than at the Supervisor level. This leaves the company open to the potential of misuse of the system, leading to higher costs.

Supervisors observed spent a large percentage of their time filling out paperwork to approve overtime, report progress on jobs, file for permits etc., leaving very little time to supervise workers on the field. Data gathered using the tools developed during this project supported management belief regarding a direct correlation between onsite supervision of working crews and worker productivity. Greater supervision correlates with more productive hours as a percentage of total time worked by the crews.

4. **Incentives Misalignment**: On the US Gas Operations side of the company, unlike the Electric Operations side, Supervisors are allowed overtime. However, they are only allowed overtime if their crews work overtime. As can be imagined, this reduces supervisor incentive to manage crew productivity and overtime effectively.
5. **Lack of standardized processes across yards or within a yard**: The consequences of not adapting processes that employ best practices and are standardized across the company are:
    a. Adopting best practices across the company allows for knowledge sharing and ensures that yards that encounter similar issues have the right tools to deal with them.
    b. Without standardized processes, which are carefully controlled with expected outcomes, it is difficult to immediately detect issues and take corrective action. If issues are not detected in time, they may have impacts that cause more severe issues down the road.

6. **Restructuring within the company:** This has reduced the number of Resource Planners and Supervisors available per yard, leading to further pressure underlining the importance of efficient operations.
7. **Age of the Infrastructure:** Another issue, one not reasonable for the company to fix immediately given the massive capital expenditure, is the old gas distribution infrastructure and growing capacity utilization of the infrastructure. Due to the age of the pipes, gas may often leak from the pipe joints, which sometimes manifest as Grade 1 Leaks that cause a lot of issues for the National Grid crews and Resource Planners.

4.7 Chapter Summary

This chapter looks at the yard operations at National Grid in close detail. We saw how Resource Management creates yearly plans of the pipeline construction, and maintenance and customer related work that needs to be carried out over the year. The Resource Planners base their daily plans on the yearly targets they have to meet and the supervisors and crew members take the daily plans and execute on it. We also saw that overtime was one of the most significant costs at the yard, and what were some of the reasons behind the current levels of overtime.

5 Process Creation and Model Design

5.1 Overview

We propose to solve the issues explained above by following a two pronged approach. The first is using a tool we built – the Resource Allocation and Planning Tool (RAPT) to optimally schedule jobs, and allocate crews to meet weekly and monthly targets at the lowest possible cost. The second is to create and improve processes related to resource planning, and overtime management with built in accountability and the ability to hone in quickly on deviations. The following sections describes in detail the processes and the tool created.

5.2 Resource Allocation and Planning Tool

5.2.1 Tool Goal and Requirements

The goal of this tool was to effectively handle the problem of automated schedule generation in a yard environment. The requirements of the tool were that it:

a. Be simple to use, i.e. the interface not expose too much complexity to the end-user
b. Allocate jobs to each day, and assign crews to the jobs and minimize cost while meeting work targets
c. Be straightforward to maintain
d. Use open-source or cheap software solutions whenever possible
e. Interface with the multiple databases that currently hold timesheet and historical and future job information for different yards
f. Be modular such that any changes can be made without too much difficulty

5.2.2 RAPT Design

We built the Resource Allocation and Planning Tool to be a web based tool with a Python based backend running on a Windows-Apache-Oracle-Python stack on National Grid servers. RAPT was built from scratch and comprises a backend of roughly 9,000 lines of Python code and SQL statements, and a front end built using HTML, CSS, and Javascript. Table 1 compares the requirements of the software listed in the previous section, and our approach to meeting those requirements.

Requirements	How Requirement was met
Simple to use	RAPT only accessible to Resource Planners and others at a yard through a web-based graphical interface and is extremely simple to use. Only analysts well-versed in the operational and software side have access to the underlying code.
Allocate jobs to each day, and assign crews to the jobs and minimize cost while meeting work targets	One of the major components of RAPT is a sophisticated optimization model that does job scheduling and resource allocation. This is explained in detail in this chapter.
Straightforward to maintain	All code is extensively commented. A detailed document explaining RAPT in detail was provided to the company.
Use open-source or cheap software solutions whenever possible	The code was created using open-source freely available tools in non-proprietary software languages. The only exceptions are underlying OS (Windows) and the mathematical programming solver used (Gurobi) which is a closed source tool, but the best suited for the purpose.
Interface with the multiple databases that currently hold timesheet and historical and future job information for different yards	This is a requirement without which the analytical capabilities and the automated schedule generation would not be possible in RAPT.
Modular design	All components of RAPT have been created in a modular manner, such that minimal changes are required if the underlying technologies such as the database, or the solver change.

Table 1: Table comparing requirements for RAPT and the approaches used to meet them

RAPT incorporates three pieces of functionality:

1. A Web based Stochastic Optimization Model that optimally picks jobs, crews and schedules them.

2. A Strategic Decision tool to the company, to conduct '*what-if*' analyses.

3. An Analytics tool to provide yard level comparisons on key metrics.

We will discuss these pieces of functionality later on in this section.

The structure of RAPT can be seen in Figure 8 below. There are several key components to RAPT:

1. **The Website:** This is the front end to the RAPT tool and can be accessed through any web browser within National Grid by typing the URL of the tool. It was built using HTML, CSS and Javascript and it provides a quick way for a Resource Planner to set up the relevant variables and request a schedule.
2. **Analytics Engine:** This is the business intelligence component of RAPT, comprising of several thousand lines of Python code. It enables management to ask sophisticated questions about their yard operations. It interfaces with the Employee Timesheet database and the different regional Jobs Databases that hold historical and pending job information. The Analytics Engine supplies key information about yard performance, historical leak distributions, historical data about time taken per job type, and other pieces of relevant information to the Optimization Engine.

3. **Optimization Engine:** This is the heart of the program. It uses a stochastic optimization model to create a schedule that picks ***the right jobs*** for each day, and assigns the jobs to the ***best crews*** to ensure that the Resource Management targets can be met at a minimum cost[1]. The factors to select the ***right*** jobs for a day are those that enable the lowest cost, meet the goal of regulatory compliance, and perform jobs within the company mandated deadlines for customer satisfaction goals. The model creates the best schedule with the expectation that uncertain events such as a variable number of Grade 1 or Emergency Leaks may occur.

