RISK BASED WORKER ALLOCATION

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In a labor-intensive manufacturing system worker allocation plays an important role in determining the efficiency. The workers processing times have high variability; however most of worker allocation problems are studied in a deterministic condition. Thus, this paper proposes a worker allocation problem with uncertainty in workers' processing time and quality. The objective is to minimize the workers allocation risk. The proposed approach is investigated for two scenarios. In the first scenario there is only one task per station, production line is balanced, and workers are allocated to processes in order to minimize the overall risk of delay in processing time. In the second scenario, the production line is not balanced and multiple workers can be assigned to a process to balance the production line in order to minimize the overall risk. The result of simulation indicates that the risk based approach has increased throughput and efficiency compared to deterministic method.

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I. INTRODUCTION

Worker allocation is defined as the problem of assigning a set of available workers to a set of process by which the performance of the system increases. Workers can have different processing time and quality for each process. In addition, not all of workers can do all the processes. There are many research addressed this problem with different assumptions. However, most of them are dealing with the case where workers process time and quality are deterministic. However, in practical cases there are always uncertainty associated with processing time and quality level of a worker. Hence, the purpose of this paper is to address the worker allocation problem with uncertain process time and quality.

Traditionally, a worker is allocated to a process based on several criteria such as experience, productivity, seniority, and often some arbitrary measures (Nembhard, 2001). In a competitive environment, production efficiency plays an important role in determining profit of a firm. For a system to be highly productive, a worker should be allotted to a process based on productivity measures. Because processing time and quality levels of a worker are the dominant productivity measures in context of worker allocation. Thus, a worker with the lowest processing time and highest quality is more likely to be allotted to a process.

A worker allocation problem can be formulated by assuming any of these three strategies: Single-worker-Single-process, Single-worker-Multi-process, and Multi-worker-Multi-process. In "Single-worker-

Single-process", workers possess only one skill. In "Single-worker-Multi-process", each worker could be assigned to multiple possesses. This is more common in U-Shaped production lines. In "Multi-worker-Multi-process", multiple workers possess multiple tasks such that skills overlap within workers. Worker profile could be defined as the operational characteristics associated with individual workers. Based on previous literature, worker allocation can be classified into:

1) Sole profile allocation
2) Multi profile allocation

In sole profile allocation, all workers with similar skills are assumed to have the same productivity measures. The differences in productivity due to inherent variability associated with workers are not considered. Sole profile allocation is often preferred for simplicity in mathematical modeling. Since individual worker profiles are not considered in sole profile allocation, the objective is to determine the worker staffing level at each work station. Several formulations were developed to solve sole profile worker allocation model (Table 1).

TABLE 1. FORMULATIONS - SOLE PROFILE ALLOCATION

Formulations	Authors
Mixed integer programming	Kuo and Yang (2005), Suer and Bera (1998), Davis and Mabert (2000), Min and Shin (1993) and Suer (1996)
Heuristic	Vembu and Srinivasan (1997), Bhaskar and Srinivasan (1997), and Nakade and Ohno (1999)
Network flow problem	Wittrock, 1992
Data envelopment analysis	Ertay and Ruan, 2005
Non linear programming	Davis and Mabert, 2000

Wittrock (1992) modeled sole profile operator assignment problem as a network flow problem with a lexicographic objective which tries to maximize the capacity in a machine intensive manufacturing system. Vembu and Srinivasan (1997) developed a heuristic approach for operator allocation and product sequencing in production lines with an objective of minimizing makespan. Bhaskar and Srinivasan (1997) used a heuristic approach to solve static and dynamic variety worker allocation problem. Suer (1996) proposed a two-stage hierarchical methodology which simultaneously does operator allocation and cell loading in a labor intensive manufacturing system. Suer and Bera (1998) is an extension of previous work by Suer (1996). In this research, lot-splitting

between cells are allowed and setup times for the products were included. Kuo and Yang (2005) implemented mixed integer formulation developed by Suer and Bera (1998) for operator staffing level decisions in a TFT-LCD inspection and packaging (I/P) process. Min and Shin (1993) developed a multiple objective sole profile allocation model, which simultaneously forms machine and human cells in cellular manufacturing. Davis and Mabert (2000) presented two mathematical models for making order dispatching and worker assignment decisions in linked cellular manufacturing systems.

Ertay and Ruan (2005) presented a data envelopment analysis approach for optimal number of worker allocation in cellular manufacturing. Nakade and Ohno (1999) proposed a heuristic which optimally selects minimum number of workers which minimizes overall cycle time thereby meeting demand in a U-shaped production line. In the research papers discussed above, it is assumed that workers possess equal productivity. However, in labor intensive manufacturing such as aircraft industries, variability in worker productivity is very prevalent. There is high variability in the time taken by the worker in performing the same task. Data regarding the variability in time taken by workers in the aircraft manufacturing industry is available in Pachaimuthu [2010].

In multi-profile allocation, worker differences in terms of productivity are considered. Worker profile differences are modeled either based on multiple skill levels or individual workers. In profile differences based on multiple skill levels, it was assumed that each skill had a different skill level and the workers within each skill level possess equal productivity. However, worker profiles obtained from a local aircraft manufacturing company show that there are difference between individual workers for each skill level. Several formulations were developed to solve multi-profile worker allocation model and is shown in Table 2**.**

TABLE 2. FORMULATIONS - MULTI PROFILE ALLOCATION

Formulations	Authors
Mixed integer programming	Askin and Huang (2001), Chaves, Insa, and Lorena (2007), Miralles et al., (2008), Suer and Tummaluri (2008), Fitzpatrick and Askin (2005) , and Norman et al., (2002)
Heuristics	Fowler, Wirojanagud, and Gel (2008) and Nembhard (2001)
Non-linear integer programming	Aryanezhad, Deljoo, and Al-e-Hasheem (2009) and Heimerl and Kolish (2009)
Particle swam optimization technique	Yaakob and Watada, 2009

