8-1-2013

Workforce planning and facility utilization using a two-stage stochastic recourse approach

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August, 2013

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Submitted in partial fulfillment of the requirements

for the degree of Master of Science in Industrial Engineering

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August 05, 2013

M.S. DEGREE THESIS

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has been examined and approved by the

thesis committee as satisfactory for the

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Acknowledgements

I wish to express my sincere gratitude toward all who provided me with their support and help in completing my thesis.

I like to thank Dr. Scott Grasman for providing me with an opportunity to work on this wonderful problem. Dr. Grasman showed the way when I was lost and he was the light whenever I found myself in the darkness. He encouraged me to grow not only academically but also professionally. I also like to thank Dr. Hewitt for deeply ingraining the basics of Operations Research through his courses.

This thesis is an extension of the doctoral dissertation by Dr. Jarugumilli who has been constant source of guidance right from the day we first met at Informs Annual Meeting, Phoenix. He taught and corrected me for my own benefit like friend and sometimes like a teacher. I will like to thank you for your patience and understanding and I know I owe you big time. I like to thank Dr. Keng from Intel for his valuable inputs, feedback and knowledge that allowed us to build a better system that fits to practical needs of an industry. This work is part of Dr. Grasman's ongoing research in workforce headcount solver and graciously supported by the Intel Corporation.

Further, I like to thank my parents, especially my father for being a source of inspiration. Your love for Mathematics motivates me to build better and robust systems using simpler logic. I also like to thank my extended family at Rochester, my friends Chaitu, Amey, Omkar, Atul, Anshul, Nisharth and Mugdha for making this journey so memorable. Finally, I will take a moment to deeply thank God for getting all these amazing people in my life and for providing me with His strength that allowed me to go through with the objective.

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Abstract

Hi-tech manufacturing uses sophisticated and capital intensive processes that require a highly skilled workforce. Fluctuating demand leads to either a shortage of skilled workers that causes unmet demand or an excess of skilled labor that causes worker idleness. This mismatch in the available and required skillsets is a source of potential loss for the organization. This thesis formulates an industry-motivated workforce planning and facility utilization problem as a two-stage stochastic recourse program that considers fluctuating demand over a long planning horizon and includes business and labor rules, e.g., hiring, firing, overtime, cross-training, and shift swapping, that govern the structure of the workforce. Solutions to this problem are computed using a scenario-based approach and indicate that the cost of workforce formation can be significantly reduced by using the recourse problem.

1 Introduction

Manufacturing firms maintain diverse segments of products that require different manufacturing techniques, and have to balance their production to meet the demand for all product segments reasonably. Therefore, manufacturing organizations invest heavily in manufacturing technology and workforce. Composed of various intricate and capital-intensive processes, hi-tech manufacturing requires highly skilled workers who are greatly in demand in the labor market (Morrison et al. 2008). Due to the uncertain nature of the demand, organizations have to manage the available workforce on a regular basis. Organizations need to meet the market demand by making workers with necessary skills available to do the required tasks and, at the same time, manage the idleness among the highly skilled workforce. Therefore, workforce planning and facility utilization is one of the most important aspects that organizations with labor-intensive manufacturing need to address. Short product lifecycles, on-demand production, high training and recruitment costs, and different personal learning patterns also directly affect organizational success.

Problems with Short-term Personnel Planning Models

Personnel planning models, e.g., those formulated by Jarugumilli et al. (2010) perform well with known demand. These models assign individual multi-skilled workers to operations over single and multiple shifts in an attempt to reduce the "gap" in worker assignments, i.e., the mismatch in the required and available skills. Though these models assign workers to operations very efficiently, gaps occur when there are not enough workers to operate the processes. As these are short planning horizon models, they ignore actions such as hiring and cross-training. To satisfy the unmet demands, these models assign workers to overtime or idle workers are assigned to tasks that they are not skilled to perform. The quality of assignment produced by these models

can be improved by making a right mix of workforce available by applying various actions such as hiring, cross-training, and shift swapping.

The cross-training model developed by Gandhi et al. (2013), an extension of Jarugumilli et al. (2010), is used to assign workers to cross-training jobs in order to increase flexibility within the workforce. Cross-training is a strategic decision, and requires trainee and trainer to leverage their efforts toward an activity that does not directly contribute to the daily production routine, but offers an opportunity to add an extra resource for future production cycles. Therefore, it is important for the model to cross-train the correct number of workers that are anticipated to contribute to production work in the future while not hampering the daily production. Better decisions can be delivered using this model if mismatch in the workforce can be predicted before the actual demand occurs.

Actions for Workforce Planning

To support their ongoing production, industries maintain a workforce composed of workers with varied skill-sets to operate the processes. Each worker has a fixed work schedule, which remains the same unless changed. Such workers are referred as regular workers. Work schedule depends on skill-sets possessed by the worker and market demand, and the size of this regular workforce can be altered using various actions.

Based on requirements, an organization can change the work schedules for the regular workers by changing the time s/he reports to work, i.e., changing the worker’s shift. This action is termed as shift swapping. Regular workers can also be assigned to overtime wherein workers work for a longer duration than their regular required effort. For this extra effort, they are paid at a higher rate than the regular compensation rate.

Conerly et al. (2013) identifies cross-training as one of best business strategies for it increases workforce flexibility. In cross-training, a worker can be formally trained to perform a particular operation so that the worker can contribute to production. Cross-training is advantageous as it lowers the cost of workforce formation since the training is performed during the regular worker hours. However, time for cross-training may vary depending on the cognitive abilities of the trainee, availability of both trainer and trainee, and demand scenarios.

Hiring, on the other hand, can be used to add new workers to the regular workforce. Hiring involves a onetime fixed cost, which is usually very high. Hiring is useful when there are no idle workers for cross training or available workers, e.g., startup organizations. Therefore, both cross-training and hiring decisions require a long planning horizon and they cannot be effectively implemented over in the short term (Jordan et al. (2004) and Bowen et al. (1991)).

The right size and mix of a workforce needs to be determined well in advance in order to provide enough time to the organization to recruit and cross-train workers before short-term planning models are solved. Considering the time involved in planning for hiring and cross-training, the organization will determine the size of the workforce for a long planning horizon, e.g., quarterly, to reduce the overall operations cost. Further, this workforce size should be robust enough to handle uncertain demand. Thus, there is a need for flexible workforce-planning models that manage a multi-skilled workforce over a long planning horizon with uncertain demand. The aim of these workforce-planning models will be to utilize the available workforce effectively.

In this thesis, the workforce-planning problem is modeled as a two-stage stochastic program with recourse. In the first stage, based on the nature of the demand distribution, the size of the workforce is determined that will remain constant throughout the planning horizon. Long-term

actions such as hiring, cross-training and shift swapping will be taken to determine the composition of the workforce. In the second stage, once the value of the demand is revealed, short-term decisions such as overtime may be used to satisfy the demand. This model is implemented as a strategic workforce management system equipped with interactive user interfaces for importing/exporting data, implemented on .Net platform using C# object oriented programming framework, and CPLEX concert libraries to solve the mathematical model.

The thesis is organized as follows: Section 2 presents a review of literature related to workforce planning and personnel scheduling, and highlights the existing gap in the research that calls for a stochastic workforce-planning model over a long planning horizon. In Section 3, we describe the industrial setting considered in this problem, and present notation. This section also discusses the mathematical model used to solve the problem including the intuition behind constraint building. Section 4 describes the general form of a stochastic linear program and parallels are drawn between the problem formulated in Section 3 and the general form. Solution methodology used to solve this problem is also illustrated in this section. As a solution methodology, we discuss a scenario-based approach and show how the formulation mentioned in Section 3 translates to that form. Section 5 presents numerical experiments conducted to validate the model. This section presents the data used as input to the model and using a simple example, the functionality of the model is explained. A summary of larger test cases and the computational time is also described in this section. Finally, Section 6 discusses the conclusions and the future works. Appendix is dedicated to the implementation of the formulation into software. This section describes the modules, methodologies, and framework used to build the workforce planning system.