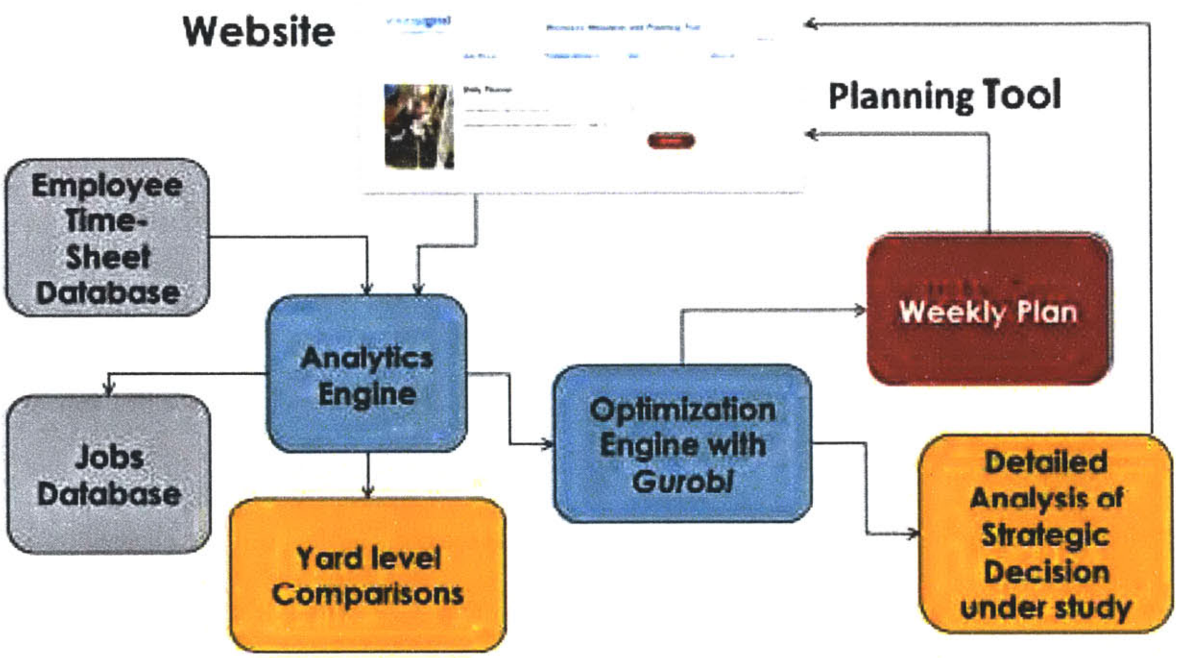

Figure 8: Structure of the Resource Allocation and Planning Tool

[1] As the reader no doubt remembers, overtime is the most significant component of cost for a yard. It certainly is a component that can directly be reduced by effective management. It thus makes sense for a tool like RAPT to focus on minimizing this cost. Henceforth in this document, we interchangeably use cost and overtime cost when referring to the optimization performed by RAPT.

5.2.3 RAPT Functionality

As previously mentioned, RAPT incorporates a web based scheduling tool, a strategic decision making tool and an Analytics tool to provide yard level comparisons for any requested metrics. Let us take a look into the plan creation aspect of RAPT. At the beginning of the day, the Resource Planner navigates over to the RAPT site to create a plan for ***that*** day. She already has the weekly plan that was created the day before, so she has some idea what to expect. On the website, she picks her yard, enters the number of days she wants to create the plan for (typically a week), and marks the crews that are present for the day, as well as those who are expected to be present for the scheduling time period, and hits Submit. Within a few seconds, the site returns the optimal schedule for that time period.

The output generated by running the web based scheduling portion of RAPT is given in Figure 9. The job and crew data has been disguised from its original form and only one day of the output has been shown in the figure. The output depicts the jobs assigned to each crew present on that day. It also indicates that if one or more Grade 1 Leaks occur, which crews should take care of them. When the Resource Planner requests a schedule, RAPT uses historical data to build a distribution of Grade 1 leaks and then generates the schedule to minimize overtime costs in the presence of that distribution. For every possible number of leaks that may realistically occur (this information is encapsulated in the distribution), RAPT decides which crews would be responsible for fixing the leaks. The expected number of Grade 1 Leaks is given at the bottom of the figure and the minimized value of overtime expected is also given. This number enables Resource Planners and Supervisors to determine the root cause of issues if the crew reported overtime deviates significantly from this value. The model behind this optimization is explained in the Optimization Engine section.

Resource Allocation and Planning Tool

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The RAPT Model took 2.0 seconds and allocated 93 jobs across 8 days.

Date	Day	Crew ID	Crew Lead	WorkOrder	Job Type	Avg Hrs Per Employee	Final Deadline	Task ID	Address		IF Leaks Seen =0 , Number of Leaks Completed by Crew	IF Leaks Seen =1 , Number of Leaks Completed by Crew	IF Leaks Seen =2 , Number of Leaks Completed by Crew	IF Leaks Seen =3 , Number of Leaks Completed by Crew	IF Leaks Seen =4 , Number of Leaks Completed by Crew
2011-09-29	THU	1	Allan	771996	CUSTREQ	5.1	2011-12-31	771996.2	"11 GRAYSTONE DR, DAN"		0	0	0	1.0	0
				726511	CMP	5.7	2011-10-06	726511.7	"289 HALE ST, BEV, MEETING PL @ENDICOTT COLL"						
2011-09-29	THU	2	Bob	738866	CMP	5.7	2011-12-31	738866.4	"CALLER ST, PEA, @ CANAL WAY"		0	0	0	0	0
				681662	CUSTREQ	5.1	2011-12-31	681662.2	"WILL SAWYER ST,PEA"						
2011-09-29	THU	3	Carmack	494265	SDP	6.5	2011-12-31	494265.7	"7 PRINCE STPL,SAL"		0	1.0	1.0	1.0	1.0
2011-09-29	THU	4	David	526665	SRP	6.3	2011-10-06	526665.2	"319 CABOT ST,BEV"		0	0	1.0	0	1.0
				526660	SRP	6.3	2011-10-06	526660.1	"269 CABOT ST,BEV"						
2011-09-29	THU	5	Estonian	562791	LK EMER	8.7	2011-12-31	562791.5	"9 LYNNFIELD ST,PEA"		0	0	0	0	0
				774324	CMP	5.7	2011-12-31	774324.2	"WATER ST, DAN"						
2011-09-29	THU	6	Fallacy	776004	CMP	5.7	2011-12-31	776004.2	"3 WINTER ST, SAL, @ 4"" VALVE AT CONTROL PIT"		0	0	0	0	0
				660492	CUSTREQ	5.1	2011-12-31	660492.2	"5 EDGEWOOD RD,MID"						
				792101	CUSTREQ	5.1	2011-12-31	792101.1	"ROCKPORT RD,GLO"						
2011-09-29	THU	7	Grime	792106	CUSTREQ	5.1	2011-12-31	792106.2	"NAHANT RD,NAH"		0	0	0	0	1.0
				726880	CMP	5.7	2011-10-06	726880.4	"1 CROSS ST, PEA, LINCOLN MERCURY GARAGE"						
2011-09-29	THU	8	Holden	792104	CUSTREQ	5.1	2011-12-31	792104.7	"OCEAN AVE,MAR"		0	0	0	1.0	1.0
				771964	CUSTREQ	5.1	2011-12-31	771964.7	"6 ECHO AVE, BEV"						
				480512	CUSTREQ	5.1	2011-12-31	480512.2	"41 RIVER ST, BEV"						

Planned Overtime: 34.0

Expected Number of Leaks: 1.5

Figure 9: Sample Output of the RAPT Tool

Another feature of RAPT is its ability to allow management to see the impact of strategic decision. This utilizes both Analytical and Optimization Engines to see the future impact of implementing yard level policies on cost, schedule, overtime levels, productivity and management-chosen metrics. With the help of this tool, management can determine the impact of various strategic and tactical policies on yard level work that may include but are not restricted to:

- The benefit of reducing the average time taken to do a job.
- The number of jobs completed if management constrains Overtime.
- The best policies to follow in the yard to reduce cost e.g. :
    - The benefit of tasks such as prior job scoping, where a light duty worker or retiree is sent to a job before hand to determine how long the job would take.
    - Maximum number of absences (due to training etc) that a yard can bear, and still finish their jobs within a hard overtime limit.