Nembhard (2001) developed a heuristic approach for multi profile worker allocation based on individual worker learning profiles for machine intensive manufacturing system. Chaves, Insa, and Lorena (2007) modeled an integer programming formulation for assembly line worker assignment and balancing problem (ALWABP) in sheltered work centers. This model assumes that individual workers have different deterministic processing time values. Miralles, Garcia, Andres, and Cardos (2008) extended the previous work by Chaves, Insa, and Lorena (2007) by providing a different solution methodology using branch and bound algorithm. Fowler, Wirojanagud, and Gel (2008) developed a mixed integer program for making decisions on hiring, training, and firing workers. Individual workers are assumed to have different profiles based on their general cognitive ability. Suer and Tummaluri (2008) developed a three stage operator allocation procedure for worker allocation in labor intensive manufacturing. This research assumes that the processing time of individual workers are different deterministic values depending on the skill level of workers. Heimerl and Kolish (2009) modeled a non-linear integer program for assigning multi-skilled workers to tasks considering the worker learning, forgetting, and company skill level targets. Askin and Huang (2001) developed a mixed integer, goal programming model to form worker teams for cellular manufacturing based on psychological, organizational, and technical factors. Norman et al. (2002) modeled a mixed integer program which assigns workers to task in a cellular manufacturing environment considering both technical and human skills. Fitzpatrick and Askin (2005) formed multiple worker teams with multifunctional skill requirements for cellular manufacturing. The technical and inter-personnel skills of workers are considered to form worker teams. McDonald, Ellis, Aken, and Koelling (2009) proposed a mathematical model to assign cross trained workers to tasks in a lean manufacturing cell. This research considers both processing time and quality level of workers and assumes it as different deterministic values based on current skill level of workers. Aryanezhad, Deljoo, and Al-e-Hasheem (2009) formulated a non-linear integer program for simultaneous dynamic cell formation and worker assignment problem (SDCWP). Yaakob and Watada (2009) developed a methodology for worker assignment in cellular manufacturing using particle swam optimization technique. In all the research discussed above, it is assumed that workers possess different deterministic productivity values. However, the time study data that was obtained from a local aircraft industry shows a high degree of variability in worker productivity measures (Pachaimuthu, 2010).

In previous literature deterministic processing time and quality level is assumed for the workers which is not a realistic assumption and a change in processing time or quality level of any worker will result in a modified relationship between the worker and the process, thus affecting the optimal worker allocation.

Whenever, an existing uncertainty in a system incurs a cost it is called “risk”. In a production line since the uncertainty associated with the worker processing time and quality, workers allocation will directly affects the throughput and consequently system’s cost, which will bring risk to the system it is essential to assess and quantify the risk associated. According to Modarres, 2006, risk is defined as “a measure of the potential loss occurring due to natural or human activities”. In the context of worker allocation, risk can be defined as the potential loss due to delay in process or due to the bad quality of the product. When variability in processing time and quality level increases, risk due to delay in process and bad quality product also increases. In order to reduce risk in worker allocation process, advanced techniques have to be developed which captures the risk and minimizes its impact. Thus, in real world scenarios, uncertainty is predominant in worker processing time and quality level. Therefore, an optimal worker allocation methodology should take into consideration the associated uncertainties. A single product dedicated labor intensive manufacturing line is considered in this research.

In general, manufacturing systems could be classified into machine-intensive manufacturing and labor-intensive manufacturing (Suer, 1996). In machine intensive manufacturing, productivity of the system is primarily based on total number of machines available in the system. Involvement of worker is often limited in machine intensive manufacturing. Workers are bound to tasks such as loading/unloading parts from the machines, transferring products from one station to other, etc. On the contrary, in a labor intensive manufacturing system, performance of a system typically depends on worker involvement. Workers are often equipped with small, inexpensive equipment's performing the processes on products. Labor intensive manufacturing is more predominant in jewelry, apparel, leather, and sport goods manufacturing industries (Das and Kalita, 2009). Other manufacturing industries that have labor intensive manufacturing are aircraft manufacturing, ship building etc. However, in aircraft manufacturing, the problem is more accentuated as the cost of equipment is very high. There is higher variability in task times and quality levels when the same worker performs the same job. There is also variability between workers with respect to task times and quality levels. A greater importance on worker allocation has to be imposed in order to obtain a strategic competitive advantage in manufacturing systems (Jordon, 1977). Thus, worker allocation plays an important role in determining the efficiency of a labor intensive manufacturing system.

1.1 Research Objective

The objective of this paper is to investigate new worker allocation strategies when there is high variability in the worker profiles with respect to processing times and quality levels. These worker allocation strategies are developed with an objective to mitigate the risk inherent in processing time variability and quality level variability. In the allocation of workers, the problem is categorized into the following scenarios: a) balanced production lines and unbalanced production lines or b) production lines with single task per station and multiple tasks per station. In single task per station balanced line scenario, the objective of the risk based worker allocation is to allocate the best worker to the station by minimizing the overall risk in the production line. Two kinds of risks considered in this research are the processing time risk and quality level risk. In single task per station unbalanced line scenario, since the line is unbalanced, multiple workers have to be allocated to the bottleneck stations to ensure that the demand is met. Thus, the research objective in single task per station unbalanced line scenario is to allocate multiple workers in bottleneck stations, thereby minimizing the overall risk in production line and to ensure that the demand is met. The research objective of this paper is to develop and solve a risk-based worker allocation model which takes into account the associated uncertainties in production lines which has:

1. Single task per station - balanced line scenario
2. Single task per station - unbalanced line scenario

This paper is organized as follows. Section 2 presents methodologies for risk based worker allocation in single task per station for both balanced and unbalanced line scenarios. In Section 2.1, the formulation and solution of worker allocation when a single task per station is needed is performed for a balanced line with deterministic characteristics (processing times and quality levels are considered deterministic). In Section 2.2, the formulation and solution of worker allocation when a single task per station is needed for a balanced line with stochastic characteristics (processing times and quality levels are considered stochastic). In Section 2.3, the deterministic and stochastic cases are compared for the same case studies. In Section 2.4, methodologies for worker allocation in unbalanced lines are detailed.

II. RISK-BASED WORKER ALLOCATION METHOD

The notations used in risk based worker allocation in balanced and un-balanced production line are follows:

X_{ij} Random variable representing processing time of worker *i* for process *j*

Y_{ij} Random variable representing quality level of worker *i* for process *j*

P_{ij}	Processing time of worker *i* for process j
X_i	Set of processes that cannot be assigned to worker *i*
$P_{\sigma ij}$	Standard deviation in processing time of labor *i* for process *j*
Q_{ij}	Quality level of worker *i* for process *j*
$Q_{\sigma ij}$	Standard deviation in quality level of worker *i* for process *j*
Spj	Standard processing time for process *j*
SQ_j	Standard quality level for process *j*
D_{Pj}	Delay penalty for process *j*
Q_{Pj}	Quality penalty for process *j*
Pr_j	Profit associated with process *j*
Qr_j	Quality cost due to bad quality in process *j*
C_{ij}	Cost of worker *i* for process *j*
D	Demand for the period
T	Time interval
M	Max number of workers allowed
L_{ij}	Worker *i* for process *j* (Binary variable)
N_r	Number of replications
DP_j	Delay penalty cost for process *j*

2.1 Worker Allocation in Single Task per Station Balanced Line-Deterministic

A manufacturing line is “balanced” when the cycle time associated with all processes/stations are the same. There are various kinds of uncertainties associated with worker allocation, such as uncertainty in worker processing time, quality level, part arrival pattern, and demand. Among these, uncertainty in worker processing time and quality level of worker is more common and dominant. Before the uncertainty based model is developed, a deterministic model is developed. This is necessary to have a benchmark to validate against risk based worker allocation model. Thus, worker allocation in the balanced line is performed without considering uncertainty first and then taking into consideration the stochastic nature of task times and quality levels.