2 Literature Review

There has been extensive research in the field of workforce planning, aimed at solving problems in functional areas such as manufacturing, healthcare, and other services. Comprehensive reviews by Ernst et al. (2004) and Van et al. (2013) reference 250 research papers published between 1970 and 2012. Papers are divided into categories based on personnel characteristics, solution methodology, and areas of applications. These works provide strong support to the work undertaken here. Similar work, e.g., Wang et al. (2005) and Brecht et al. (2010), provide insights into work undertaken in the scope of workforce scheduling in a variety of industries.

Apart from these reviews there are other works in the field of strategic workforce planning and management that are more relevant with respect to the nature of problem solved. These works can be broadly divided as deterministic and stochastic models. Apart from this distinction, there are models that manage homogenous (single-skilled) as well as heterogeneous (multi-skilled) workforces. These models can also be distinguished based on various actions used to form a workforce.

Deterministic Workforce Planning Models

As mentioned, earlier deterministic personnel planning models formulated by Jarugumilli et al. (2011) can be used over a short planning horizon. The workforce problem is formulated as a mixed integer program and is solved using an iterative decomposition algorithm. Though these models assign workers to operations very efficiently, they do not compute the required size of the workforce and might result in 'gap' in the assignments. As these are short-term planning horizon models, they cannot use strategic actions such as hiring and cross-training, and have to use overtime to satisfy the excess demand. Though assigning overtime is cheaper in short term,

this action generally cannot satisfy a prolong shortage as effectively as long term planning actions such as hiring and cross-training.

Subramanian et al. (2008) models a deterministic workforce-planning problem for a service industry by formation of a multi-skilled workforce using cross-training. The work integrates the hiring, firing and contracting of employees of desired skills for the given time period into the model, which is solved using an algorithmic approach. As the desired skill is the primary focus, the model also considers the lead time for cross-training employees. Fowler et al. (2008) states that though cross-training adds flexibility to the workforce not all employees have the same learning curves. To portray this behavior, Fowler et al. (2008) designed heuristics to solve the workforce-planning model that integrates hiring, firing, and cross-training of multi-skilled employees, along with considering their different cognitive abilities.

Drexl et al. (2008) obtains substantial cost savings by solving a multi-skilled workforce-planning problem for a multi-process industrial setting over a long planning horizon. This problem is formulated as an integer program, solved using a column generation technique for generating bounds and a local search to arrive at an integer solution. This model determines the aggregate optimal level of the workforce required for deterministic demand.

Al-Salamah et al. (2011) integrates the workforce planning problem and multi-product production management problem to determine the optimal temporary workforce to satisfy a deterministic demand over a long planning horizon. To determine the optimal size of the workforce, regular and temporary contractual workers with finite contract validity are used. The model also includes backlogging and inventory.

While implementing production planning for a multi-product line production, Techawiboonwong et al. (2003) formulates a model to build a homogenous workforce using swapping of workers between production lines and assigning overtime. It also uses hiring/firing of workers to satisfy a deterministic forecasted demand over a given planning horizon. It also considers product inventory and subcontracting of the demand.

Stochastic Workforce Planning Models

Ozgur et al. (2008) builds a multi-skilled workforce using cross-training and firing. It formulates the problem over a single period as a scenario-based two-stage stochastic problem and solves it using Bender's decomposition algorithm. Bard et al. (2007) models a workforce-planning problem as a two-stage stochastic recourse problem over a long planning horizon and solves it using a scenario-based approach. In this model, the size of the workforce, in the form of the number of regular and part-time workers, is determined in the first stage and worker assignment to specific shifts and estimation of the number of overtime and temporary workers is made in the second stage. Slack variables in the model facilitate hiring decisions, if required. The random demand is quantified as the number of required workers and is divided over shifts and days. This model is based on the assumption of a single operation and a single skill and a scenario-based approach with the three demand scenarios (low, medium and high).

Zhu et al. (2007) uses a methodological framework similar to that of Bard et al. (2007) to build a multi-skilled workforce for a financial firm with functional (skill) demand located in different centers (processes) that have different capacity and recruitment constraints. To satisfy the demand, the model determines the size of the workforce using retention and hiring in the first

stage, and transferring the demand to a different shift and center in the second stage. Bender's decomposition algorithm is used to solve the problem.

Leung et al. (2005) estimates the required workforce size in a stochastic aggregate planning model by formulating a multi-product, single-skill problem as two-stage stochastic problem and solving using robust optimization. Apart from the traditional aggregate planning decisions such as hiring, firing and overtime, Leung et al. (2005) adds subcontracting as one of first stage decisions. In the second stage, backordering and inventory decisions are made that are out of scope of the current problem. Using discrete convexity, Ahn et al (2005) delves into optimal staffing policies for firms that employ a multi-skilled workforce. This problem is solved for a stochastic demand and does not consider cross-training as a demand fulfillment action.

Assuming stochastic demand, Song et al. (2008) uses hiring, firing, and labor swaps to determine the optimal size of an homogenous workforce. This problem is formulated as a multi-stage linear stochastic program and solved by a successive convex approximation method. Campbell et al (2010) formulates a two-stage stochastic model to assign regular and cross-trained workers to jobs. This problem is solved over a shorter planning horizon in order to address the cross-training of individual workers. Ertogral et al. (2008) aims at building a flexible workforce that is used to satisfy demand on a daily basis. This work uses two models, one of which considers flexible workers and other which those not.

Dellaert et al. (2011) determines the budget allocation required to satisfy stochastic demand using permanent and contingent workers. The approach followed by Dellaert et al. (2011) determines the size of the workforce for the entire planning horizon.

Table 1 summarizes the literature review.

	Deterministic /Stochastic	Single/ Multi Skilled	Regular	Hiring/Firing	Shift Swapping	Cross-training	Overtime
Subramanian et al. (2008)	Deterministic	Multi-Skilled	×	×		×	
Fowler et al. (2008)`	Deterministic	Multi-Skilled	×	×		×	
Drexl et.al (2008)	Deterministic	Multi-Skilled		×			
Al-Salamah et. al. 2011)	Deterministic	Single-Skilled		×			
Techawiboonwong et. al. (2003)	Deterministic	Multi-Skilled		×	×		×
Ozgur et al. (2008)	Stochastic	Multi-Skilled	×	×		×	
Bard et al. (2007)	Stochastic	Single-Skilled	×	×			
Zhu et al. (2007)	Stochastic	Multi-Skilled	×	×	×		
Leung et al. (2005)	Stochastic	Multi-Skilled	×	×			
Ahn et.al (2005)	Stochastic	Multi-Skilled	×	×			
Song et. al. (2008)	Stochastic	Single-Skilled		×	×		
Campbell et.al (2010)	Stochastic	Multi-Skilled				×	
Ertogral et al. (2008)	Stochastic	Multi-Skilled	×				
Dellaert et.al (2011)	Stochastic	Single-Skilled	×				

Table 2.1: Comparison of Relevant Literature

While planning for uncertain demand, a more flexible workforce can be formed by using shift-swapping, cross-training and hiring in a single optimization model. Identifying the mismatch in required and available skills in the workforce, and taking actions to reduce it well before the actual demand is revealed can amount, to a better style of workforce management. Cross-training

idle workers can sometimes be beneficial in reducing the need for hiring and firing, and can often reduce the need of overtime for the planning horizon.