The third piece of functionality offered by RAPT is the ability to determine yard level, management-chosen metrics and perform comparisons between yards. This functionality also enables management to ask sophisticated questions about their operations. This piece of RAPT is explained in detail in the next section.

5.2.4 Analytics Engine

As mentioned above, this engine enables management to perform yard level comparisons between their yards, as well as ask sophisticated questions about the gas operations. An example of the data generated by the Analytics Engine is given by Figure 10 (disguised data used) to let us know how different yards compare with each other in terms of their productivity.

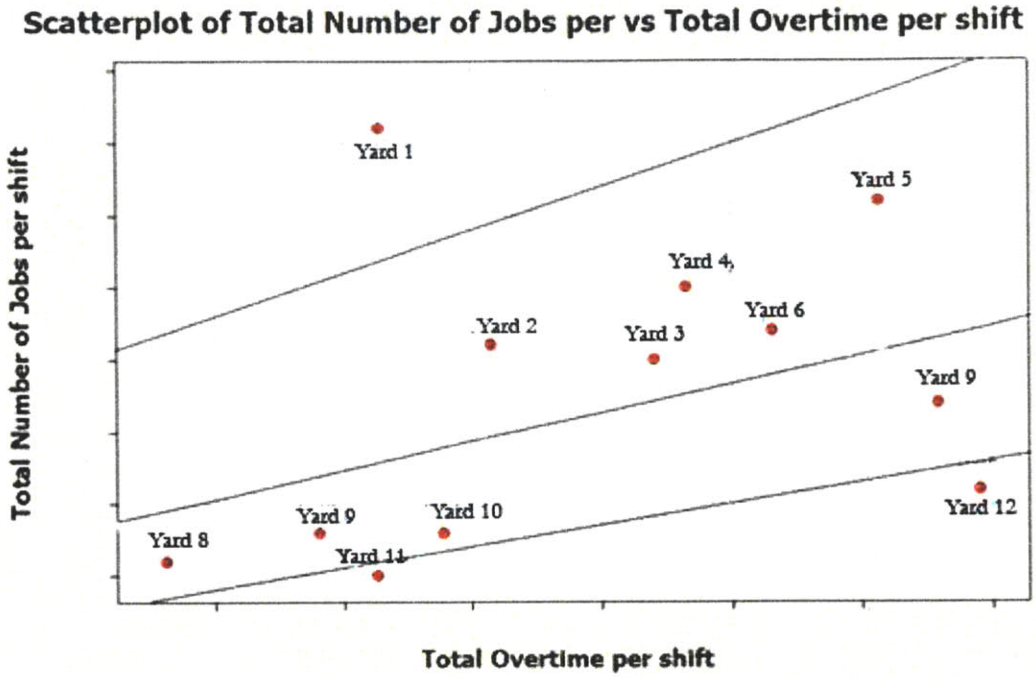

Figure 10: Sample Overtime vs. Productivity Chart for a select number of yards

The above graph plots the average number of jobs that are done per employee per shift against the average overtime used per employee per shift. The three lines across the graph are iso-cost lines, with the lowest cost line at the top, and the highest at the bottom. We can see in this particular case that Yard 9's employees take a lot of overtime per shift, but accomplish very few jobs as compared to Yard 3's workers who seem more productive with a much lower level of overtime taken per employee per shift. This is just one example of how RAPT's Analytics Engine can provide useful information to management to better understand company operations.

If, for instance, after looking at that particular graph, management were interested in zooming into yards 3,9,2, and 5 and wanted to understand how the amount of overtime used in those yards varied by job type, they could use RAPT again and obtain the data for Figure 11. As can be seen in the figure, LK EMER or Grade 1 Leaks for some reason take a lot more overtime to complete in Yard 9 as compared to the other yards. This insight could be followed by further research into the issue through RAPT and subsequently might be a good starting point to launch a study into the processes at Yard 9 to determine the root cause.

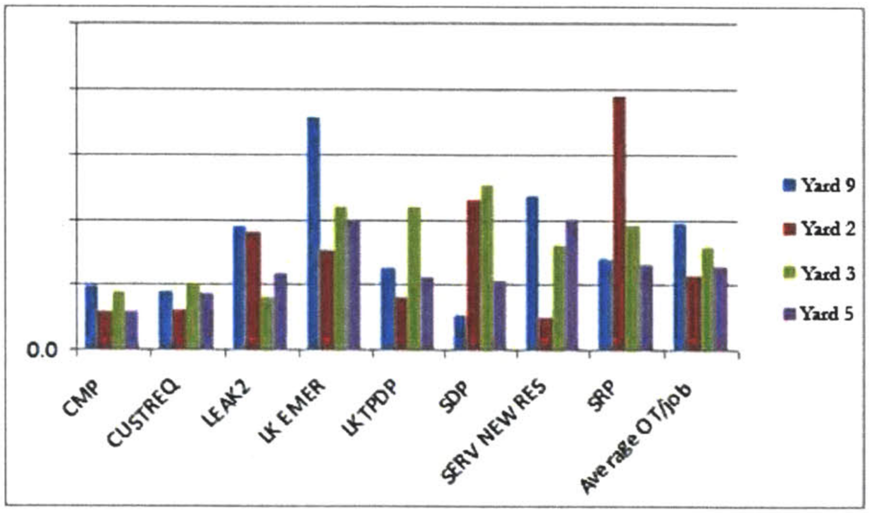

Figure 11: Average Overtime Per Job type across 4 selected yards

The Analytics engine is flexible enough that one can ask almost any question regarding previous yard performance. Some examples of questions include:

- What is the historical impact of close supervision on overtime?
- What was the impact of the last storm, where workers had to be diverted to storm damage repair work, on productivity across the company?

- Are certain supervisors more prone to granting overtime for the same kind of work than other supervisors?
- How often do crews arrive at customer appointments on time?

Another function of the analytics engine is to provide data such as historical leak distributions, historical times taken to complete jobs of different types, number of jobs waiting to be scheduled, number of crews available on the days that jobs need to be scheduled and a lot more information to the Optimization Engine.

Let us take a brief look at how the Analytics Engine works. The Analytics Engine is the largest module in RAPT in terms of line of code and as shown above, it is a powerful tool for business intelligence. It extracts the data from multiple regional jobs databases and the employee time sheet database, and compiles them into meaningful structures internally. These structures can be queried to understand the relationships between the disparate pieces of data. The task of querying these structures involves writing Python code. There already exist several functions in the Analytics Engine that analyze the internal data structures, and provide reports and graphs on the most commonly asked questions about yard performance. A few examples of these questions have been given above. New questions posed by management would have to entered by analysts in the form of a short Python function (typically under 30 lines, but is question dependent) that is called by the Analytics Engine. We believe that in the very capable hands of National Grid analysts, this can be a valuable tool for management to gain an in-depth perspective on the company operations.