Worker allocation can be performed considering expected values for the processing time and quality level, while not taking into consideration the uncertainty associated with the workers. Thus, the objective for worker allocation without considering uncertainty is to minimize the cost (maximize the profit) by allocating the best worker to the process based on their deterministic processing time and quality level. The assumptions for worker allocation without considering uncertainties are listed below:

- Expected processing time of each worker is known
- Expected quality level of each worker is known
- A worker can only be allocated to a single process
- At least one worker should be allotted to a process

The proposed worker allocation model for balanced line without considering uncertainty requires the following input parameters for testing the proposed approach:

1) Expected value of operation times of all workers
2) Expected value of quality level of all workers
3) Cost of workers for each process
4) Total number of processes required for the product
5) Standard time for each process
6) Standard quality level for each process
7) Revenue per process of the product
8) Quality loss per process of the product
9) Maximum number of workers in the line
10) Maximum number of workers per process

In this research, quality level of a worker is defined as the number of products produced within the control limits of the respective process per 100 products and is given in (1).

$$Q_{ij} = \frac{\text{Number of products within control limit manufactured by worker } i \text{ in process}}{100} \quad (1)$$

2.1.1 Deterministic Mathematical Formulation

In this section the objective function is to allocate workers to possess in a way which minimize the total worker allocation cost. The first term in the objective function is the cost of defective parts which is the product of *(1-Q_{ij})*, penalty cost, and a binary variable, L_{ij}, which activate the cost term when the worker *i* allocated to a process *j*. The second term of objective function is the product of labor cost, C_{ij}, number of working hours and binary variable L_{ij}. The last term of the objective function is the profit which is the product of number products produced by workers within the available time and the binary variable L_{ij}.

A Linear Integer Programming (LIP) model was developed to find optimal worker allocation. The objective function and constraints are explained as follows;

Objective function:

$$Min \quad \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\left(1-\frac{Q_{ij}}{100}\right)*\left[\frac{T}{P_{ij}}\right]*Qr_j*L_{ij}+\left[C_{ij}*\frac{T}{60}\right]*L_{ij}-\left[\frac{T}{P_{ij}}\right]*\Pr_j*L_{ij}\right) \quad (2)$$

Subject to:

$$\sum_{j=1}^{n} L_{ij} \le 1 \qquad \forall i \in I \quad (3)$$

$$\sum_{i=1}^{m} L_{ij} \ge 1 \qquad \forall j \in J \quad (4)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} L_{ij} \le M \quad (5)$$

$$\sum_{j \in X_i} L_{ij} = 0 \qquad \forall i$$

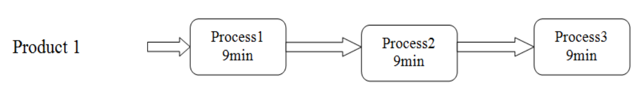
$$L_{ij} \in \{0,1\} \quad (6)$$

The objective is to minimize the cost by assigning the best worker *i*, *i=1*, *2*, *3*…m to process *j*, *j=1*, *2*, *3*…n and is given in (2). The first term is the loss due to bad quality from, which is the product of total number of defective parts produced and their associated quality loss. The third term is the cost of workers. The last term in the objective function calculates the profit by multiplying total number of parts produced and revenue per part. Constraint (3) ensures that each worker *i*, is assigned to only one process. Constraint (4) assures that process *j*, has at least one worker. Constraint (5) places an upper bound for the total number of workers (*M*) allotted to the line. Constraint (6) avoids selecting unskilled workers for a process.

2.1.2 Case Study–3-Process-6-Worker (Deterministic)

A balanced line with 3 processes and 6 workers is used as a sample case study to illustrate the proposed worker allocation model for the deterministic case (Fig. 1). Standard processing time of all three processes was assumed to be 9 minutes.

Figure 1 Case Study-3-Process-6-Worker



The operation time, quality level, and cost of workers associated with their respective processes for 3-process-6-worker case study are shown in Table 3. Expected worker quality level is obtained from previous historical data.

Maximum number of workers allowed in the 3-process-6-machine case study is set to

5 and time interval at 2880 minutes. Also, the Pr_j and Qr_j values associated with each process are given in Table 4.

TABLE 3. OPERATION TIME, QUALITY LEVEL, AND COST FOR 3-PROCESS-6-WORKER CASE STUDY

Operation/ Worker		Operation 1	Operation 2	Operation 3
1	Operation Time(minute)	8.8		9.2
	Quality Level	98.9		99.2
	Cost/hour($)	10.00		9.37
2	Operation Time	8.9	8.9	
	Quality Level	99.3	98.7	
	Cost	8.75	10.00	
3	Operation Time		8.8	8.9
	Quality Level		98.3	98.8
	Cost		11.80	10.62
4	Operation Time	9.0		8.9
	Quality Level	99.0		99.1
	Cost	10.62		9.37
5	Operation Time	9.1	9.1	
	Quality Level	98.8	98.3	
	Cost	11.87	10.00	
6	Operation Time		8.9	8.8
	Quality Level		99.6	99.2
	Cost		11.87	13.75

TABLE 4. PROFIT AND QUALITY LOSS FOR 3-PROCESS-6-WORKER CASE STUDY

Process *(j)*	**1**	**2**	**3**
Profit (*Prj*)	$36.0	$33.0	$37.5
Quality Loss *(Qr_j)*	$33	$39	$39

Once the input variables are obtained, the NLIP model is solved using LINGO Optimizer 12.0 and the results are presented in Table 5.