Long planning horizons reduce the deterministic nature of the demand. The previously mentioned, deterministic models are inadequate as they cannot model the stochastic nature of the demand, and are not recommended for long planning horizons. Previously mentioned stochastic models are more focused on determining the size of the workforce using the respective actions than managing the available workforce efficiently. Though models formulated by Song et al. (2008) and Ertogral et al. (2008) determine the level of the workforce required but ignore the various actions used to form workforce. Models by Bard et al (2007), Song et al. (2008) and Dellaert et al. (2011) consider homogenous (single-skilled) workforce, an assumption that doesnot hold for most of the manufacturing settings. These models prove inefficient for managing multi-skilled workforces, since cross-training is not considered. Models of Leung et al. (2005) and Ahn et al. (2005) use hiring/firing in addition to a multi-skilled regular workforce that in real world can greatly increase the cost of workforce management which can reduced using other workforce management actions. Workforce planning models by Zhu et al. (2007), Campbell et.al (2010) and Ozgur et al. (2008) do not consider all actions for managing a flexible multi-skilled workforce.

In this thesis, the strategic workforce management problem is modeled as a two-stage stochastic program with recourse. In the first stage, the size of the workforce is determined that will remain constant throughout the planning horizon. Long-term actions such as hiring, cross-training, and shift swapping will be taken to determine the composition of the workforce. These actions add flexibility to the workforce and reduce the requirement of overtime over a long planning horizon.

In the second stage, once the value of the demand is revealed, short-term decisions such as overtime are used to satisfy the demand.

3 Problem Description

Consider an organization that utilizes highly skilled workers to operate processes. A worker qualified to operate a process has the necessary certification. There are different levels of certifications, and workers with a mix of certifications are required for a process.

The mentioned industrial environment is depicted in the Figure 1. Each of the circles represents the set of workers qualified to operate a process, three such processes are shown in the diagram. The workers that are qualified to operate more than one process form the part of the overlapping regions of the respective process sets. A Venn diagram formed by the overlapping of these three process sets represents a single shift; two such shifts are shown. To build its workforce, an organization takes various actions such as shift swapping, cross-training, and hiring/firing. In the figure, movement of workers to overlapping regions is shown by the red arrows. Shift swapping and hiring are shown using green and blue arrows respectively. Workers can be assigned to overtime if on the same day if there is shortage of skilled workers in a different shift. As per organization policies, there is a limit on total overtime and shift swapping for the entire planning horizon. The objective of the organization is to minimize the cost of workforce required to meet uncertain market demand while satisfying all business rules.

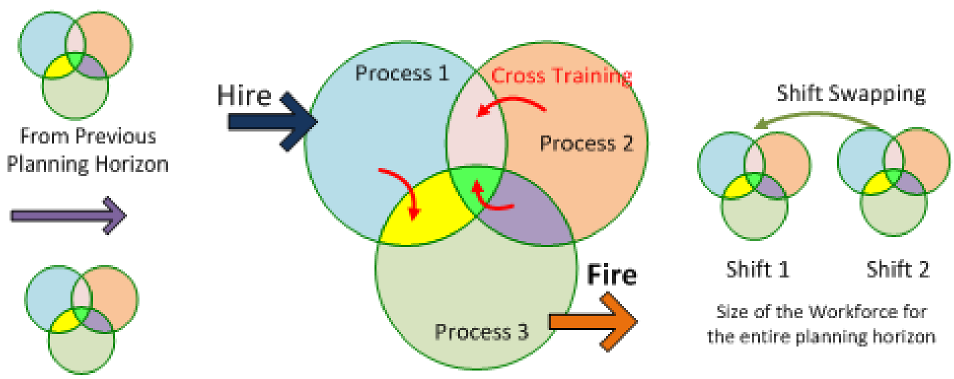

Figure 3.1: Strategic Workforce Model

3.1 Model Development

Consider an industry for which we need to determine the size of the workforce for a long planning horizon ***t***. This industry utilizes ***J*** intricate processes such that each process ***j, j*** ∊ {1…J} requires highly skilled workers. A worker ***i*** belongs to the set of ***I*** workers, i ∊ {1…I}. A worker ***i*** is qualified to operate a process ***j*** if the worker has the necessary certification. There are ***L*** certification levels for all ***J*** processes. If a worker ***i, i*** ∊ {1…I} undergoes a certification for skill level ***l*** , ***l*** ∊ {1…L} and process ***j, j*** ∊ {1…J}, the worker can said to be qualified to operate process ***j*** with skill level ***l, l*** ∊ {1…L}.

Each process requires workers with a mix of skill levels. A worker ***i*** may be certified to operate more than one process. Such a worker is referred as a flexible worker; On the contrary, a worker with a single certification (qualified to operate a single process) is referred as an inflexible worker (Jarugumilli, 2011). An entire production cycle is divided into ***K*** shifts and shift ***k*** lasts ***k*** ∊ {1…K}. The workers are assigned to a particular shift ***k*** are part of the regular workforce and termed as regular workers. Workers operate processes for a shift ***k*** and, once that shift is over these workers are replaced by a different set of workers to carry out the remaining production.

Uncertain market demand $\boldsymbol{R_{jkl}}$, is converted to required number of workers per process $\boldsymbol{j}$, skill level $\boldsymbol{l}$ and shift $\boldsymbol{k}$, and has a known discrete distribution with probability mass function of $F_{jkl}(R)$. This conversion is based upon the type of the machines, speed of the machines, criticality of the process, and type of skills required. Let X_{jkl} be the size of the workforce formed to satisfy the $\boldsymbol{R_{jkl}}$ demand for shift $\boldsymbol{k}$, process $\boldsymbol{j}$ and skill level $\boldsymbol{l}$ for the given planning horizon.

Regular Workforce

There are X_{jkl}^{0} available regular workers at the start of the planning horizon for process $\boldsymbol{j}$ with skill level $\boldsymbol{l}$ for shift $\boldsymbol{k}$. Due to the flexibility in workforce, there may be $\mu_{jj'kll'}$ number of workers in shift $\boldsymbol{k}$ who are qualified to operate processes $\boldsymbol{j}$ and $\boldsymbol{j'}$, $\boldsymbol{j'} \in \{1 \ldots J\}$ and $\boldsymbol{j} \neq \boldsymbol{j'}$, with skill levels $\boldsymbol{l}$ and $\boldsymbol{l'}$, $\boldsymbol{l'} \in \{1 \ldots L\}$ and $\boldsymbol{l} \neq \boldsymbol{l'}$, respectively. As a result, it can also be inferred that $\sum_j \sum_k \sum_l X_{jkl}^{0} \geq \varepsilon$ where net size of the workforce from the previous planning horizon. Let XF_{jkl} be the maximum of the number of workers that are retained in shift $\boldsymbol{k}$ to perform process $\boldsymbol{j}$ with skill level $\boldsymbol{l}$ out of the X_{jkl}^{0} number of workers. The organization pays cx_{jkl} to retain a worker who can perform process $\boldsymbol{j}$ with skill level $\boldsymbol{l}$ in the $\boldsymbol{k}^{\text{th}}$ shift.

Shift Swapping

Workers may be rotated through the shifts depending upon organizational rotation policies. Therefore, at the start of the planning horizon a worker can be transferred from shift $\boldsymbol{k}$ to $\boldsymbol{k'}$ depending on the requirement, a procedure defined as shift-swap. Shift swapping requires a worker to work as a regular worker in a different shift for a period of some weeks or for the entire planning horizon. $Y_{jkk'l}$ workers can be swapped from shift $\boldsymbol{k}$ to $\boldsymbol{k'}$ to perform process $\boldsymbol{j}$ with skill level $\boldsymbol{l}$ by at a cost of $cy_{jkk'l}$ per worker. These actions can be taken whenever there is a

shortage of workers in one shift and an excess in another. There is a limit $\boldsymbol{\beta}$ on the number of workers that can be swapped.

Cross-training

Cross-training is one of the strategic decisions for building a workforce. Cross-training increases the flexibility among the workers as they might be skilled to perform more than one process. If there is a prolonged shortage of skill ***l*** at a process ***j*** and a prolonged surplus of skill at a different process, cross-training of the workers can be undertaken. Also through cross-training, lower skilled workers can undergo necessary certifications that allow them to perform higher skilled tasks. To differentiate the cross-training activities in this work, the latter is termed as skill training. At the start of the planning horizon CT_{jkl} and ST_{jkl}number of workers can be considered for cross-training and skill training by paying cost of ct_{jkl} and st_{jkl} respectively, per worker for a given process ***j*** with skill level ***l*** in ***k***th shift. Availability of the trainers lies outside the scope of this problem.