5.2.5 Optimization Engine

The Optimization Engine is the heart of RAPT and contains code that implements the Stochastic Optimization Model that enables the scheduling of jobs. This Optimization model, like the Analytics Engine, is written in Python. It is solved using the Python libraries of the commercial solver Gurobi Optimizer. A high level view of the Optimization Engine is depicted in Figure 12.

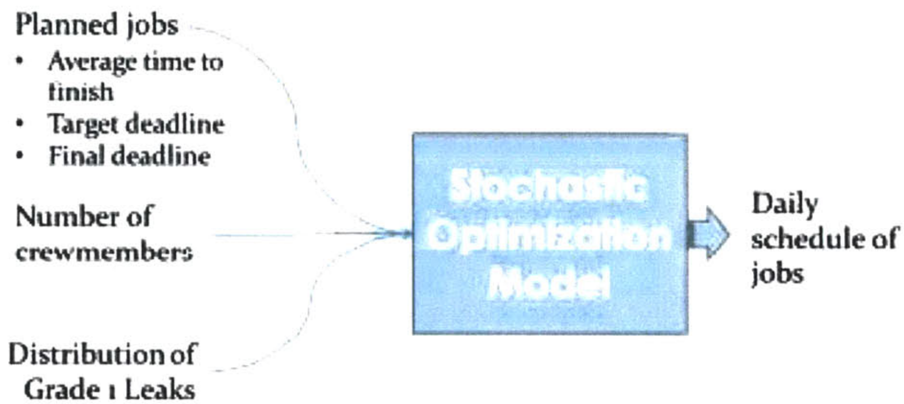

Figure 12: High Level overview of Optimization Engine

Let us take a closer look at the Stochastic Optimization model that is the core of the Optimization Engine. As we can see from Figure 12, the optimization model takes in the planned jobs, the number of crew members present, and the distribution of Grade 1 Leaks to create a daily schedule.

For the planned jobs, the two decisions that need to be made to create a schedule are the date at which the job is done (job scheduling), and the crew that is assigned to the job (crew assignment). Each planned job has a deterministic service time (based on historical data) and a deadline. The number of Grade 1 Leaks in a day is a random variable with a known distribution over all possible instances. In this section, we present two stochastic optimization models that solve a yard's scheduling problem.

5.2.5.1 The Full Model

The job scheduling and crew assignment decisions for this model are made simultaneously. The objective is to minimize the sum (over all crews and all days) of expected number of overtime hours. The constraints are: (i) that the job must be assigned to a crew by its deadline, and (ii) that in each leak instance, crews must be assigned to address the leaks. Table 2 explains the notation we use in this model.

Notation	Brief Explanation
T	This is the planning horizon across which the model is to run
t	Day index
k	Crew index
i	Job index
g	Number of unknown Grade 1 Leaks in the scenario
$q_t(g)$	Probability of g leaks appearing on day t
H_t	Number of straight time hours that a normal crew shift has on day t
L_i	Time to complete i^{th} planned job
L_g	Time to complete Grade 1 Leak.
D_i	Deadline of i^{th} job
y_i	Job type of i^{th} job
Q_s	Minimum quota needed of jobs of type s

Table 2: Notation and Explanations for Full Model

We denote the decision variables as X_{itk} and Z_{gtk}. X_{itk} is a binary variable which takes a value of 1 if job *i* is assigned to crew *k* at day *t*, and takes a value of 0 otherwise. Z_{gtk} is a variable which corresponds to the number of leaks assigned to crew *k* on day *t* when the number of leaks that are called in is equal to *g*. Therefore, it can only take integer values between 0 and *g*. We assume the following:

a. A job can only be assigned to one crew and has to be done within a single day.

b. A job must also be done by its deadline. If the deadline is beyond the horizon of the model, *T*, then the job may or may not be assigned in the model.

c. There is a minimum quota of jobs of each type that needs to be finished by the planning horizon. This should be specified by the Resource Planner based on monthly and weekly targets.

The full model can be represented mathematically as:

Objective: minimize $\sum_t \sum_k \sum_g q_t(g) * \max(0, L_g * Z_{gtk} + \sum_i L_i X_{itk} - H_t)$

subject to the constraints:

1. All jobs must be done by their deadlines:

$\sum_{t=1}^{D_i} \sum_k X_{itk} = 1$ for all *i* such that $D_i \leq T$,

2. If a job's deadline extends beyond the assignment horizon, it need not be assigned:

$\sum_{t=1}^{T} \sum_k X_{itk} \leq 1$ for all *i* such that $D_i > T$,

3. A minimum quota of each job type needs to be completed:

$\sum_{i:y_i=s} \sum_{t=1}^{T} \sum_k X_{itk} \geq Q_s$ for all job types *s*,

4. All Grade 1 Leaks must be assigned:

$\sum_k Z_{gtk} = g$ for all *t,g*,

5. Binary constraints for job assignment (jobs can either be assigned or not):

$X_{itk} \in \{0,1\}$ for all *i,t,k*,

5. Integrality constraints for the number of leaks worked on (the number of leaks worked on must be an integer):

$$Z_{gtk} \in \{0,1 \dots g\} \qquad \text{for all } g,t,k,$$

We rewrite the model to be a Mixed Integer Program, by introducing the variable V_{gtk} , we have the final ***full*** model.

minimize $\sum_t \sum_k \sum_g q_t(g) * V_{gtk}$

subject to

$$V_{gtk} \geq L_g Z_{gtk} + \sum_i L_i X_{itk} - H_t \qquad \text{for all } g,t,k$$

$$\sum_{t=1}^{D_i} \sum_k X_{itk} = 1 \qquad \text{for all } i \text{ such that } D_i \leq T,$$

$$\sum_{t=1}^{T} \sum_k X_{itk} \leq 1 \qquad \text{for all } i \text{ such that } D_i > T,$$

$$\sum_{i:y_i=s} \sum_{t=1}^{T} \sum_k X_{itk} \geq Q_s \qquad \text{for all job types } s,$$

$$\sum_k Z_{gtk} = g \qquad \text{for all } t,g,$$

$$X_{itk} \in \{0,1\} \qquad \text{for all } i,t,k,$$

$$Z_{gtk} \in \{0,1 \dots g\} \qquad \text{for all } g,t,k,$$

$$V_{gtk} \geq 0 \qquad \text{for all } g,t,k,$$

There are several factors which make solving the full model impractical. First, the model can have a large number of integer decision variables. Therefore, solving the full model for some instances may take too long. Second, the schedule that the full model produces might be suboptimal when the model parameters are not specified correctly (e.g., times taken to do a job, number of crews, leak distribution). In reality, these parameters are often unknown; for instance, accurate estimates of job service times are only available after crews start working on the job. These practical considerations motivated us to look at a second optimization model, the aggregate model.

5.2.5.2 The Aggregate Model

The aggregate model performs the same job scheduling and crew assignment but decomposes them into two separate stages, which are done sequentially. The functions of these stages are:

a. The first stage does the allocation of the jobs to be scheduled to the specific dates, keeping in mind that some number of Grade 1 leaks may occur on each day. The probability of any given number of Grade 1 Leaks on a day is given by the historical distribution as previously mentioned. In this stage, the model assumes there is only a single crew. The number of straight-time hours (non-overtime hours) for this crew is an aggregation of the straight-time hours of the individual crews. The model finds a schedule that minimizes the sum (over all days) of expected overtime hours, subject to jobs being done before the deadline.
b. The second stage takes the schedule produced by the first stage. On each day, the set of jobs scheduled for that day is assigned to the individual crews, with the objective of minimizing the sum (over all crews) of expected overtime hours. The constraint is that all leaks must be assigned to crews under each leak scenario.