TABLE 5. RESULTS - 3-PROCESS-6-WORKER CASE STUDY

Process	**1**	**2**	**3**
Worker	Worker 1	Worker 3	Worker 6

2.1 Worker Allocation Considering Stochastic Processing Time and Quality Level

Most of the worker allocation methods in past literature are based on deterministic values of worker processing time and quality level. However, in labor intensive manufacturing systems such as aircraft manufacturing, there is a high degree of variability in processing times and quality levels in the jobs performed by the same workers and between workers. Thus, the objective for worker allocation considering uncertainty is to allocate the best worker to the process, thereby minimizing the overall risk in the production line. In this research, influence of processing time and quality risk in worker allocation is assessed using risk assessment methodology. Modarres (2006) defined risk as;

$$RISK = \sum_i u_i c_i$$

Where, u_i is the probability of event i occurring and c_i is the consequence associated with the event. For worker allocation, probability of occurrence is defined as the probability of delay in processing time and probability of bad quality. The consequence can be viewed as delay and quality penalty respectively. Thus, in order to overcome the problems associated with existing methodologies for worker allocation, risk based worker allocation methodology for balanced line is proposed in the following sections.

The assumptions for worker allocation in balanced line considering uncertainties are listed below:

- Processing time of each worker is stochastic and follows a normal distribution
- Quality of each worker is stochastic and follows a normal distribution
- A worker can only be allotted to a single process
- Minimum number of worker per process is one
- Demand is deterministic and known for each period
- Workers are constrained to perform certain operations

The proposed risk based worker allocation model requires following input parameters for testing the proposed approach:

1) Operation times of all workers
2) Quality level of all workers
3) Cost of workers for each process
4) Total number of processes required for the product
5) Delay penalty associated with each process
6) Quality penalty associated with each process
7) Standard time for each process
8) Standard quality level for each process
9) Maximum number of workers in the line
10) Maximum number of workers per process

2.2.1 Risk-Based Mathematical Formulation

A NLIP model is developed for optimal risk based worker allocation, which, given an uncertain processing time and quality level of workers, allocates workers to the process thereby reducing the overall risk in the line. The objective function contains three terms. The first term is the risk when worker processing time exceeds standard processing time. This risk is defined as the probability of exceeding standard processing time

$P(X_{ij} > SP_j)$ multiplied by delay penalty for process j. If X_{ij} is the random normal variable representing the processing time of worker i for process j, with mean value of P_{ij} and standard deviation of $P_{\sigma ij}$, then:

$$P(X_{ij} > SP_j) = 1 - P(X_{ij} \le SP_j) = 1 - 1/2\left[1 + erf\left(\frac{SP_j - P_{ij}}{P_{\sigma ij}\sqrt{2}}\right)\right] \tag{7}$$

The *erf(.)* in (7) stands for Gauss error function or probability integral. The cumulative distribution function (*cdf*) describes probabilities for a random variable to fall in the intervals of the form $(-\infty, x]$. The *cdf* of the standard normal distribution is denoted with the capital Greek letter *Φ*, and can be computed as an integral of the probability density function. This integral can only be expressed in terms of a special function ***erf***, called the error function.

$$\phi(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\pi} e^{-t^2/2}dt = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right], x \in R \tag{8}$$

Second term of objective function minimizes the risk due to worker quality level, which is the product of probability of quality below standard quality level and quality penalty. By using the definition of Gauss error function in (8) the probability that quality level of worker i for process j, Y_{ij} , falls below the standard quality level, SQ_j, is calculated in (9)

$$P(Y_{ij} < SQ_j) = 1/2\left[1 + erf\left(\frac{SQ_j - Q_{ij}}{Q_{\sigma ij}\sqrt{2}}\right)\right] \tag{9}$$

Third part minimizes the cost of hiring workers. This cost is the product of hourly rate for assigning worker i to process j, number of working hours, and the binary variable L_{ij} which shows if worker i is assigned to process j. The objective function and constraints for the problem are presented as follows:

Objective Function

$$Min\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left[1 - 1/2\left[1 + erf\left(\frac{SP_j - P_{ij}}{P_{\sigma ij}\sqrt{2}}\right)\right]\right] * DP_j * L_{ij}\right] + \left[\left[1/2\left[1 + erf\left(\frac{SQ_j - Q_{ij}}{Q_{\sigma ij}\sqrt{2}}\right)\right]\right] * QP_j * L_{ij}\right] + \left[\left[C_{ij} * \frac{T}{60}\right] * L_{ij}\right] \tag{10}$$

Model Constraints

$$\sum_{j=1}^{n} L_{ij} \le 1 \quad \forall i \in I \tag{11}$$

$$\sum_{i=1}^{m} L_{ij} \ge 1 \quad \forall j \in J \tag{12}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} L_{ij} \le M \tag{13}$$

$$\sum_{j \in X_i} L_{ij} = 0 \quad \forall i \tag{14}$$

$$L_{ij} \in \{0,1\}$$

The objective is to minimize the total risk due to worker processing time and quality level by optimal allocation of workers to processes which is given in (10). Constraint (11) ensures that each worker i, is assigned to only one process. Constraint (12) assures that at least one worker is assigned to process j. Constraint (13) places an upper bound for the total number of workers (M) allotted to the line. Constraint (14) avoids selecting unskilled workers for a process.

Delay penalty DP_j is the penalty incurred if the processing time of certain process exceeds the standard processing time. Delay penalty will change as the criticality of the process changes. When a highly critical process is delayed, cost incurred is comparatively more than a low critical process. Quality penalty QP_j is the penalty incurred if the quality level of certain process is below the standard quality level. Quality penalty will increase linearly when moving towards downstream of the line, since every process in downstream adds value to the product. To demonstrate the risk based worker allocation model, two sample case studies are given in the following sections.

2.2.2 Case Study – 3-Process-6-Worker (Risk Based)

The same 3-process-6-worker case study (Fig. 1) is used to illustrate the proposed risk based worker allocation model. Standard processing time of all three processes is assumed to be 9 minutes. It is assumed that the worker processing time and quality level is stochastic and follows normal distribution due to uncertainties in processing time and quality. The modified operation time, quality level, and costs of all workers associated with their respective processes for 3-process-6-worker case study are given in Table 6.

Maximum number of workers allowed in the 3-process-6-worker case study is set to 5 and standard quality level of all the processes is set at 99%. Also**,** the Pr_j and Qr_j values associated with each process are given in Table 7.

Once the input variables are obtained, the NLIP model is solved using LINGO Optimizer 12.0 and the results are shown in Table 8. Another case study with 4 Processes and 8 Workers is presented in the Appendix A.