Overtime Assignment

A worker ***i*** from shift ***k*** with skill level ***l*** may be assigned to overtime if for the same process ***j*** on the same day there is shortage of skill set ***l*** in a different shift ***k'*.** As per organization policies and labor rules, only $\boldsymbol{\alpha}$ workers can be assigned to overtime within the entire planning horizon. To assign OT_{jkl} workers a cost of cot_{jkl} per worker assigned to process ***j*** with skill level ***l*** in ***kth*** shift is incurred.

Hiring

In case of unavailability of workers within the regular workforce to satisfy the demand, organizations use hiring ti introduce new workers in the regular workforce. In the scope of this work, hiring can be analogous to shift swapping where in the workers are transferred to a shift ***k*** from a fictitious shift, ***k*** = 0. Based on this convention, whenever a worker ***i*** is hired, the worker can be said to have transferred from a zero^th^ shift, where the zero^th^ shift can be said have infinite capacity. It is assumed that whenever the workers are hired by an organization they shall be directly recruited into the required shifts and that these hired resources are not available to be cross-trained during the planning horizon. In the start of the planning horizon, the organization will hire $Y_{j0k'l}$ number of workers respectively, to perform process ***j*** with skill level ***l*** in shift ***k*** at a cost of $cy_{j0k'l}$ per worker.

Excess/ Shortage

It is imperative for the organization to satisfy the demand, at the time same time reduce the idleness among the workers. Let s_{jkl}^{+} be the number of idle workers in shift ***k*** for process ***j***, skill level ***l***, and p_{jkl}^{+} is the cost incurred per worker. Similarly, let s_{jkl}^{-} be the shortage of workers for process ***j***, skill ***l*** and shift ***k***, and p_{jkl}^{-} is the cost paid per worker.

Cost Structure

In this section, we shall discuss the cost parameters that will be used in the objective function of the model. Retaining the workers from the previous planning horizon in the same shift to perform the same process with the same skill is considered the most desirable action. Shift swapping involves workers operating the same process with the same skill level but in a different shift. Therefore, workers should be transferred to the other shifts only if there is an excess in their original shift and a shortage in the other shift, making it costlier than retaining workers in

the same shift. Cross-training requires the trainee and the trainer to leverage their effort toward a process that does not contribute to production. Therefore, cross-training should be performed only if there is an excess of workers in a process/skill-level and shortage in the other. Further, as cross-training involves addition of certifications, it is costlier than shift swapping. Hiring adds an extra resource to the workforce, however is considered to the costliest action. Assigning overtime can be cheaper over a shorter planning horizon; therefore this cost is more than the cost of retaining workers in the same shift but is less than shift swapping cost. However, for a long planning horizon, the cumulative cost of overtime assignment is generally greater than the cost of shift swapping, hiring, and cross-training. Relative costs for workforce planning actions are considered in this problem. Jarugumilli, 2011 proves that proper relative cost structure leads to a optimal formulation.

The objective of the organization is to build a flexible workforce for the entire planning horizon such that the overall cost of workforce formation is the least. As we are planning over a long planning horizon, an aggregate planning approach will be used; thus, all variables are positive rational numbers.

3.2 Notation

The following notation will be used throughout the thesis. Any additional notation may be introduced as required.

Sets

$j \epsilon \{1..J\}$ *Set of Processes*

$l \epsilon \{1..L\}$ *Set of Skill Levels*

$k \epsilon \{0..K\}$ *Set of Shifts*

Cost Parameters

cx_{jkl}: Cost of retaining workers for skill level *l* for process *j* during shift *k*;

$cy_{jkk'l}$: Cost of swapping workers with skill level *l* for process *j* during week *t* from shift *k* to *k'*;

cot_{jkl}: Cost for overtime workers for skill level *l* for process *j* during shift *k;*

ct_{jkl}: Cost of cross-training workers for skill level *l* for process *j* during shift *k*;

st_{jkl}: Cost of skill-training workers for skill level *l* for process *j* during shift *k*;

$p_{jkl}^{+/-}$: Cost of having shortage or surplus workers for process *j* with skill *l* in shift type *k;*

Other Parameters

R_{jkl}: The requirement with probability mass function $F_{jkl}(R)$ of workers for process *j* with skill level *l* during shift type *k;*

X_{jl}^{0}: The number of worker with skill *l* for process *j* from the previous planning horizon*;*

α: Limit on the total overtime both primary and secondary within a planning horizon*;*

β: Limit on the swapping of workers among the shifts within a planning horizon*;*

ε : Total number of workers, without double counting available, at the start of planning horizon*;*

$\mu_{jj'kll'}$: Total number of workers, that are qualified on process *j* and skill level *l* as well as process *j'* and skill level *l'* in a shift k.

Decision Variables

XF_{jkl}: is the maximum number of workers with skill *l* for process *j* from previous planning that can be retained from previous planning horizon*;*

$$XF_{jkl} \epsilon \mathbb{Q}^{+} \geq 0$$

X_{jkl}*:* is number of workers in shift *k* that can perform process *j* with skill level *l* in the given planning horizon*;*

$$X_{jkl} \epsilon \mathbb{Q}^{+} \geq 0$$

$Y_{jkk'l}$: is number of workers swapped from shift *k* to *k'* that can perform process *j* with skill level *l;*

$$Y_{jkk'l} \epsilon \mathbb{Q}^{+} \geq 0$$

Note: Hiring decisions when *k* =0

OT_{jkl}*:* is number of overtime workers allocated to perform process *j* with skill level *l* during shift *k*

$$OT_{jkl} \epsilon \mathbb{Q}^{+} \geq 0$$

CT_{jkl}: is number of workers that can undergo cross-training to perform process *j* with skill level *l* during shift *k;*

$$CT_{jkl} \epsilon \mathbb{Q}^{+} \geq 0$$

ST_{jkl}: is number of workers that can undergo skill-training to perform process *j* with skill level *l* during shift *k;*

$$ST_{jkl} \in \mathbb{Q}^{+} \geq 0$$

Deviational Variables

$s_{jkl}^{+/-}$: are the deviational variables to indicate the excess/shortage workers allocated to perform process *j* with skill level *l* during shift *k;*

$$s_{jkl}^{+/-} \in \mathbb{Q}^{+} \geq 0$$

3.3 Objective Function

Using the above notation, the model is formulated as follows:

$$Minimize \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} cx_{jkl} X_{jkl} \quad (3.1)$$

$$+ \sum_{j \in J} \sum_{k \in K} \sum_{k' \in K \setminus k} \sum_{l \in L} cy_{jkk'l} \,.\, Y_{jkk'l}$$

$$+ \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} ct_{jkl} CT_{jkl}$$

$$+ \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} st_{jkl} ST_{jkl} \quad + \; E(F(X,R))$$

where,

$$F(X,R) = \; Minimize \; \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} cot_{jkl} COT_{jkl} \quad (3.2)$$

$$+ \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} p_{jkl}^{+} s_{jkl}^{+} + \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} p_{jkl}^{-} s_{jkl}^{-}$$

As this model is a two-stage stochastic program with recourse, the size of the workforce will be determined in the first stage, and will be fixed for the entire planning horizon. Regular workers

from the previous planning horizon will be carried into the next planning horizon and remain in the same shift unless they are swapped to a different shift. The swapping variable will capture the transfer of workers and the hiring and firing activity. Cross-training and skill-training are long-term decisions and therefore, also form the part of first stage. Based on the availability of the workers, cross-training variables will be used to increase flexibility of workers that should lead to a reduction in idleness.