There are several practical advantages of the aggregate model presented. First, the complexity of the model is drastically reduced since the number of decision variables is fewer. Second, in simulation experiments, the cost of the schedule produced by the aggregate model is no more than 6% higher than the cost of the optimal full model schedule. Third, we find that the aggregate model is more robust to model parameters that aren't specified correctly (job service times, number of crews, leak distribution). In reality, these parameters are often difficult to get right; for instance, an accurate estimate of job service times is only available after crews start working on the job. Therefore, due to these practical considerations, we chose to use the aggregate model for implementation in the Optimization Engine. In this section we present the final model implemented in the aggregated model. Due to this, while going through the following sections, the reader will notice that the Aggregate model stages are more complex, with more constraints and requirements than the Full Model. We have modified the major assumptions behind the Full Model as follows:

a. Now, while a job can only be assigned to one crew, it may be done over multiple days in the same shift, as is the case with a number of jobs in the yards. Multiple day jobs must be done over consecutive workdays (if a multiday job starts on Friday, it continues on Monday on the same shift). Grade 1 Leaks, given their severity and impact to customers, cannot be shifted on to the next day however, and must be done in a consecutive shifts (with potential crew replacements if the leak is scheduled to last very long)
b. We modify the single deadline assumption used in the Full Model to a two deadlines per job. The first deadline a target deadline, and the Resource Planner can specify a service level for the percentage of jobs of a type she wants complete by their target deadlines. The service level can be derived based on the targets set by Resource Management. The second deadline for a job is its final one, and all jobs must be finished by that date.
c. Customer service jobs, which need to occur on a specific date, are automatically added to the list of jobs to be scheduled on that date in the first stage of the optimization. In the second stage, these along with the other jobs present are

assigned to crews.

The following terms are useful in understanding the structure of the aggregate model:

Planning horizon: Time horizon for which the jobs are to be scheduled, but not necessarily assigned to a crew. For example: April 1, 2011 to April 30, 2011

Assignment horizon: Time horizon for which the scheduled jobs are to be assigned to crews. This must be a subset of the planning horizon, and starts from the beginning date of the planning horizon. For example: April 1, 2011 to April 7, 2011

Figure 13 provides a graphical illustration of the inputs and outputs in the two stages:

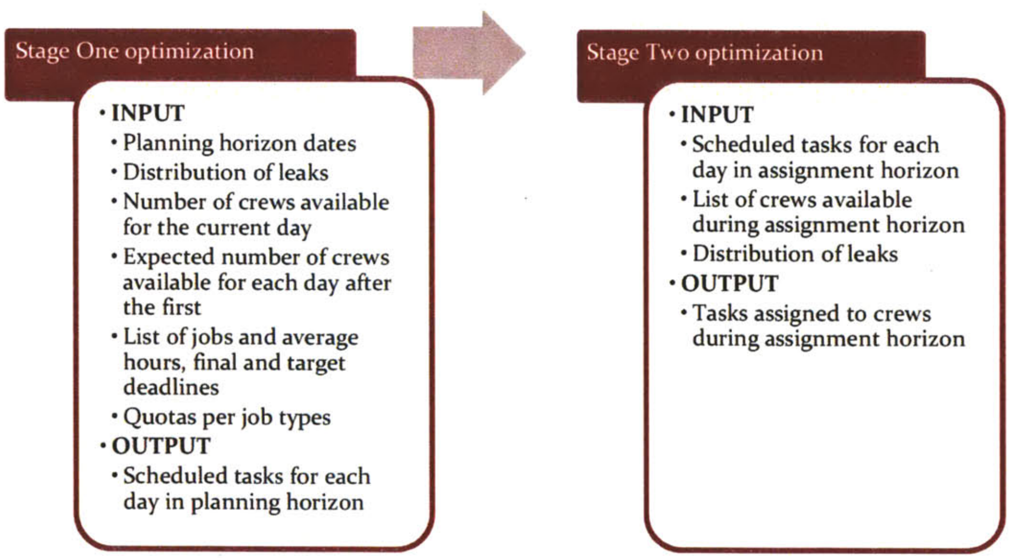

Figure 13: Graphical illustration of optimization engine stages

5.2.5.2.1 Stage One Optimization: Job Scheduling

The goal of the stage one optimization is to do a high-level scheduling of jobs for the planning horizon, but without assigning them to specific crews. For this stage, we assign jobs to each day assuming a single crew whose straight time hours available are an aggregate of the straight time hours of the crews scheduled for that day. We have observed that the type of work done on weekdays and weekends differ greatly, as do the Grade 1 leak distributions that occur during these two time periods. Therefore we treat these two time periods separately. Table 3 lists the notation, and indices used in the optimization model and provide a brief explanation for them and Table 4 lists its decision variables.

Data

Notation	Brief Explanation
g	The number of unknown emergency leaks in the leak scenario
r, t	Day indices. This model incorporate jobs that can last multiple days, hence two indices are needed to track the assignments of all days in the multiday work period
i	Job index
v	Type of the job (e.g. customer service request, Grade 2 Leak et
$q_r(g)$	Probability of g leaks appearing on day r
H_r	Number of straight time hours available on day r on a normal crew shift
C_r	The aggregate number of crews working on day r
I_v	Subset of all jobs that are of job type v
Q_v	Minimum quota on the number of jobs of job type v that need to be scheduled before either the end of the planning horizon or the target deadline, whichever is earliest
D_i^{target}	Target deadline for job i. This is the deadline that a certain percentage of the jobs to be assigned should be done by
D_i^{final}	Final deadline for job i . All jobs must be done by their final deadlines
L_i	Time to complete i^{th}planned job
L_g	Time to complete Grade 1 Leak in one shift
$L_i'(r,t)$	This is the average number of hours remaining to complete a job beginning with day r (this may be a multi-day job in that case, if this term is greater than zero, r has to be some day in the multiday period)
S_i	The number of shifts it takes to complete job i. For most jobs this term's value is 1. In the case of multiday jobs, recall that a multiday job is done on the same shift (first, or second) over a period of days. Most commonly, a multiday job is worked on for the full shift for every day except the last, eg: a three day/shift job that takes an estimated 20 hours to complete, will have 8 hours worked by the crew on the first day, 8 on the second day , and four on the last one.
wf_i	Weekend flag to indicate that job i can be worked on during the weekend
T	List of dates in planning horizon
G_r	List of all leak scenarios possible on day r

Table 3: Notation and Explanation for Stage 1 of the Aggregate Model

Decision variables

Notation	Brief Explanation
V_{rg}	Aggregate number of overtime hours on day r if g emergency leaks appear on that day
X_{it}	Binary variable indicating completion of job i on day t