TABLE 6. OPERATION TIME, QUALITY LEVEL, AND COST FOR 3-PROCESS-6-WORKER CASE STUDY

Operation/ Worker		Operation 1	Operation 2	Operation 3
Worker 1	Operation Time(minute)	8.8±1.05		9.2±0.39
	Quality Level	98.9±0.22		99.2±0.11
	Cost/hour($)	10.00		9.37
Worker 2	Operation Time(minute)	8.9±0.33	8.9±0.66	
	Quality Level	99.3±0.14	98.7±0.21	
	Cost/hour($)	8.75	10.00	
Worker 3	Operation Time(minute)		8.8±1.11	8.9±0.68
	Quality Level		98.3±0.54	98.8±0.25
	Cost/hour($)		11.80	10.62
Worker 4	Operation Time(minute)	9.0±0.87		8.9±0.23
	Quality Level	99.0±0.08		99.1±0.08
	Cost/hour($)	10.62		9.37
Worker 5	Operation Time(minute)	9.1±0.48	9.1±0.18	
	Quality Level	98.8±0.19	99.3±0.18	
	Cost/hour($)	11.87	10.00	
Worker 6	Operation Time(minute)		8.9±0.36	8.8±0.98
	Quality Level		98.6±0.26	99.2±0.34
	Cost/hour($)		11.87	13.75

TABLE 7. PROFIT AND LOSS FOR 3-PROCESS-6-WORKER CASE STUDY

Process *(j)*	**1**	**2**	**3**

Profit (*Pr_j*)	$450	$500	$320
Quality Loss (*Qr_j*)	$300	$400	$500

TABLE 8. RESULTS –3-PROCESS-6-WORKER CASE STUDY

Process	**1**	**2**	**3**
Worker	Worker 2	Worker 6	Worker 4

2.3 Validation

Worker allocation results obtained for 3-process-6-worker case study by deterministic method and risk based methodology for single task per station balanced line are compared for validation purposes. Simulation is used to compare the solutions obtained. Because of the variability in skill levels and quality level, simulation is the most effective tool for comparison. The variability is analyzed by taking into consideration costs of delay and quality. In the context of production lines, costs can be classified as,

1) Internal costs
2) External costs

Internal costs are incurred if processing time of a certain process exceeds the standard processing time, such as cost for re-scheduling jobs. External costs are penalty incurred if the cycle time of a product exceeds the desired cycle time (or) costs due to poor quality of the product.

Since the processing time and quality level of workers are assumed to follow a normal distribution, a single run may not be sufficient to eliminate randomness in output. Hence, the model is replicated several times. Number of replications is calculated using (15), where ‘α’ denotes the confidence interval, ‘σ’ denotes the standard deviation and ‘h’ denotes the accuracy.

$$N_r = t^2_{\frac{\alpha}{2}, n-1} \frac{\sigma^2}{h^2} \qquad (15)$$

Simulation is carried out using discrete event simulation software QUEST with the worker allocation results obtained using deterministic and risk based worker allocation techniques and the outputs were compared. Simulation is run for 2880 minutes. The simulation model developed using worker allocation results from the deterministic worker allocation model is replicated for 24 runs and risk based worker allocation model is replicated for 12 runs. It is assumed that internal cost is $20/min, external cost associated with cycle time is $100/min and external cost associated with bad quality is $500/part. The results of the simulation are shown in Tables 9 and 10.

From the above tables, it can be observed that risk based worker allocation outperforms deterministic worker allocation methodology. Throughput increased by 5.8% and simultaneously non-value added time is reduced by 60.38%. Fig. 2 compares the value added and non-value added times of deterministic and risk based methodology.

III. WORKER ALLOCATION IN SINGLE TASK PER STATION FOR UNBALANCED LINE

A production line in which sequential operations have different processing times is called an unbalanced line. An unbalanced production line can be balanced by allocation of multiple workers to the bottleneck processes. Thus in a single task per station unbalanced production line, proposed risk based worker allocation methodology allocates multiple workers to the bottleneck processes to meet the demand. In addition to allocating the

TABLE 9. COST COMPARISON BETWEEN DETERMINISTIC AND RISK BASED METHODS

	Deterministic method		Risk based Method		Percent Change
Throughput	286.58		303.41		5.8%
	Internal Cost	**External Cost**	**Internal Cost**	**External Cost**	-
Time exceeded by process 1 (min)	93.02x20 =$1,860.4	-	25.84x20 =$516.8	-	72.22%
Time exceeded by process 2 (min)	98.38x20 =$1,867.6	-	28.83x20 =$576.6	-	70.69%
Time exceeded by process 3 (min)	80.43x20 =$1,608.6	-	14.34x20 =$286.8	-	82.17%
Time exceeded by cycle time (min)	-	330.80x100 =$33,080	-	121.74x100 =$12,174	63.19%
Total bad quality parts	-	11.91x500 =$5,955	-	9.25x$500 =$4,625	22.33%
TOTAL COST	**$44,371.6**		**$18,179.2**		

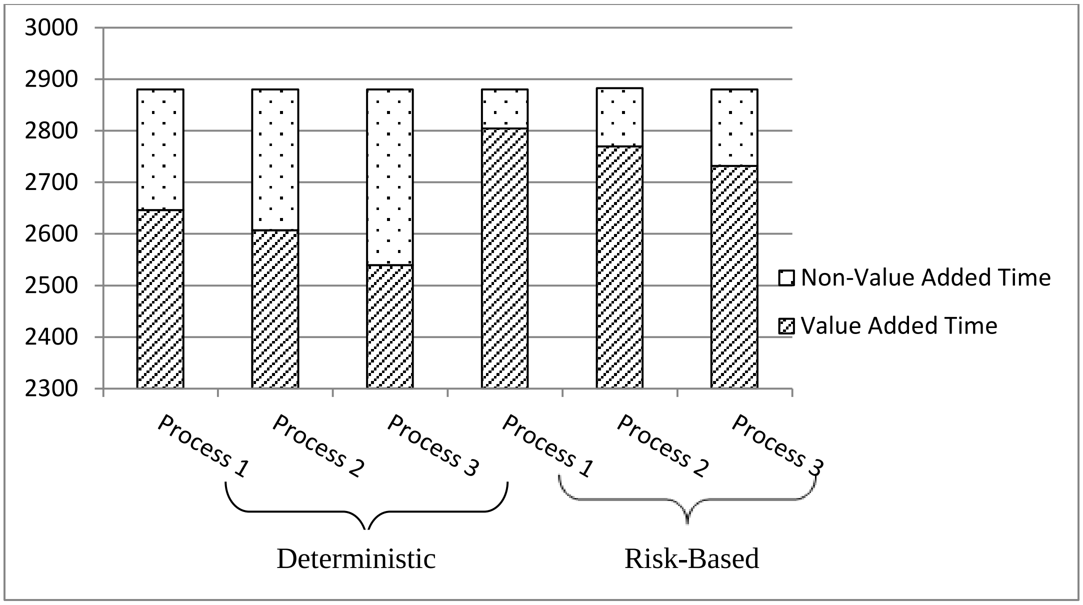
TABLE 10. VALUE ADDED TIME COMPARISON BETWEEN DETERMINISTIC AND RISK BASED METHOD

