Department of Industrial and Systems Engineering

ISE 560, Stochastic Models in Industrial Engineering – Dr. Julie Ivy

Course Project Report

Optimizing Customer Service Delivery for Lenovo Data Center Group

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Executive Summary

The Lenovo Group is one of the largest technology companies in the world. For a technology company like Lenovo, early and efficient issue resolution plays a key role in reducing costs and driving customer satisfaction. Towards this end, in collaboration with Lenovo, a decision support system was proposed to help identify the appropriate service action to resolve an issue. The scope of the project was restricted to High Performance machines in the Asia Pacific and PRC regions. The methodology of this project involved accurately identifying key factors that exhibit similar issue resolution behaviors and ultimately translating these behaviors into a consistent prediction and action scheme through a Markov Decision Process.

Preliminary data analysis was conducted to identify areas where Lenovo's current policy can be improved. The key findings from the preliminary analysis revealed a significant proportion of issues being fixed through NPRA. It also revealed many unsuccessful SSR attempts while an issue was being resolved.

The five components of the Markov Decision Process (State space, Action space, Epoch, Transition probabilities and Cost matrix) were defined carefully to capture as much of the available information about a particular issue. After the costs and probabilities for each transition were accounted for, the optimal decision policy was generated using linear programming. The linear program accounts for all potential transitions, in terms of costs and their likelihoods, and then decided which service action is the most optimal choice in terms of cost. As the Markov Decision Process was built based on few assumptions, a range of sensitivity analysis was conducted to test the validity of the model under different scenarios. The sensitivity analysis, to summarize, showed that that the policy was not influenced by moderate changes in service action costs and transition probabilities.

As a next step, the results could be improved further by addressing the limitations present in the data such as a lack of information on the contribution of each service action towards issue resolution and the unavailability of information about the nature of the issue.

Introduction

The Data Center Group at Lenovo provides enterprises with high quality server, storage and networking solutions. Current Lenovo uses the following process for resolution of customer issues. If a customer faces an issue with their product, they call Lenovo's Level1 (L1) Technical Support Teams and request their product to be fixed. When a L1 technician receives a call, they open a claim associated with the problem that customer is describing. L1 technician searches for the known problems and tries to fix the issue. If the issue is not known and seems like a hardware problem, the call is directed to Level2 (L2) for deeper problem determination. L1/L2 reps can also dispatch a Support Service Representative (SSR) to customer's location to work on the problem. If the issue can still not be resolved and the L1/L2 teams or SSR believes that it is a defect, the problem may be escalated to Lenovo's Product Engineering Team (Level3 – L3), who work on solving the problem. Below is a schematic describing the current policy followed by Lenovo to resolve customer issues.