Table 4: Decision Variables of Stage 1 of the Aggregate Model

Objective function

The objective of the stage one optimization is to minimize the sum of average number of overtime hours in the planning horizon. Using our notation, the objective function is:

$$\sum_{r\in T}\sum_{g\in G_r} q_r(g)\times \max\left(0, g\times L_g + \sum_{i:wf_i=1}\ \sum_{t:days(r,t)\le S_i-1} L_i'(r,t)\times X_{it} - C_r\times H_r\right)$$

As before we can make this linear by simplifying to:

$$\sum_{r\in T}\sum_{g\in G_r} q_r(g)\times V_{rg}$$

Model constraints

1. The variables V_{rg} must be equal to the overtime hours at day r when g leaks appear:

$$V_{rg}\ge 0$$

$$V_{rg}\ge\ g\times L_g + \sum_{i:wf_i=1}\ \sum_{t:days(r,t)\le S_i-1} L_i'(r,t)\times X_{it} - C_r\times H_r$$

2. The aggregate number of hours worked in any scenario cannot exceed the following upper bound:

$$g\times L_g + \sum_{i:wf_i=1}\ \sum_{t:days(r,t)\le S_i-1} L_i'(r,t)\times X_{it}\ \le\ 2\times C_r\times H_r$$

3. Jobs whose final deadlines are within the planning horizon, must be scheduled job before their final deadline:

$$\sum_{t:t \leq D_i^{\text{final}}} X_{it} = 1$$

4. Jobs whose final deadlines are past the planning horizon, may or may not be scheduled:

$$\sum_{t:t \leq T} X_{it} \leq 1$$

5. Every job type, must meet its minimum quota of number of jobs, by having jobs scheduled by the first of the end of planning horizon or by the target deadline, whichever comes earliest.

$$\sum_{i \in I_v} \sum_{t:t \leq \min(T, D_i^{\text{target}})} X_{it} \geq Q_v$$

Model feasibility

It is possible that, in rare cases, the number of days between the start of the planning horizon and the final deadline date for certain multiday jobs is less than the number of shifts required to complete the job. This situation naturally would make the model infeasible. To avoid this, we perform a model feasibility check before performing the Stage 1 optimization, and if infeasibility is found, the following actions are performed to make the model feasible:

1. If the job that fails the infeasibility test (fewer days between the start of planning and final deadline date) can be done during the weekend, and is infeasible, then the final deadline is shifted so that the number of days between the start of the planning horizon and the final deadline is exactly equal to the number of shifts required to finish the job.

2. If the job can only be done during weekdays, and is infeasible, set it to be able to be done during the weekend. Do Step 1 again. Practically speaking, the weekend crews are trained to work on any kind of jobs, and this approach is reasonable.

Model output

After stage one optimization has been executed, it returns a list of tasks scheduled to be done for every day of the planning horizon.

5.2.5.2.2 Stage Two Optimization: Job Assignment to Crews

After the set of all jobs have been initially scheduled to the different dates in the planning horizon, the next step is to assign the scheduled jobs in the assignment horizon to specific crews. Table 5 provides the notation used and a brief explanation for them, and Table 6 lists the decisions variables used by the mathematical representation of this model.

Data

Notation	Brief Explanation
k	Crew index
j	Task index. Here a task is defined as the job (or a piece of a job for a multiday job) that is scheduled for a day.
K	The set of all crews available to work during a current day
I	Entire set of all tasks to be done during the current day
L_j	Time required to do task j

Table 5: Notation and explanation for Stage 2 of the aggregate model

Decision variables

Notation	Brief Explanation
V_{kg}	The set of all crews available to work during a current day

X_{jk}	Binary variable indicating task j is to completed by crew k
Z_{kg}	This is the number of emergency leaks that crew k is assigned to do when the total number of leaks is g

Table 6: Decision variables for Stage 2 of the aggregate model

Objective function

The objective in the stage two of the aggregate model is to minimize the sum of the per-crew overtime hours for a current day. This optimization is done separately for each of the days in the assignment horizon, based on the task list produced by the stage one optimization. Using our notation, it is

$$\sum_{g\in G}\sum_{k\in K} q(g)\times V_{kg}$$

Model constraints

1. The variable V_{kg} must be equal to the number of overtime hours for crew k when g emergency leaks appear during the current day.

$$V_{kg} \geq 0$$

$$V_{kg} \geq L_g \times Z_{kg} + \sum_{j\in I} L_j \times X_{jk} - H_r$$

2. All scheduled tasks must be assigned to a crew.

$$\sum_{k\in K} X_{jk} = 1$$

3. All Grade 1 leaks that occur must be assigned to a crew.

$$\sum_{k \in K} Z_{kg} = g$$

4. Variables X_{jk} and Z_{kg} must be integral.

$$X_{jk} \in \{0,1\} \quad \text{and} \quad Z_{kg} \in \{0,1,\ldots,g\}$$

Model output

After the stage two optimization is executed, it returns a list of task and assignments to crews for each day in the assignment horizon. RAPT takes this final output, and dynamically generates a webpage (sample output shown in Figure 9: **Sample Output of the RAPT Tool**) that is sent by the webserver to the Resource Planner's browser.

5.3 Process Design

New processes were created, and existing ones were changed along two key themes:

1. **Data Integrity:** During the course of the thesis, we observed that a lot of the data was either missing, inappropriately gathered or not vetted before entry into the system. Having bad data makes it very difficult to apply a data-driven tool and makes it even more difficult to address the right issues.
2. **Accountability:** We attempted to create processes with multiple levels of accountability to enable oversight and better cost control. Incorporating accountability also bolsters the practice of continuous improvement as practiced by the company.

The following is a non-comprehensive list of the process changes made:

5.3.1 Data Integrity

1. Adding and Updating the Jobs database
    a. Processes were created to ensure that when new jobs were added to the Jobs Databases, they had the right database fields set, in a consistent manner across all jobs and yards.
    b. Prior to this work, certain job types were not entered into the Jobs Databases and were instead tracked on paper at each yard. Our changes attempted to fix that issue and add this information to the database.
    c. Training was scheduled for Resource Planners, Supervisors and Crew members to familiarize them with the new process flows.

2. Work Execution and Time Sheet Entry
    a. To avoid the issue of jobs being left marked incorrectly incomplete in the system, we recommended that a crew that finished work on a job marks it completed in the Jobs Database on same day, preferably before leaving job site. Supervisors would also be required to approve the job completion on the same day.
    b. This process is also to be followed at the end of the day for time sheets. Crews would be required to enter the hours they worked into the time sheet database before end of day, which should be examined and approved by their Supervisor on the same day.

5.3.2 Accountability

1. Granting Overtime

a. The process currently followed in certain yards and described in the **Overtime** Granting Process section is a solid baseline, which we felt needed to be propagated across all yards.

b. It made sense to stop granting more than 2 hours overtime on any day to execute multiday jobs, as these were expected to be assigned by RAPT to the same crew for the next day.