The objective function (3.1) is a combination of the cost of the building regular workforce, shift swaps, hiring/firing, cross-training, and an expected value function. The expected value function (3.2) consists of the cost of using second stage variables to take recourse once the actual demand is revealed. Overtime can be assigned to meet the demand that is left unsatisfied after first stage. Deviational variables in the expected value function penalize the excess or shortage of worker hours.

3.4 Constraints

In constraint set (3.3), regular workforce is formed using the workers from the previous planning horizon, shift swapping, cross-training, and hiring. As the workforce is flexible, only a part of the workforce from the previous planning horizon may be assigned. Shift swapping variables will capture the shift swapping as well as the hiring and firing activity. To satisfy the revealed demand, along with the workforce built in constraint (3.3), overtime will be used as shown in constraint set (3.4). Any excess or shortage in the required worker hours is captured by the slack and surplus variables.

$$X_{jkl} = XF_{jkl} + CT_{jkl} + ST_{jkl} + \sum_{k' \epsilon K \setminus k} Y_{jkk'l} - \sum_{k \epsilon K \setminus k'} Y_{jkk'l}\ , \forall j, k, l \qquad (3.3)$$

$$X_{jkl} + OT_{jkl} + s_{jkl}^{-} - s_{jkl}^{+} = R_{jkl}\ , \forall j, k, l \qquad (3.4)$$

Both the maximum number of workers that can be assigned to an process, and the number of workers that can be swapped out of a shift are bounded by the total number of available workers from the previous planning horizon as shown in constraint sets (3.5) and (3.6), respectively.

$$XF_{jkl} \leq X^0_{jkl}, \forall\, j, k, l \tag{3.5}$$

$$Y_{jkk'l} \leq X^0_{jkl}, \forall\, j, k, k', l \tag{3.6}$$

In cross-training, workers skilled in one task are trained to perform another task. Therefore, cross-training constraint set (3.7) restricts the number of cross-training workers for a given process below the total number of workers available to perform different processes. Contrary to the cross-training constraints, the skill-training constraints will look for lower skilled workers in the same process. Constraint set (3.8) restricts the number of workers promoted from a lower skill level to a higher skill level in the same process to below the number of workers available in the lower skills.

$$CT_{jkl} \leq \sum_{m \epsilon J \setminus j} X^0_{mkl}, \forall\, j, k, l \tag{3.7}$$

$$ST_{jkl} \leq \sum_{m \epsilon L, m<l} X^0_{jkm}, \forall\, j, k, l \tag{3.8}$$

Business rules may set a limit on the workers that can be assigned to overtime and/or swapped out of a shift. Constraint sets (3.9) and (3.10) model these business rules, respectively. Note that constraint set (3.10) implicitly restricts the movement of workers into the shifts.

$$\left(\sum_{j \epsilon J} \sum_{k \epsilon K} \sum_{l \epsilon L} OT_{jkl}\right) \leq \alpha \tag{3.9}$$

$$\sum_{j \epsilon J} \sum_{k \in K} \sum_{k' \epsilon K \setminus k} \sum_{l \epsilon L} Y_{jkk'l} \leq \beta \tag{3.10}$$

To model a flexible workforce, it is very important to avoid double counting of the workers. Suppose that at the start of planning horizon there are 10 workers who can do task A and 10 workers who can do task B. Let the requirement for both processes A and B be 10 workers. In this case, each task can be assigned 10 workers each if there are no workers who are qualified to do both the tasks. If there are 5 workers who can perform both task A and B, the actual size of the workforce becomes 10 + 10 - 5 = 15, which cannot satisfy a total demand of 20. This phenomenon is due to counting the flexible workers in all processes for which they are qualified.

To avoid double counting of the flexible worker hours, constraint set (3.11) imposes a limit on the workforce built for a process, skill, and shift. The workforce is less than the sum of actual number of workers from the previous planning horizon and number hired/fired. As per constraint set (3.12), the sum of the maximum number of workers assigned to each process in a shift, the number of workers cross-trained and the number of workers swapped out of shifts should be less than the actual number of workers available.

$$\sum_{j\in J}\sum_{k\in K}\sum_{l\in L} X_{jkl} \leq \varepsilon^0 + \sum_{j\in J}\sum_{l\in L}\sum_{k\in K} Y_{jk'kl} - \sum_{j\in J}\sum_{l\in L}\sum_{k\in} Y_{jkk'l}, \forall, k' = 0 \qquad (3.11)$$

$$\sum_j\sum_k\sum_l XF_{jkl} + \sum_j\sum_l\sum_k Y_{jk'kl} + \sum_j\sum_l\sum_k CT_{jkl} + \sum_j\sum_l\sum_k ST_{jkl} \leq \varepsilon^0 \qquad (3.12)$$

It is required to restrict the maximum number of regular workers that can be assigned to any two processes. Using the information about the number of flexible workers in a shift for any two processes skill-level pair, constraint set (3.13) states that the summation of the maximum number of workers that can be assigned from the previous planning horizon should be less than or equal to actual (net) number of workers who are qualified on either of the two processes skill-level pairs. This actual (net) number can be obtained by adding the number of workers available from the previous horizon to do those tasks minus the number of workers who can do both tasks.

$$XF_{jkl} + XF_{j'kl'} \leq X^0_{jkl} + X^0_{j'kl'} - \mu_{jj'kll'}, \forall j, k, l, l', j', l' \neq l, j \neq j' \quad (3.13)$$

Constraint set (3.14) ensures that if there are no workers skilled to operate a process with a required skill, overtime cannot be assigned until a worker is cross- trained or hired.

$$OT_{jkl} \leq X^0_{jkl} + \sum_k CT_{jkl} + \sum_k Y_{jk'kl} - \sum_k Y_{jkk'l}, \forall j, l, k' = 0 \quad (3.14)$$

Constraint set (3.15) imposes non-negativity restrictions on all variables.

$$X_{jkl}, XF_{jkl}, Y_{jkk'l}, OT_{jkl}, CT_{jkl}, s^{+/-}_{jkl} \geq 0 \quad (3.15)$$

4 Solution Methodology

In real world scenarios, there are instances in which values of the parameters are uncertain. Unlike deterministic modeling, stochastic modeling is the class of mathematical programs that consists of parameters whose values are not known before solving the problem. Values of these parameters are in a form of a probability distribution that can be used in the stochastic problem-solving framework in order to obtain a solution.

4.1 Two-Stage Stochastic Linear Problem with Recourse

A two-stage stochastic problem consists of two phases of decision-making: the first and second stage decisions. First stage decisions are made before the actual values of uncertain parameters in the model are revealed by assuming values based on the distribution of the uncertain parameter. In the second stage, the value of the uncertain parameters is revealed and is used, along with the values of first stage variables, to determine the second stage decisions. Second stage variables, known as recourse variables, patch the solution to reduce the effect caused due to the actual values of the uncertain parameters.

The following expression is the general form of a two-stage stochastic linear program with recourse. (Birge and Louveaux, 1997)

$$Minimize\ C^T x + E[Q(x,h)] \tag{4.1}$$

where $Q(x,h) = \min\{Q^T y | Wy = h - Tx, y \geq 0\}$

$$s.t. \quad Ax = B \tag{4.2}$$

$$x \geq 0 \tag{4.3}$$

The first stage decisions are represented by vector $\boldsymbol{x}$ and the second stage decisions are represented by vector $\boldsymbol{y}$. Let the cost vector for first and second stages variables be represented by vectors $\boldsymbol{C}$ and $\boldsymbol{Q}$**,** respectively. The objective function for a general two-stage stochastic linear problem is minimization of the summation of the cost of first stage variables and the expected value function of the second stage variables. In other words, the expected value function is the cost incurred due to the uncertainty in the model. $\boldsymbol{W}$, $\boldsymbol{h}$ and $\boldsymbol{T}$ are the components of the expected value function that form a constraint to establish the relation between the first stage and second variables. In this constraint, the vectors $\boldsymbol{W}$ and $\boldsymbol{T}$ are deterministic parameter multipliers of variable vectors $\boldsymbol{y}$ and $\boldsymbol{x}$, respectively, while $\boldsymbol{h}$ is the uncertain constant. From the general form it can clearly be seen that the values of the second stage decisions $\boldsymbol{y}$ are dependent on the values of $\boldsymbol{x}$, while the first stage variables are independent.