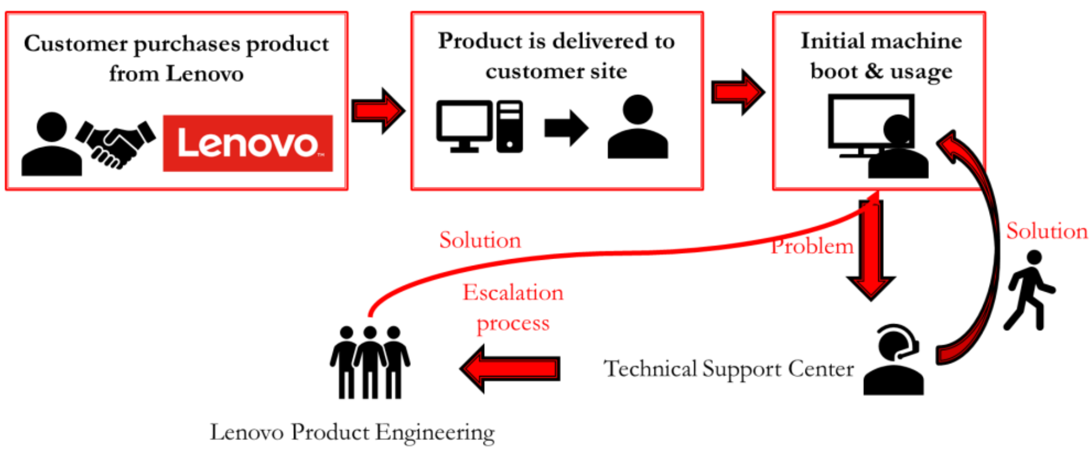

Figure 1: Schematic description of the current issue resolution policy

On several occasions, the immediate service action chosen did not lead to an issue resolution. This results in an increase in both the cost and time involved in providing a solution to the customer's problem. Hence, the current process is suboptimal and can be significantly improved by incorporating the likelihood of a service action leading to a resolution based on history. Through the project, we aim to develop a robust decision support system to assist Lenovo in determining the optimal service action to be chosen at each stage of the issue resolution process for High Performance Machines in the Asia Pacific and PRC Region.

The following key information was provided by Lenovo to help assess the existing policy and to identify potential areas of improvement.

- Country Code
- Machine Type
- Serial Number
- Commodity: Which part was replaced
- Part count: How many parts were replaced
- Service date: Date of the service
- Month in service: Age of the machine when service action happened
- Box count: Tracks the number of service actions performed to resolve an issue
- Service delivery type:
    - FOP – Fix on Phone
    - CRU – Customer replaceable unit
    - ONS – Technician sent onsite
    - NPRA – No-Part repair action
    - L3 – Escalated to Product Engineering team

The methodology of this project involves accurately identifying key factors that exhibit similar issue resolution behaviors and ultimately translating these behaviors into a consistent prediction and action scheme through a Markov Decision Process

Assumptions

1. All calls for a specific machine received within 30 days after the first call were considered to be for the same issue. The machine is considered to be fixed if no additional service action was performed within 30 days of the last service action
2. The last service action performed on a specific machine was considered to be the fixing service action
3. Service actions performed on a single day were considered to be distinct attempts at fixing the machine. For instance, if ONS was attempted twice on the same day, it was considered as two separate onsite visits.
4. All claims escalated to L3 are considered to be fixed by the L3 Product Engineering team

Exploratory Data Analysis

In the PRC region, machine types M23, M24, M26 and M27 together accounted for 90% of all issues. Further, M23&M26 and M24&M27 were found to behave similarly in terms of service actions which fixed the issue.