Process	Process 1	Process 2	Process 3	Total
Deterministic method				
Value Added Time	2646.059	2606.869	2539.582	7792.51
Idle Time	0	149.456	340.418	489.874
Waiting Time	233.941	123.674	0	357.615
Non-Value Added Time	233.941	273.131	340.418	847.49
Risk based Method				
Value Added Time	2804.605	2770.01	2732.069	8306.684
Idle Time	0	68.663	147.931	216.594
Waiting Time	75.394	43.77	0	119.164
Non-Value Added time	75.394	112.437	147.931	335.762

workers, the result has to be validated by ensuring that the required throughput is met. Hence, in addition to the worker allocation further validation has to be done using some heuristic to ensure that the throughput is met. In this research, simulation is used to validate the results. An optimal risk based worker allocation methodology for unbalanced line is described in the following sections. The proposed risk based worker allocation model for unbalanced line requires following input parameters for testing the proposed approach:

1) Operation times of all workers for their associated processes
2) Quality level of all workers for their associated processes
3) Cost of workers for each process respectively
4) Planning horizon

Figure 2 VA/NVA Comparison Chart



5) Demand of the product for given planning horizon
6) Total number of processes required for the product
7) Delay penalty associated with each process
8) Quality penalty associated with each process
9) Standard time for each process
10) Standard quality level for each process
11) Maximum number of workers in the line
12) Maximum number of workers per process

3.1. Mathematical Formulation

A NLIP is developed to solve the risk based worker allocation model for unbalanced line, which, given an uncertain processing time and quality of workers, allocates the best workers to the processes.

Objective function:

$$Min\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left[\left[1-1/2\left[1+erf\left(\frac{SP_j-P_{ij}}{P_{\sigma ij}\sqrt{2}}\right)\right]\right]*DP_j*L_{ij}\right]+\left[\left[1/2\left[1+erf\left(\frac{SQ_j-Q_{ij}}{Q_{\sigma ij}\sqrt{2}}\right)\right]\right]*QP_j*L_{ij}\right]+\left[C_{ij}*\left(\frac{T}{60}\right)*L_{ij}\right]\right] \tag{16}$$

Subject to

$$\sum_{j=1}^{n} L_{ij} \le 1 \quad \forall i \in I \tag{17}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} L_{ij} \le M \tag{18}$$

$$\left[\sum_{i}^{m}\frac{(Q_{ij}-3Q_{\sigma ij})}{(P_{ij}+3P_{\sigma ij})}*L_{ij}\right] > \frac{D}{T} \quad \forall j \in J \tag{19}$$

$$DP_j = \frac{1}{\sum_{i=1}^{n}\left[\frac{L_{ij}}{P_{ij}}\right]-\frac{D}{T}}*DP \quad \forall j \in J \tag{20}$$

$$\sum_{j \in X_i} L_{ij} = 0 \quad \forall i \tag{21}$$

$$L_{ij} \in \{0,1\}$$

The objective function minimizes the total risk due to worker processing time and quality level by allocating worker i, *i*=1,2,3…m to process j, *j*=1,2,3…n. The first part of the objective function minimizes the risk due to processing time of worker which is the product of probability in exceeding standard processing time and delay penalty. Second part minimizes the risk due to quality level of the worker which is the product of probability in quality of product below standard quality level and quality penalty. Third part includes the worker cost in the objective function.

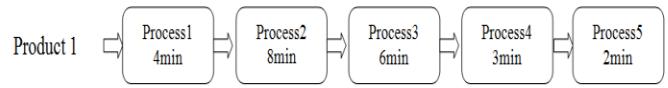
In the above set of constraints, (14) ensures that worker *i*, *i*=1, 2, 3,…, n, can perform at most one process in a given time period. Equation (15) provides an upper bound for the total number of workers (M) allotted to the line. Equation (16) allots multiple workers to the processes and makes sure that the line is producing more than the demand. Demand constraint was met by ensuring that each process produces greater than the Takt time of the line even in the worst case scenario. Equation (17) allots dynamic delay penalty values to the processes based on the idle time of the process, such that the busiest process will have more delay penalty in comparison with other processes. Constraint (18) avoids selecting unskilled workers for a process.

The NLIP model is solved using LINGO 12.0 optimizer for minimum risk after worker allocation. Output of LINGO optimizer gives the binary value for L_{ij}. If L_{ij} equals 1 then it is inferred that worker *i* is allocated to process *j* and if equals 0 then it is inferred that worker *i* is not allocated to process *j*. A sample case study for solving the NLIP for the unbalanced line is given in the following section.

3.2 Case Study - 5-Process-10-Worker

A case study with 5 processes and 10 workers in an unbalanced line is used to illustrate the proposed risk based worker allocation model. The standard processing times for all five processes are different as shown in Fig. 3.

Figure 3 Case Study - 5-Process-10-Workers



It is assumed that the worker processing time follows normal distribution which is collected from previous historical values and workers are constrained to certain operations. Operation time chart for 5-process-10-workers case study are shown in Table 11. In this research, quality level of a worker is defined as the number of products produced within the control limits of the respective process per 100 products. It is assumed that the worker quality level follows normal distribution which was obtained from previous historical data. Quality level chart for 5-process-10-workers case study are shown in Table 12.

Demand for product 1 in 5-process-10 worker case study is assumed to be 600 products and the associated planning horizon is 2880 minutes. The costs of all workers associated with their respective processes for 5-process-10-worker case study are shown in Table 13.

Dynamic delay penalty:

Delay penalty is the penalty incurred if the processing time of certain process exceeds the standard processing time. Delay penalty will change as the criticality of the process changes. Thus a dynamic delay penalty constraint is introduced which allots delay penalty based on the idle time of the process.