The model formulated in Section 3 has a structure analogous to that of the above general form (Equations 4.1- 4.3) of the two- stage stochastic program with recourse. It can be seen that decisions of retaining workers, shift swapping, hiring and cross-training are the first stage decisions (analogous to vector $\boldsymbol{x}$) that will be taken before the actual value of demand $\boldsymbol{R}$ (analogous to vector $\boldsymbol{h}$) is revealed. These decisions collectively contribute to determining the size and composition of the workforce for the entire planning horizon. In the second stage, once the actual values of the demand are revealed, overtime (analogous to vector $\boldsymbol{y}$) will be used as recourse to satisfy the actual value of the demand.

4.2 Scenario Based Approach

The two-stage stochastic recourse problem can be solved using scenarios, converting the problem to an extended deterministic problem (Birge and Louveaux, 1997). Using the known distributions of the uncertain parameters, scenarios are generated that consist of point values of

the parameters along with the probability of occurrence of each of these point values. Let **S** be the set all scenarios and ***s*** such that $s \epsilon \{1..S\}$ be the subscript that denotes the scenarios. Let $\boldsymbol{h_s}$ be the value of the random parameter for scenario ***s*** and let $\boldsymbol{P_s}$ denote its respective probability, which will be used in the expected value objective function. While solving a two-stage stochastic program using a scenario-based approach, the first stage variables take on values irrespective of the scenario and therefore, these variables will not have a scenario subscript. Once the actual demand is revealed, the second stage will build a matrix of the customizable options based on the value of uncertain parameters that were not satisfied using the first stage variables.

Upon solving this problem using a scenario-based approach, we get a single vector for the first stage variables and **|S|** vectors for second stage variables. These |S| vectors can be used as recourses depending on the actual value of the uncertain parameter. On applying this solution methodology to equations 4.1 - 4.3, we obtain an extended deterministic form as shown in equations 4.4 - 4.6. In this form of problem, the expected value function is represented by the known scenario wise probability vector P_s and scenario wise point value vector of uncertain parameter h_s.

$$Minimize\ C^T x + E[Q(x,h)] \tag{4.4}$$

where $$Q(x,h) = \min\{P_s Q^T y_s | Wy = h_s - Tx, y_s \geq 0\}$$

$$s.t. \quad Ax = B \tag{4.5}$$

$$x \geq 0 \tag{4.6}$$

4.3 Conversion of Formulation to Extended Deterministic Form

The above approach can be used to solve the problem formulated in section 3. Using equations 4.4 - 4.6, the formulation in Section 3 can be converted to an extended deterministic problem by

adding an extra subscript ***s*** to the uncertain parameter ***R*** and introducing a probability vector P_s. Let $\boldsymbol{R_s}$ be the demand vector for scenario ***s*** and let $\boldsymbol{P_s}$ denote its respective probability. The first stage variables take on values irrespective of the scenario and, therefore regular, cross-training, hiring and shift swapping variables will not have a scenario subscript, while the overtime variables will be scenario dependent. The original formulation in Section 3 is updated as below;

<u>Extended deterministic formulation</u>

Objective Function

$$Minimize \quad \sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{l\epsilon L} cx_{jkl}X_{jkl} \tag{4.7}$$

$$+\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{k'\epsilon K\backslash k}\sum_{l\epsilon L} cy_{jkk'l} \,.Y_{jkk'l}$$

$$+\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{l\epsilon L} ct_{jkl}CT_{jkl}$$

$$+\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{l\epsilon L} st_{jkl}ST_{jkl} \quad + \; E(X,R)$$

where,

$$E(X,R) = (\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{l\epsilon L}\sum_{s\epsilon S} cot_{jkl}^{s}OT_{jkl}^{s} \tag{4.8}$$

$$+\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{l\epsilon L}\sum_{s\epsilon S} p_{jkl}^{+s}s_{jkl}^{+s} + \sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{l\epsilon L}\sum_{s\epsilon S} p_{jkl}^{-s}s_{jkl}^{-s})\; P_s$$

Subject to:

$$X_{jkl} = \; XF_{jkl}^{0} + CT_{jkl} + ST_{jkl} + \sum_{k'\epsilon K\backslash k} Y_{jkk'l} - \sum_{k\epsilon K\backslash k'} Y_{jkk'l}\,, \forall j,k,l \tag{4.9}$$

$$X_{jkl} + OT_{jkl}^{s} \; + \; s_{jkl}^{s-} - s_{jkl}^{s+} = R_{jkls}\,, \forall j,k,l,s \tag{4.10}$$

$$XF_{jkl} \leq X^0_{jkl}, \forall\, j, k, l \tag{4.11}$$

$$Y_{jkk\prime l} \leq X^0_{jkl}, \forall\, j, k, k', l \tag{4.12}$$

$$CT_{jkl} \leq \sum_{m\epsilon J\backslash j} X^0_{mkl}\,, \forall\, j, k, l \tag{4.13}$$

$$ST_{jkl} \leq \sum_{m\epsilon L, m<l} X^0_{jkm}\,, \forall\, j, k, l \tag{4.14}$$

$$\left(\sum_j \sum_k \sum_l OT^{s}_{jkl}\right) \leq \alpha, \forall\, s \tag{4.15}$$

$$\sum_{j\epsilon J} \sum_{k\in K} \sum_{k\prime\epsilon K\backslash k} \sum_{l\epsilon L} Y_{jkk\prime l} \leq \beta \tag{4.16}$$

$$OT^{s}_{jkl} \leq X^0_{jkl} + \sum_k CT_{jkl} + \sum_k Y_{jk'kl} - \sum_k Y_{jkk^{'}l}\,, \forall j, l, k^{'} = 0, \forall s \tag{4.17}$$

$$\sum_{j\in J} \sum_{k\in K} \sum_{l\in L} X_{jkl} \leq \varepsilon^0 + \sum_{j\in J} \sum_{l\in L} \sum_{k\in K} Y_{jk\prime kl} - \sum_{j\in J} \sum_{l\in L} \sum_{k\in} Y_{jkk'l}\,, \forall\,, k' = 0 \tag{4.18}$$

$$\sum_j \sum_k \sum_l XF_{jkl} + \sum_j \sum_l \sum_k Y_{jk\prime kl} + \sum_j \sum_l \sum_k CT_{jkl} + \sum_j \sum_l \sum_k ST_{jkl} \leq \varepsilon^0 \tag{4.19}$$

$$XF_{jkl} + XF_{j\prime kl\prime} \leq X^0_{jkl} + X^0_{j\prime kl\prime} - \mu_{jj\prime kll\prime}, \forall\, j, k, l, l', j', l' \neq l\,, j \neq j' \tag{4.20}$$

$$X_{jkl}, XF_{jkl}, Y_{jkk'l}, OT^{s}_{jkl}\,, CT_{jkl}, s^{+/-}_{jkl} \geq 0 \tag{4.21}$$

5 Numerical Experiments

Using the model developed in the previous section, insights can be gathered on workforce planning. Experiments are conducted to verify and validate the functionality of the model.

5.1 Data

For illustrative purpose, a dataset is created similar to that contributed by our industrial collaborator. This dataset consist of information for an industrial setting with 57 flexible and inflexible workers, three processes, four shifts, and two skill levels. Each process requires a different mix of workers with varied skill levels L1 and L2. Table 2 shows the gross number of workers at the start of the planning horizon.