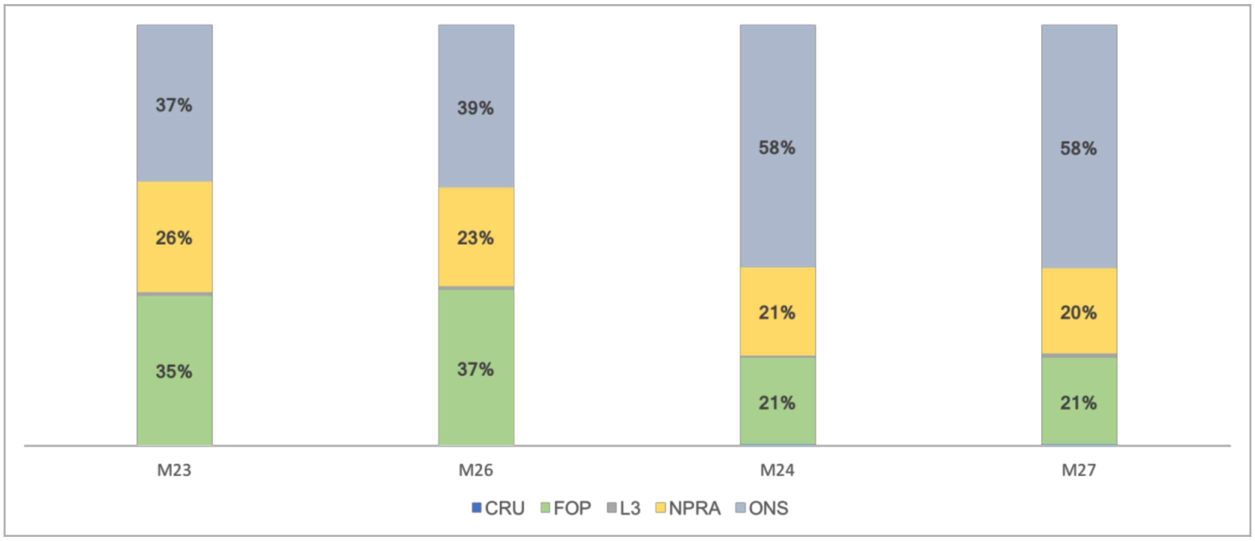

Figure 2: % of service action fixing an issue by machine type in the PRC region

No such similarities were observed for issues in the Asia Pacific Region.

In order to identify areas where Lenovo is losing money, we classified issues into two categories

1. Issues resolved through a single service action (**1 service action category**)
2. Issues that required more than one service action for resolution (**'>1' service action category**)

Figure 3 describes the process by which this classification was done on all the issues.

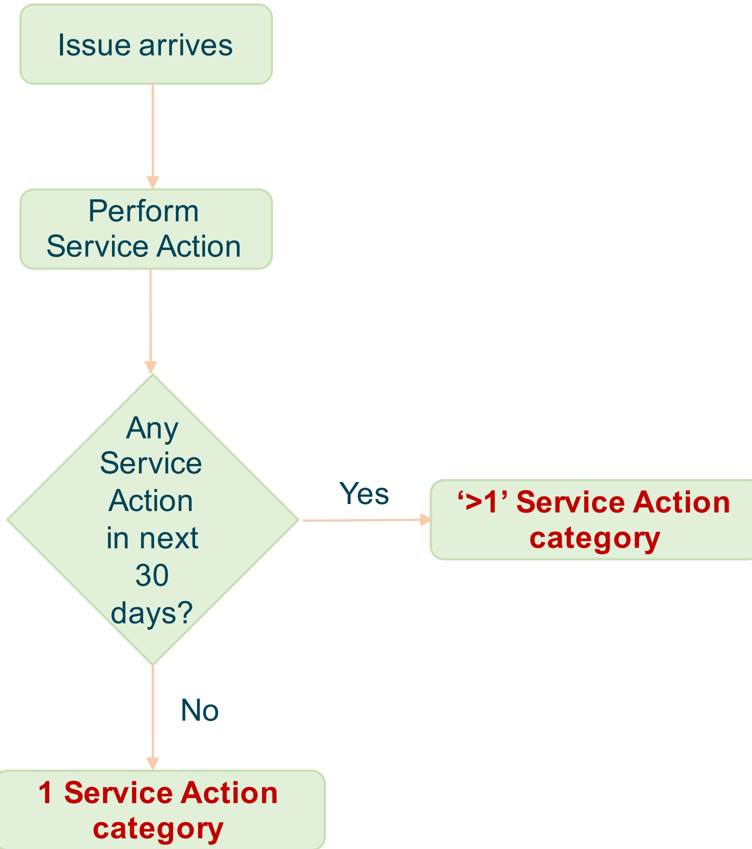

Figure 3: Flow chart depicting issue categorization

1 Service Action category analysis

71% of the issues in Asia Pacific region and 83% of the issues in the PRC region were resolved using a single service action

While this is a good indicator of a robust policy, we identified certain aspects where the policy could be further improved. On dissecting the '1 service action' category issues, we noticed NPRA as the fixing service action for a significant number of issues (45% for Asia Pacific and 23% for PRC region). A service action is categorized as an NPRA when a technician goes onsite thinking that a part needs to be replaced but returning without any repair action being performed. This leads to a significant increase in the expenses associated with issue resolution. Accurate assessment of the issue can lead to a reduction in the number of NPRAs. For Asia Pacific region, a closer inspection revealed few outlier countries experiencing a significantly larger percentage of issues resolved through NPRA. Figure 4 illustrates the numbers mentioned above graphically