TABLE 11. OPERATION TIME (MIN) CHART FOR 5-PROCESS-10-WORKER CASE STUDY

Operation /Worker	1	2	3	4	5
Worker 1	3.5±0.16		6.2±0.1		
Worker 2		7.0±0.6		3.0±0.16	
Worker 3	4.5±0.06				1.5±0.33
Worker 4		7.5±0.33		3.5±0.16	
Worker 5			5.8±0.2		2.0±0.2
Worker 6	4.2±0.6		6.0±0.16		
Worker 7		6.8±0.16		2.8±0.2	
Worker 8	4.0±0.13				2.2±0.06
Worker 9		6.5±0.26		2.5±0.33	
Worker 10			6.5±0.16		2.5±0.16

TABLE 12. QUALITY LEVEL CHART FOR 5-PROCESS-10-WORKER CASE STUDY

Operation /Worker	1	2	3	4	5
Worker 1	98±0.1		99±0.16		
Worker 2		98±0.5		99±0.1	
Worker 3	99±0.13				97±0.5
Worker 4		98.5±0.33		99.5±0.16	
Worker 5			98±0.06		98±0.16
Worker 6	98.5±0.1		98±0.16		
Worker 7		99.5±0.1		98±0.13	
Worker 8	98±0.16				98.5±0.33
Worker 9		99.5±0.13		98.6±0.13	
Worker 10			98.8±0.16		99±0.33

The busiest process in the production line is allotted the highest delay penalty to make sure the best worker was allotted to the busiest process. The delay penalty calculations for the

5-process-10-worker case study are explained below:

Delay penalty for process 1 =

$$\frac{1}{\sum_{i=1}^{10}\left[\frac{L_{ij}}{P_{ij}}\right]-\frac{D}{T}} * DP = \frac{1}{\left[\frac{1}{3.5}+\frac{0}{4.5}+\frac{0}{4.2}+\frac{0}{4.0}\right]-\left[\frac{600}{2880}\right]} * 40 = \$516.92 \qquad j=1$$

By using the same formulation delay penalties for processes 2, 3, 4 and 5 are calculated \$555.10, \$339.19, \$208.69, and \$162.46 respectively. Maximum number of workers allowed in the case study is 9 and standard quality level of all processes is set at 98%. Quality penalty is incurred if the quality

TABLE 13. WORKER COST/HOUR ($) CHART FOR 5-PROCESS-10-WORKER CASE STUDY

Operation /Worker	1	2	3	4	5
Worker 1	12.50		13.33		
Worker 2		11.66		15.00	
Worker 3	13.33				14.16
Worker 4		15.83		12.50	
Worker 5			11.66		15.00
Worker 6	14.16		13.33		
Worker 7		18.33		14.16	
Worker 8	12.50/hr				13.33/hr
Worker 9		18.33/hr		15.83/hr	
Worker 10			13.33/hr		14.16/hr

level of certain process is below the standard quality level. Quality penalty will increase linearly when moving downstream on the line. Quality Penalties for 5-process-10-worker-case study is given in Table 14.

TABLE 14. QUALITY PENALTY ASSOCIATED WITH PROCESSES FOR 5-PROCESS-10-WORKER CASE STUDY

Process	1	2	3	4	5
Quality Penalty for Process ($)	300	400	500	600	700

TABLE 15. RESULTS – 5-PROCESS-10-WORKER CASE STUDY

Process	1	2	3	4	5
Worker	Worker 1	Worker 2, Worker 4	Worker 5, Worker 10	Worker 9	Worker 8

The NLIP model was solved using LINGO Optimizer 12.0 and the results obtained are shown in Table 15.

The results obtained from the LINGO model for the case study is simulated using QUEST software for validation. Simulation is replicated 16 times and the average throughput is found to be 622.4 products. A larger case study with 5-process and15-worker is presented in Appendix B.

IV. CONCLUSION

From the time study data obtained from a local aircraft manufacturing company, it was evident that a high degree of variability exists in worker processing times. This, variability in worker processing time and quality is more common in labor intensive manufacturing systems. In all previous approaches for worker allocation, variability in worker processing time and quality level is not addressed. If the worker allocation is done assuming a deterministic processing time and single quality level for workers, it may degrade the performance of the line. The objective of this research was to model and solve risk based worker allocation methodology in which variability in worker processing time and quality is also taken into consideration.

In this paper, definition of risk from the perspective of worker allocation was presented. There were two classes of risks associated with worker allocation - processing time risk and quality level risk. Processing time risk is defined as the increase in delay penalty cost due to uncertainty in worker processing time. Quality level risk is defined as the increase in quality penalty cost due to uncertainty associated with worker quality level. A deterministic worker allocation methodology for single task per station balanced line scenario was also developed as a benchmark for the problem being addressed. Non Linear Integer Programming (NLIP) models have been developed which found the optimal worker allocation by minimizing the risk in labor intensive single task per station balanced/unbalanced production lines for stochastic cases. The risk based worker allocation for balanced line is validated against deterministic worker allocation methodology, in which risk based methodology outperformed deterministic methodology with an increased throughput. In single task per station unbalanced line scenario, in addition to allocation of best worker to the process, it also allocates multiple workers to the processes in order to balance the bottleneck stations and to meet the demand. The methodology that is developed was validated using simulation.

Risk based worker allocation approach was shown to be an efficient tool to incorporate uncertainty in worker characteristics into worker allocation problem. The problem considered for this research is a single product problem. The methodologies for balancing product lines and assigning workers when multiple products are involved are tedious and currently there are no methods that can address this issue. The current research could be used a starting point to developing multi-product line-balancing and worker allocation issues. The methodology used in this research is to develop optimization approaches to the worker allocation problem. The largest case study that was conducted in this research is with 5 processes and 15 workers. Since, the formulation is a NLIP, as the problem size increases, the formulation and computational time increases exponentially. Hence, new heuristics that can adapt to large size problems have to be developed. In the current research, the worker profiles are assumed to be static. However, with the learning curve effect, the worker profile can be made dynamic. When including dynamic worker profile the problem of worker allocation also becomes dynamic and the improvements in workers have to be taken into consideration in the solution of worker allocation problems. However, this could make the problem size larger and will require more aggressive heuristics to be developed.

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Appendix A – Additional Case Study for Risk Based Worker Allocation in Balanced Lines

Case Study – 4-Process-8-Worker: To further test the consistency of the proposed model in section 2, a 4-process-8-worker case study is selected (Fig. A.1). The standard processing time for all the processes is assumed to be 14 minutes. The operation time, the quality levels, and the costs of all workers associated with their respective processes for the case study are shown in Table A.1. Profit and Quality Loss are also presented in table A.2.