X_{jkl}^{0}		*L*	
K	*J*	**L1**	**L2**
Shift1	Op1	2	2
Shift1	Op2	4	1
Shift1	Op3	4	3
Shift2	Op1	0	0
Shift2	Op2	0	0
Shift2	Op3	0	0
Shift3	Op1	1	4
Shift3	Op2	2	1
Shift3	Op3	2	2
Shift4	Op1	0	0
Shift4	Op2	0	0
Shift4	Op3	0	0

Table 5.1: Available Workers at the start of the planning horizon

To solve the model using the scenario-based approach, a known number of scenarios for a discrete distribution of demand were provided by an industrial collaborator. Table 5.2 shows the requirement for each of the processes for the given three scenarios and its respective probability. This requirement is quantified in terms of workers required per process, skill, and shift.

			Requirement (R_{jkl}^{s})		
k	***J***	***l***	***S***		
Shifts	Process	Skills	Scenario 1 p_1 =0.25	Scenario 2 p_2 =0.5	Scenario 3 p_3 =0.25
Shift1	Op1	L1	3	2	0.5
Shift1	Op1	L2	3	2	0.5
Shift1	Op2	L1	2	3	1
Shift1	Op2	L2	2	3	1
Shift1	Op3	L1	2	1	0.5
Shift1	Op3	L2	2	1	0.5
Shift2	Op1	L1	3	2	0.5
Shift2	Op1	L2	3	2	0.5
Shift2	Op2	L1	2	3	1
Shift2	Op2	L2	2	3	1
Shift2	Op3	L1	2	1	0.5
Shift2	Op3	L2	2	1	0.5
Shift3	Op1	L1	3	2	0.5
Shift3	Op1	L2	3	2	0.5
Shift3	Op2	L1	2	3	1
Shift3	Op2	L2	2	3	1
Shift3	Op3	L1	2	1	0.5
Shift3	Op3	L2	2	1	0.5
Shift4	Op1	L1	3	2	0.5
Shift4	Op1	L2	3	2	0.5
Shift4	Op2	L1	2	3	1
Shift4	Op2	L2	2	3	1
Shift4	Op3	L1	2	1	0.5
Shift4	Op3	L2	2	1	0.5

Table 5.2: Scenario wise requirement and probability

Table 5.3 shows a qualification matrix that provides information about workers and their individual qualifications. There are total of 57 workers at the start of the planning horizon, i.e.,$\varepsilon = 57$, with 27 workers qualified on at least one task, inclusive of all skill levels. Further, 29 workers are not qualified on any task. From the previous planning horizon, 27 workers are assigned to Shift 1 and 30 workers are assigned Shift 3, while shift 2 and Shift 4 have no workers assigned. This matrix also shows the number of flexible workers.

Name	Cert Type	Shift	Op1	Op2	Op3	Name	Cert Type	Shift	Op1	Op2	Op3
Worker01	L1	1		1		Worker30	L1	3			
Worker02	L1	1			2	Worker31	L2	1			
Worker03	L1	1		1		Worker32	L2	1			
Worker04	L1	1			1	Worker32	L2	1			
Worker05	L2	1			1	Worker33	L1	1			
Worker06	L2	1	1			Worker34	L2	1			
Worker07	L2	1			1	Worker35	L2	1			
Worker08	L1	1				Worker36	L1	1			
Worker09	L1	1	1			Worker37	L2	1			
Worker10	L1	1				Worker38	L1	1			
Worker10	L1	1				Worker39	L1	1			
Worker10	L1	1		3		Worker40	L1	1			
Worker11	L2	1	1			Worker41	L1	1			
Worker12	L1	1				Worker42	L1	1			
Worker12	L1	1			2	Worker43	L1	3		1	
Worker13	L2	1		1		Worker44	L1	3		1	
Worker14	L1	1		2		Worker45	L2	3		1	
Worker15	L1	1			2	Worker45	L2	3	2		
Worker16	L2	1			1	Worker46	L1	3	1		
Worker17	L1	1	1			Worker47	L1	3			1
Worker18	L1	3				Worker48	L2	3	1		
Worker19	L2	3				Worker48	L2	3			2
Worker20	L2	3				Worker49	L2	3			
Worker21	L2	3				Worker50	L2	3			1
Worker22	L1	3				Worker51	L2	3			
Worker23	L2	3				Worker52	L2	3	1		
Worker24	L1	3				Worker53	L1	3			1
Worker25	L1	3				Worker54	L2	3	1		
Worker26	L2	3				Worker55	L1	3			
Worker27	L2	3				Worker56	L1	3			
Worker28	L1	3				Worker57	L1	3			
Worker29	L1	3									

Table 2.3: Qualification Matrix

As per the business rules there is a limit on the number of workers that can assigned to overtime or swapped. Therefore, $\alpha = 15$ and $\beta = 15$.

5.2 Resulting Solution

In this section, the solution is obtained using the data in the section 5.1. In the first stage, the output of the model sets the level of the workforce that is to be formed before the start of the planning horizon as shown in Table 5.4. Table 5.4 also shows the composition of the workforce in the form of workers from the previous planning horizons, workers hired, swapped, or cross trained.

		Shift1			Shift2			Shift3			Shift4		
		Op1	Op2	Op3	Op1	Op2	Op3	Op1	Op2	Op3	Op1	Op2	Op3
Regular	L1	2	2	1	0	0	0	1	2	1	0	0	0
	L2	2	1	1	0	0	0	2	1	1	0	0	0
Hire	L1	0	0	0	0	0	0	0	0	0	0	0	0
	L2	0	0	0	0	0	0	0	0	0	0	0	0
Swap to Shift(Number)	L1	-	S2(1)S4(1)	S2(1)	-	-	-	-	-	S4(1)	-	-	-
	L2	-	-	S4(1)	-	-	-	S2(1)	-	S2(1)	-	-	-
Swap from Shift(Number)	L1	-	-	-	-	S1(1)	S1(1)	-	-	-	-	S1(1)	S3(1)
	L2	-	-	-	S3(1)	-	S3(1)	-	-	-	-	-	S1(1)
Cross-training	L1	0	0	0	2	0	0	0	0	0	2	0	0
	L2	0	0	0	0	1	0	0	1	0	0	0	0
Skill Training	L1	0	0	0	0	0	0	0	0	0	0	0	0
	L2	0	1	0	0	0	0	0	0	0	1	1	0
Workforce Size	L1	2	2	1	2	1	1	1	2	1	2	1	1
	L2	2	2	1	1	1	1	2	2	1	1	1	1

Table 5.4: Size and Composition of Workforce

Table 5.5 shows the overtime assignments based on revelation of the actual value of demand. From the experimental result, it can be seen that the model utilizes the overtime completely unless there is surplus. Hiring decisions are taken by the model only after the entire available workforce and the overtime is utilized. Model assigns idle workers to cross-training and skill-training before the hiring decisions are taken.

			Overtime		
Shifts	Process	Skills	Scenario 1	Scenario 2	Scenario 3
Shift1	Op1	L1	1	0	0
Shift1	Op1	L2	1	0	0
Shift1	Op2	L1	0	1	0
Shift1	Op2	L2	0	1	0
Shift1	Op3	L1	0	0	0
Shift1	Op3	L2	0	0	0
Shift2	Op1	L1	0	0	0
Shift2	Op1	L2	2	1	0
Shift2	Op2	L1	1	2	0
Shift2	Op2	L2	1	2	0
Shift2	Op3	L1	1	0	0
Shift2	Op3	L2	1	0	0
Shift3	Op1	L1	0	1	0
Shift3	Op1	L2	1	0	0
Shift3	Op2	L1	0	1	0
Shift3	Op2	L2	0	1	0
Shift3	Op3	L1	0	0	0
Shift3	Op3	L2	0	0	0
Shift4	Op1	L1	0	0	0
Shift4	Op1	L2	2	1	0
Shift4	Op2	L1	1	2	0
Shift4	Op2	L2	1	2	0
Shift4	Op3	L1	1	0	0
Shift4	Op3	L2	1	0	0

Table 5.5: Scenario wise overtime requirement

5.3 Computational Experiment

Using the data contributed by the industrial collaborator, sample data was created to generate test cases to validate the model. This sample data was created by varying the number of processes, skills, shifts, number of workers but keeping the number of scenarios same. For all the test cases, the model determines the optimal size of the workforce using various workforce-planning actions. The model was implemented on .Net platform using C# and mathematical model was solved using CPLEX 12.5. For details of the software implementation, refer to Appendix 1. Table 5.6 shows the size of the problem, and the total computational time required to solve the problem. The actual time required to solve the model is given by "Solve time."