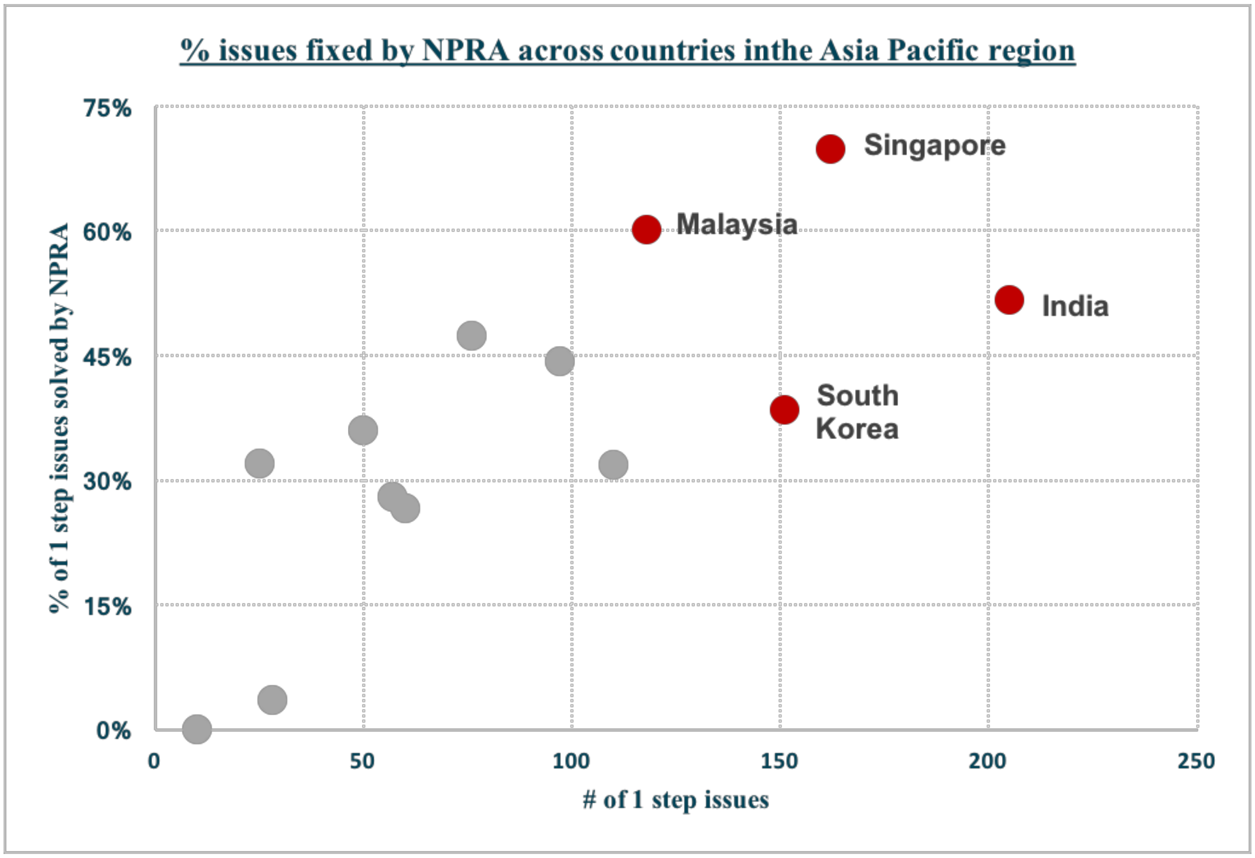

Figure 4: % of 1 step category issues fixed through NPRA across countries

'>1' Service Action category analysis

The primary objective of analyzing this category was to determine the predominant service actions which were unsuccessful in resolving the issues. Identifying methods to cut down on these unsuccessful service actions would significantly reduce the issue resolution time (this analysis assumes that service actions do not cumulatively resolve the issues). SSR accounted for 83% and 71% of the unsuccessful actions in the Asia Pacific and China region respectively.