2. Overtime and Productivity Oversight: We recommended a layer of oversight be added to yard operations through a daily morning meeting of the Field Manager of the yard, the Resource Planner and all Supervisors to discuss the previous day operations. During this meeting:

   a. Overtime and Jobs completed per Shift numbers should be discussed for every crew

   b. These numbers should be compared to those predicted by the model

   c. Any discrepancies must be accounted for. All issues seen, e.g. lack of proper tools for the crew, or perhaps an issue with RAPT, must be addressed by a specified time limit stated during the meeting.

   d. Issues brought up in previous meetings should be followed up and the Field Manager should ensure that these are closed

3. Supervisory paperwork overload: This issue seemed to come up repeatedly at different yards. Supervisors had a lot of paperwork to fill out to manage their crews and the yard they were a part of. This prevented them from carrying out their job of supervising their crews in the field as effectively as they could. As a suggestion that may be implemented in the future, we believe that since a lot of the work done is the computer entry of paperwork provided by the

crews, perhaps it could be simpler to train the crews directly to do this and simplify the data entry procedures for them.

4. Union Engagement: We noticed that for certain Unions, there was sometimes an Us vs. Them attitude regarding management. We believe that it may be possible in the longer term to reverse this attitude, if management pays sufficient attention to the issue and tries to engage the Union workers. From anecdotal experience, it appears that providing training for the workers to enable them to be more effective and develop in their careers would go a long way in alleviating this problem.

5. Incentive Alignment: We believe that in the longer term, it is important to fix incentive misalignment issue created by allowing Supervisors overtime when their crews get overtime. One potential solution is eliminating the Supervisor's ability to earn overtime or perhaps rewarding Supervisors based on the productivity of their crews[2]. This is already effectively carried out on the electricity distribution side of National Grid operations.

5.3.3 RAPT Related Improvements

Certain process changes were made that would enable RAPT to perform more efficiently, such as ensuring that the Resource Planner had permits ready for at least two weeks worth of work. This allowed the model more leeway to pick jobs and enabled it to be much more efficient in devising an optimal schedule. Other changes suggested dealt with making it easier for RAPT to pick up jobs,

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[2] Care must be taken here to structure this appropriately. Incentivizing Supervisors on the basis of crew productivity may have unintended consequences on the reporting of jobs completed or time worked.

and easier for it to distinguish clearly between jobs that were incomplete at the end of the day, and those that had not been allocated.

5.4 Chapter Summary

Chapter 5 explains in depth the Resource Allocation and Planning Tool developed to automate job scheduling and crew assignment process, provide management with insight into how policies may affect operations in the future, and serve as a business intelligence tool that offers management a new look into their operations as they are. We also discuss the important changes to certain processes at the yard to improve data quality and accountability.

6 Results

Figure 14 below, shows a disguised version of the hours worked by all crews in a selected yard in April 2011. In this case there were approximately twenty five crews over the weekday and four over the weekend. Looking at the figure, a few points stand out:

a. The hours worked by the crews per day vary greatly from day to day.

b. Although it is not obvious from this graph, the unevenness of the work causes the workers to go into overtime for certain days. At an aggregate, a yard with 25 crews per day will work 200 hours on straight time. Any hours worked by the yard over 200 hours is considered overtime.

c. Randomly occurring Grade 1 leaks are not the main cause of this yard having uneven work across the month. We can see that leaks form a small percentage of the total hours worked.

d. With better scheduling, and better crew management the picture below can be improved.

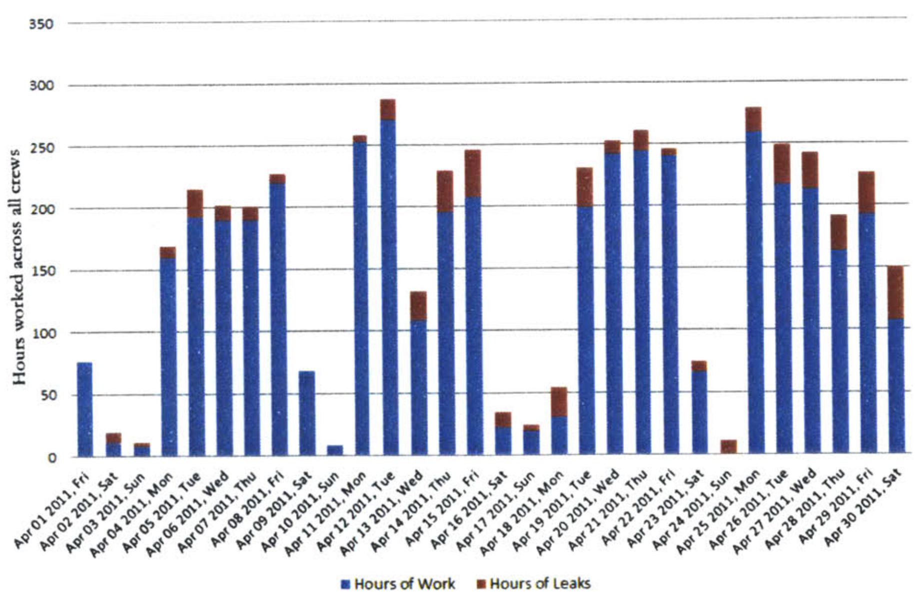

Figure 14: The Before Picture: Total Hours worked at the selected yard for the month of April

The overtime worked during this month in this yard is depicted in Figure 15. The figure represents overtime as a percentage of straight time hours. We can see that the overtime (and hence hour worked) is uneven, corroborating the results we see in the previous figure. We also can make interesting deductions from two graphs for instance we see that overtime spiked on the last day of the month, likely due to the presence of a large number leaks with a very small number of crews available to work on them.

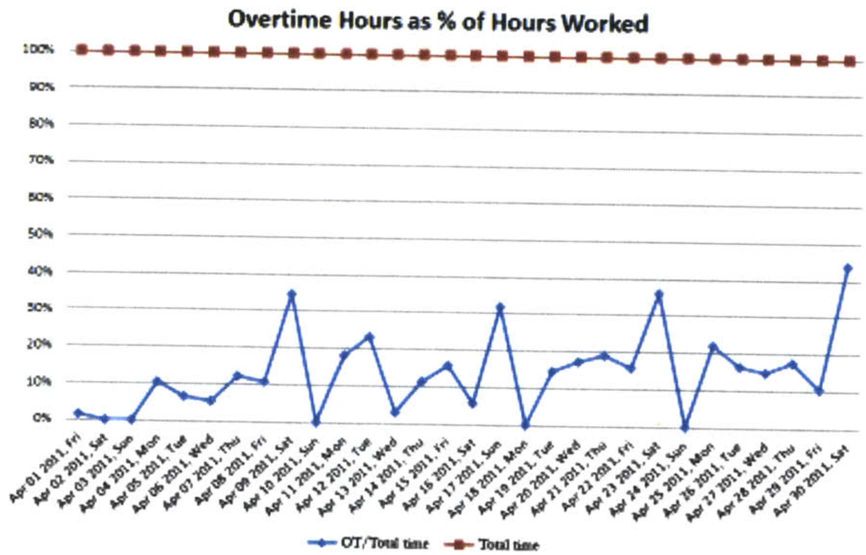

Figure 15: Before Picture- Overtime hours as a percentage of hours worked

We now look at the results of using RAPT to schedule jobs and assign crews. We set up a test system such that when generating the schedule for any given day, we know the exact information that a resource planner would. For instance, the number of urgent leaks is not known before the schedule is determined for any day nor is it known beforehand if a job is going to take much longer than expected.