Figure A.1 Case Study - 4-Process-8-Workers

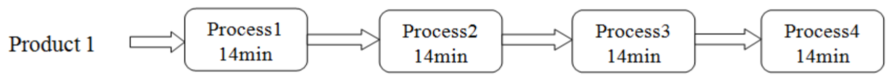

TABLE A.1 OPERATION TIME, QUALITY LEVEL, AND COST FOR 4-PROCESS-8-WORKERS CASE STUDY

Operation/		Operation 1	Operation 2	Operation 3	Operation 4
Worker 1	Operation Time(minute)	13.7±0.62		13.4±0.85	
	Quality Level	98.6±0.16		99.1±0.26	
	Cost/hour($)	15		8	
Worker 2	Operation Time(minute)		14.2±0.58		13.6±0.66
	Quality Level		98.0±0.26		98.6±0.23
	Cost/hour($)		13		10
Worker 3	Operation Time(minute)	13.5±0.53		13.3±0.92	
	Quality Level	99.0±0.33		98.4±0.13	
	Cost/hour($)	12		14	
Worker 4	Operation Time(minute)		13.8±0.76		13.7±0.48
	Quality Level		98.3±0.20		98.0±0.30
	Cost/hour($)		10		12
Worker 5	Operation Time(minute)	13.8±0.44		13.5±0.63	
	Quality Level	98.5±0.20		99.2±0.16	
	Cost/hour($)	10		15	
Worker 6	Operation Time(minute)		14.0±0.56		13.9±0.42
	Quality Level		98.7±0.26		97.5±0.83
	Cost/hour($)		13		14
Worker 7	Operation Time(minute)	14.4±0.35		13.2±1.00	
	Quality Level	97.0±1.00		98.7±0.28	
	Cost/hour($)	17		16	
Worker 8	Operation Time(minute)		13.9±0.82		13.8±0.53
	Quality Level		98.2±0.42		98.8±0.28
	Cost/hour($)		11		9

TABLE A.2 PROFIT AND QUALITY LOSS ($) FOR 4-PROCESS-8-WORKER CASE STUDY

Process *(j)*	**1**	**2**	**3**	**4**
Profit (*Pr_j*)	650	625	725	750
Quality loss (Q*r_j*)	550	600	650	700

Maximum number of workers allowed in the 4-process-8-worker case study is set to 7 and standard quality level of all the processes is 98.5%.

Once the input variables are obtained, Non Linear Integer Programming (NLIP) model was solved using LINGO Optimizer 12.0 and the results shown in Table A.3.

TABLE 3.11 RESULTS – 4-PROCESS-8-WORKER CASE STUDY

PROCESS	1	2	3	4
WORKER	Worker 3	Worker 6	Worker 1	Worker 8

Appendix B - Additional Case Study for Risk Based Worker Allocation in Unbalanced Lines

Case Study - 5-Process-15-Worker: For further testing of the mathematical model presented in Section 3, another case study has been tested. An unbalanced line with 5 processes and 15 workers was considered as case study to further test the proposed methodology for risk based worker allocation in unbalanced production line.

The operation time chart for 5-process-15-workers case study is given in Table B.1. The quality level chart for the case study is given in Table B.2. The cost of all workers associated with their respective processes for 5-process-15-worker case study is given in Table B.3. Demand for the product 1 in the case study is assumed to be 500 products and the associated planning horizon was 2880 minutes.

Table B.1 Operation Time (min) Chart for 5-Process-15-Worker Case Study

Operation /Worker	1	2	3	4	5
1	2.8±0.17		13.5±0.33		
2		5.1±0.07		8.9±0.13	
3	2.9±0.13				6.6±0.20
4		4.8±0.20		8.8±0.20	
5			13.8±0.23		6.8±0.23
6	2.5±0.33		14.1±0.17		
7		4.6±0.27		9.1±0.07	
8	3.0±0.10				7.2±0.10
9		4.7±0.20		8.7±0.20	
10			13.7±0.27		7.0±0.17
11	3.1±0.1		13.9±0.23		
12		5.0±0.20		8.8±0.23	
13	2.7±0.2				6.9±0.17
14		5.2±0.27		9.0±0.17	
15			14.0±0.13		6.7±0.27

TABLE B.2 QUALITY LEVEL CHART FOR 5-PROCESS-15-WORKER CASE STUDY

Operation /Worker	1	2	3	4	5
1	98.0±0.67		98.6±0.20		
2		98.7±0.20		99.0±0.17	
3	99.2±0.03				98.8±0.90
4		98.5±0.33		98.3±0.53	
5			98.5±0.33		99.2±0.10
6	97.5±1.0		98.8±0.17		
7		99.0±0.17		98.5±0.33	
8	98.8±0.20				99.0±0.17
9		97.0±1.0		99.5±0.20	
10			99.1±0.10		98.0±0.50
11	99.0±0.23		99.5±0.20		
12		98.8±0.27		98.7±0.20	
13	99.1±0.13				98.9±0.10
14		98.7±0.33		99.3±0.20	
15			98.9±0.23		99.1±0.13

TABLE B.3 WORKER COST ($) CHART FOR 5-PROCESS-15-WORKER CASE STUDY

Operation /Worker	1	2	3	4	5
1	10.87/hr		12.87/hr		
2		9.43/hr		9.25/hr	
3	12.87/hr				11.00/hr
4		9.56/hr		12.37/hr	
5			13.12/hr		10.75/hr
6	13.25/hr		11.93/hr		
7		10.25/hr		11.62/hr	
8	9.37/hr				12.81/hr
9		11.50/hr		9.43/hr	
10			11.06/hr		9.93/hr
11	9.12/hr		13.06/hr		
12		10.93/hr		10.18/hr	
13	12.37/hr				10.12/hr
14		13.56/hr		8.43/hr	
15			11.56/hr		12.00/hr

Delay penalty for the processes are calculated using the dynamic delay penalty constraint and their values are shown in Table B.4.

TABLE B.4 DELAY AND QUALITY PENALTIES FOR 5-PROCESS-10-WORKER CASE STUDY

Process	1	2	3	4	5
Delay Penalty for Process ($)	175.21	685.24	660.82	572.05	244.49
Quality Penalty for Process ($)	300	400	500	600	700

Maximum number of workers allowed in the 5-process-15-machine case study is set to 14 and standard quality level of all the processes is set at 99%. Input values were fed on to the LINGO Optimizer 12.0 to obtain optimal worker allocation and the results are as follows in Table 3.21.

TABLE 3.21 RESULTS – 5-PROCESS-10-WORKER CASE STUDY

Process	1	2	3	4	5
Worker	3	7	1, 10, 11	2, 9	5, 15

The results obtained from the LINGO model for this case study is simulated using QUEST software. Simulation is replicated for 18 times and the average throughput is 516.8 products.