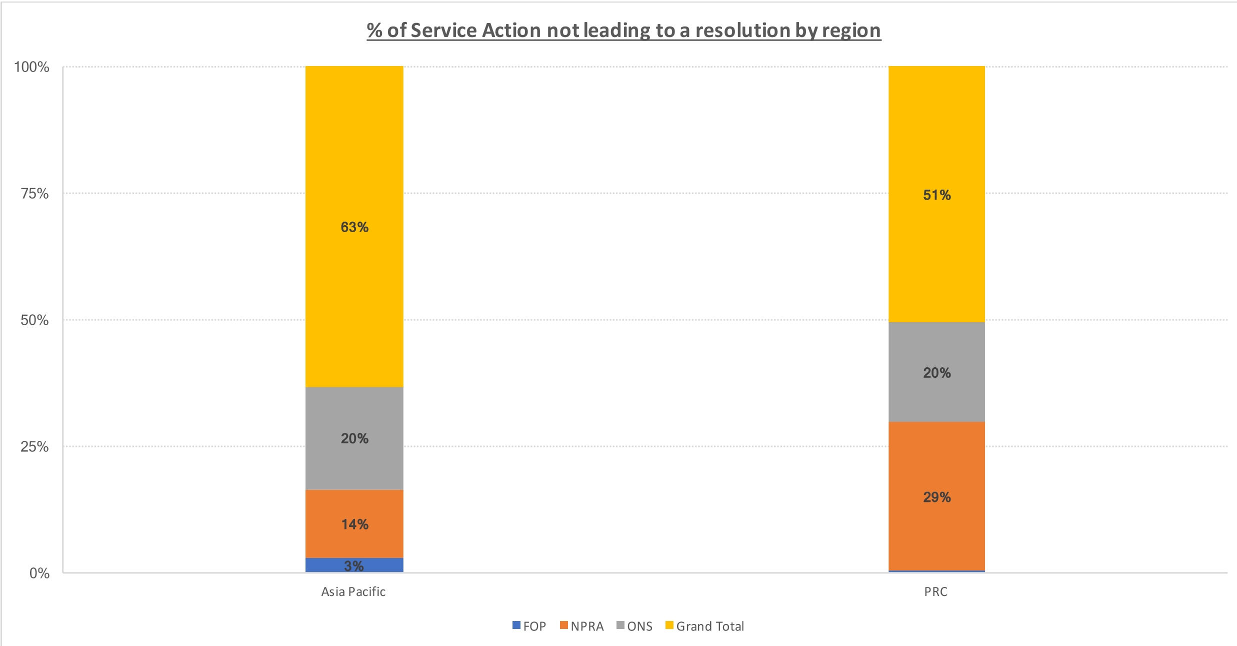

Figure 5: % of Service actions not leading to resolution by region

Statistical Model to predict the next service action

In this section, we predict the next service action for the machine based on its history and other factors. We accomplish this by building a Multinomial Logistic Regression model. The list of variables is provided below

Independent Variables:

- Machine Type (M23, M24, M25, M26, M27, M28 and M29)
- Age of the machine (Age_0_19, Age_20_39)
- Number and type of service actions that have been performed (SSR, FOP)
- Number of different commodities that were replaced in the past (O, HD, M, PS, PR)
- Number of L3 escalations for the machine in past(L3)

Dependent variable:

- Next service action (FOP, CRU, SSR, Escalation to L3)

Validation: We trained the model using 80% of randomly selected observations and tested the model using the remaining 20%.

Results: 65% accuracy was obtained in predicting the next service action using this approach.