Figure 16 illustrates the results on the total hours worked with the same yard. Please note that no improvement in crew-productivities have been assumed for this experiment.

RAPT decreases overtime by 65%!

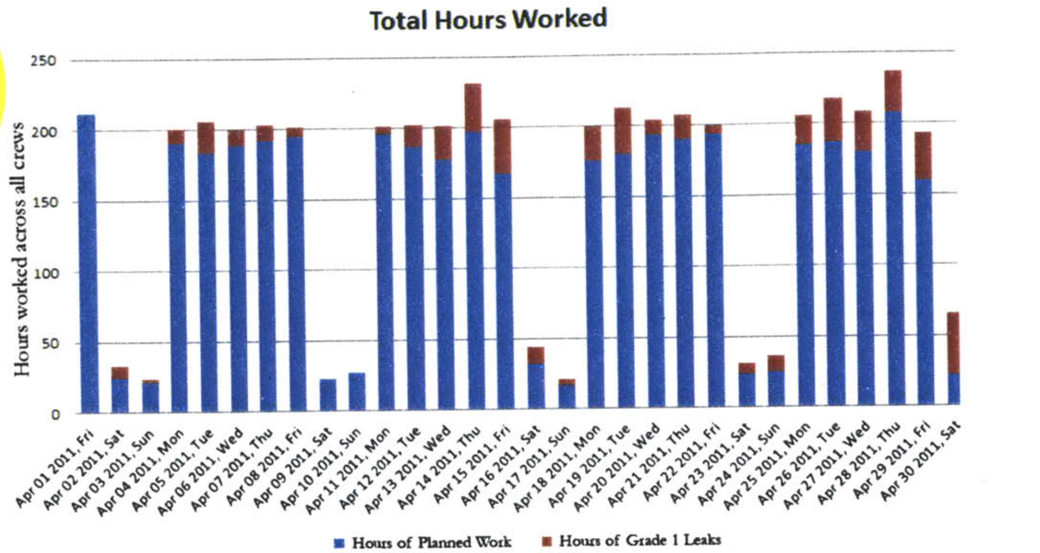

Figure 16: The After Picture: Total Hours worked at the selected yard for the month of April using RAPT

The number of hours worked per day is now a lot more even across the month. Significantly less overtime is used – 65% less. We can take a look at how the overtime per day looks in Figure 17.

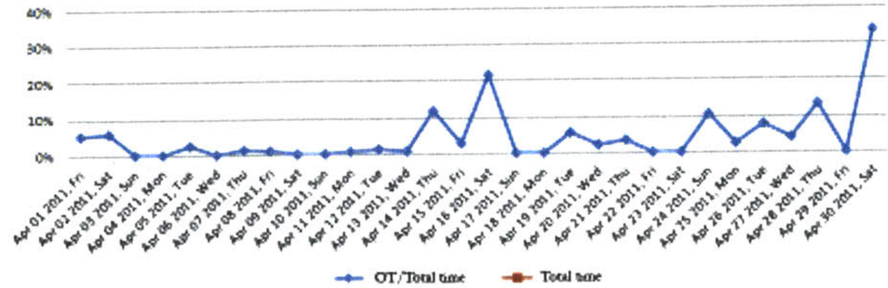

Figure 17: The After Picture- Overtime as a percentage of total hours worked

The projected savings from this system are substantial. Due to the sensitive nature of the data, unfortunately we cannot share the numbers here. However, our analysis indicates that even if we assume, very conservatively, that overtime only reduces by 10% from current levels instead of 65% as indicated, the magnitude of the savings should still warrant management deploying considerable resources to this work. National Grid has expressed strong interest in continuing this work through a pilot at a yard, and subsequently expanding it companywide. Please see the next section for details.

As a point to note, in the yard to achieve these results we see in the experiment above, we will need to deploy RAPT along with the process changes outlined in the chapter above, gain grassroots support from the worker's union and continue with strong management leadership.

6.1 Pilot

To validate the savings seen, we have been working with National Grid over the course of last year, and through this year on piloting the entire system at one of their yards. The first phase of the pilot which involved implementing the newly designed processes and letting the staff at the yard become familiar with the tool is now complete. The next phase of the pilot has just begun (as of April 2012) where the impact of the system will be tested, and the savings observed. This pilot is judged on the same metrics as the model, a few key metrics are:

- **Overtime:** Overtime/Shift, Total Overtime, Overtime per type, Overtime/Total hours
- **Jobs:** Total Jobs, Jobs/Shift, Total Jobs per type
- **Cost:** Nominal Cost (using a portfolio approach to compensate for the varying percentage of different job types through the pilot), Cost/Job

Early indications from phase 1 look very positive based on these metrics. After verifying results, National Grid plans to roll out the system across its fifty yards in the country. As a direct result of this internship, National Grid is projected to substantially reduce costs through overtime management and increased efficiency.

6.2 Conclusions

With a rapid increase in field service costs, seen by utilities in the country, National Grid has to adopt new methods of lowering costs. This thesis considers the problem of excessive costs due to high levels of overtime at yards (a major component of field costs) and proposes solutions to address the issue. We look at Resource Planning and Work Execution, two key components of work at a yard. Resource Planning, the art of picking the right jobs for the right days and assigning the right crews to them while meeting constraints of regulation, customer service, and safety at the minimum cost is an extremely difficult problem. This is exacerbated by the fact that there needs to be enough slack in the system to deal with one or more pipeline leaks that may be called in. At the execution stage, when the jobs are carried out by crews, the lack of standardization in work processes dealing with granting and approval of overtime, productivity tracking, data collection, and imperfect alignment of incentives make it difficult to get the best work from the crews.

One major outcome of this thesis is the optimization of short term resource planning. We automate the complex task of resource planning by the means of a sophisticated tool, the Resource Allocation and Planning Tool. RAPT includes a two stage stochastic optimization model, and powerful analytics tool. It serves three primary functions:

a. Automates short term planning and performs the task of job selection, crew assembly and assignment, to minimize cost in the presence of uncertain resource availability and in the presence of a variable number of pipeline leaks.
b. As an analytics tool, providing a companywide view of US gas operations efficiency, allowing management to ask sophisticated questions about yard operations and gain a deep understanding of operations at a yard, allowing management to perform companywide comparisons for metrics they prefer.
c. As a decision aid, enabling management to predict the impact of management policies on field operations.

The effort to improve the execution of yard operations focused on improving the data collection, realigning incentives and standardizing work processes. New processes were created for scheduling, crew data entry, overtime approval, adding accountability and oversight at various levels. Our work has enabled better overtime and productivity management, and has provided the company the structure for continuous improvement allowing management the ability to understand and track unexpected deviations in their work going forward.

These changes are currently being piloted at a number of yards around the company, and the initial results are very encouraging. As a direct result of work done in this thesis, National Grid is projected to achieve up to 65% reduction in overtime, saving the company a substantial amount of money.

6.3 Chapter Summary

This chapter covers the results evaluating the impact of the tool. With the tool, the number of hours worked by the crews move from a very spiky nature to much more evenly spread across the month. We see that with the work done in this thesis, National Grid has the opportunity to reduce overtime by up to 65% thus substantially reducing their costs.

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