The actual industrial level problem consists of 40 processes, three skills levels, 14 shifts, and three scenarios that can be solved using this model as shown in test case 8. The so developed is flexible that allows for solving larger size problems involving more than three scenarios, and larger number of skills, shifts and processes. However as the size of the problem increases the solve time also increases.

	Process	Skills	Shifts	Scenarios	Workers	Total Time (seconds)	Solve Time (seconds)
1	15	2	4	3	2000	84	0
2	15	3	4	3	5000	132	1
3	30	2	6	3	10000	582	2
4	30	3	6	3	10000	656	8
5	30	2	12	3	10000	677	16
6	30	3	12	3	20000	952	34
7	40	2	16	3	20000	1209	52
8	40	3	16	3	30000	2111	216

Table 5.6: Experimentation Results

6 Conclusions and Future Work

In this thesis, a strategic workforce management system is developed to determine the size of the workforce over a long planning horizon under uncertain demand. Using two-stage stochastic programming the workforce is formed using actions such as shift-swapping, cross-training, and hiring assuming a known distribution of the demand. This model utilizes the available workforce from the previous planning horizon by identifying the potential number of workers that can be swapped within shifts or cross-trained, adding flexibility to the workforce. In the second stage, the requirements of overtime during the entire planning horizon are revealed.

In all the experiments that were conducted by varying the number of processes, skills levels, and shifts, model determined optimal size of the workforce required to satisfy an uncertain demand. From the experimentation, it can be seen that model is flexible and can handle problems of larger size.

Workforce planning using this model can be used as parameters in the short-term cross-training planning models developed by Gandhi et al. (2013). Decisions obtained can be used to conduct cross-training programs before the actual demand occurs in an attempt to reduce the overtime requirement, allowing the decision makers with ample amount of time to hire and cross-train workers. Even though overtime is used as recourse, it is costly to use over a longer period. Such prolonged unsatisfied demand can easily be satisfied using the hiring, cross-training, and shift-swaps.

A variant of the model developed by Kulkarni et al. (2013) manages workforce in an industrial setting with products with independent demands, i.e., product demands are not correlated. Therefore, for $\boldsymbol{n}$ processes and $\boldsymbol{r}$ point demands there exist $\boldsymbol{r^n}$ scenarios. The assumption of independent demand increases the size of the problem exponentially making the problem

computational challenging. Thus, future work will address approaches to reduce the model building and solving time.

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Appendix 1: Software Implementation

The system is implemented in C# using CPLEX 12.5 concert libraries for .Net and experiments are conducted on machine with a 2.3GHz Intel processor. This system is broadly divided into 5 modules based on the functionalities they house;

1) **Input Interfacing Module**: This module manages a user interactive interface that allows the user to input values, which are processed to get the various parameters and costs for the mathematical model developed in Section 3.
2) **Data Storage Classes**: Data storage classes are used to securely store parameter and cost data processed by the input interfacing module. This data is then retrieved by various other modules using program generated paths and methods.
3) **Model Building and Solving Module**: In this module, mathematical model developed in Section 3 is computationally implemented and solved.
4) **Test Support and Error Detection Module**: This module houses methods used to test the integrity of the input data used to generate parameter and cost data. It also manages runtime errors, and detects inconsistencies in the model.
5) **Output Interfacing Module**: This module manages all the output functionality of the program. It houses methods that are used to model solutions. Output methods display the results to user in structured and legible manner.

All these modules are integrated in a single program. Figure (A1) shows the system architecture and the program flow. The code accompanies this thesis on CD.

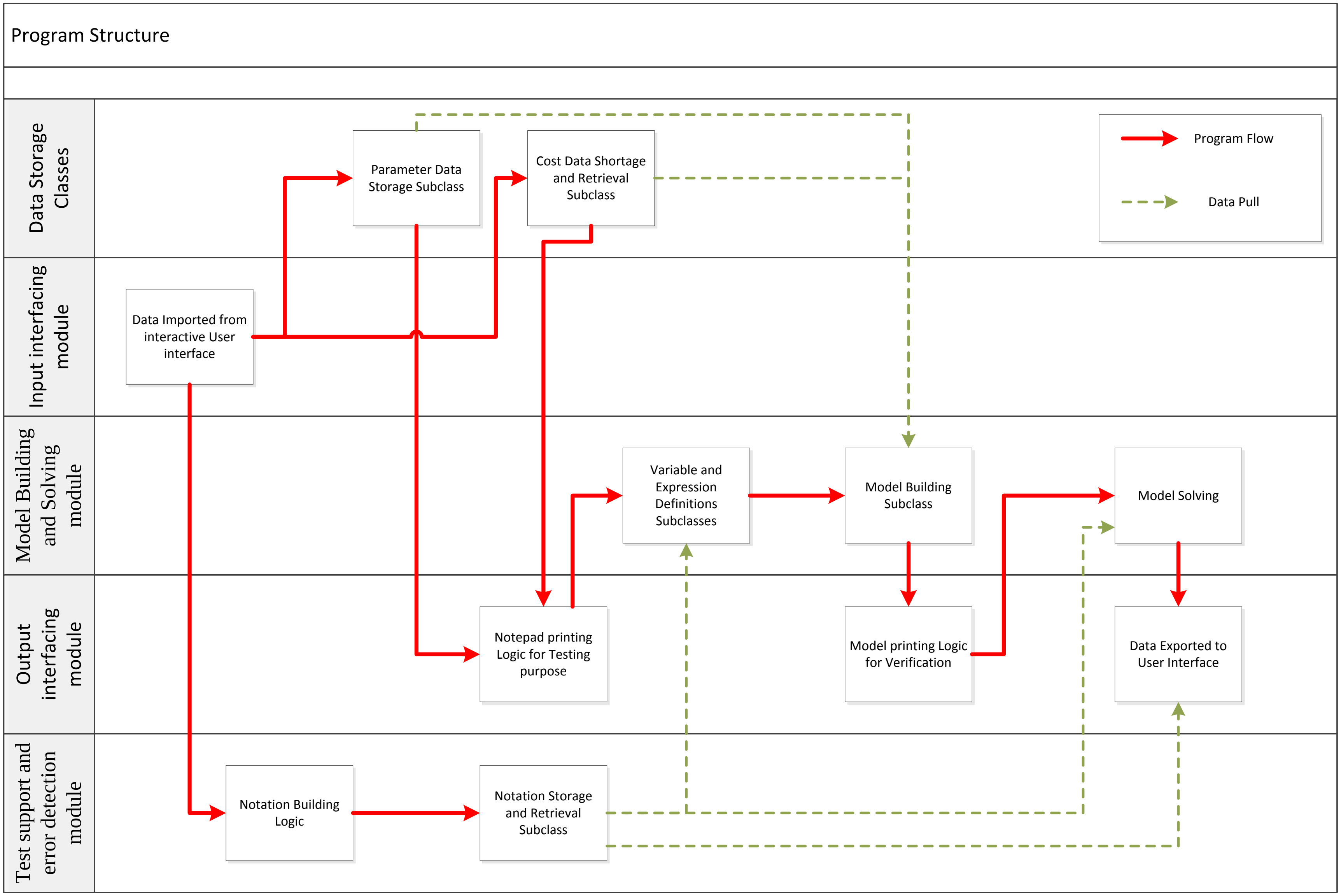

Figure A1 : Detail System Architecture