Natural Evolution of the current process

The objective of this analysis was to better understand the current issue resolution process. The key metrics we were interested in included the initial service action performed to fix a problem, the common paths that machines take in terms of service delivery types and the actual service action which fixed the problem. Given the inherent uncertainties in the existing process, a stochastic model would accurately capture the relevant metrics. It is reasonable to conclude that the above mentioned stochastic process is Markovian in nature based on the assumption that only the final service action fixes the issue and not the prior service actions. The components of this Markov Chain were defined as below

- States: These capture the relevant information associated with an issue at a given point in time. They were defined as a combination of the current status of the machine (Broken or Fixed) and the most recent service action performed to correct the issue. The list of states is B – NA, B – FOP, B – CRU, B – NPRA, B – ONS, L3, Fixed
- Epoch: It indicates all the moments in time when the machine status is recorded. $1/4^{th}$ of a day was considered to be the epoch for this Markov Chain. This was done to capture the multiple service actions done on the same day
- Transition Probability matrix: This captures the probabilities associated with moving from one state to another. This was calculated as below

$$P(State\ A \rightarrow\ B) = \frac{\#\ of\ transitions\ from\ A \rightarrow B}{total\ \#\ of\ transitions\ from\ state\ A}$$

Figure 6: Formula used to calculate the transition probability

The resulting transition probability matrix is provided in the Appendix tables A1 and A4

From the above Markov Chain, the following key metrics were calculated

Table 1: Key metrics calculated from the Markov Chain

Metric	Asia Pacific	PRC
Avg # of days to resolve an issue	2.6 days	1.7 days
% of issues being escalated to L3	5.9%	0.7%

The next step is to build a Markov Decision Process that incorporates these transition matrices along with the cost associated with each transition to generate an optimal service action policy

Policy Improvement through a Markov Decision Process

Markov Decision Process is a mathematical framework for modeling decisions where outcomes are probabilistic rather than deterministic but can be influenced by the decision maker.

Components of the Markov Decision Process

State space: States indicate the available information about an issue at given point in time. States were defined as a combination of the machine status (Broken, Fixed) along with the previous action performed for the issue. List of States is B – NA, B – FOP, B – CRU, B – NPRA, B – ONS, F – FOP, F – CRU, F – NPRA, F – ONS, F – L3

Action space: Actions are the decisions taken by Lenovo to resolve an issue. List of possible actions include L1/L2, SSR, escalation to L3 and Do Nothing. Future States of the machine are impacted by the action chosen

Epoch: It indicates all the moments where the status of the machine is recorded and a potential action can be initiated. For this MDP, epoch has been defined as 1/4th of a day

Transition Matrix: It represents the probability of moving from one state to another under a given action. The matrix is calculated based on the transitions seen historically. The transition matrix for each action in the Asia Pacific and PRC Region (both M23&M26 and M24&M27) has been provided in the Appendix section B2 to B5, B7 to B10 and B12 to B15

Cost matrix: It provides the expected cost of taking an action in a particular state. For e.g., cost associated with an L3 escalation is much higher than an L1/L2 or an SSR service action. A penalty was imposed to penalize epochs where no service actions was performed to fix the issue. This would force the model to consider not just the cost but also the time spent in the Broken state to generate an optimal policy. The details involving the cost matrix calculations has been provided in the Appendix section tables B16 to B18

Optimal policy:

After the costs and probabilities for each transition were accounted for, the optimal decision policy was generated using linear programming. The linear program accounts for all potential transitions, in terms of costs and their likelihoods, and then decides which service action is the most optimal choice in terms of cost. In the PRC Region, a different policy was generated for machine types M23&M26 and M24&M27 as they were found to behave similarly, in terms of fixing service action, within the groups and differently across the groups. The optimal policy for Asia Pacific region and PRC Region are as follows

- **Asia Pacific region**: The policy recommends attempting a Fix on Phone (FOP) under all circumstances.
- **PRC region**: For machine types M23&M26, the optimal policy recommends Fix on Phone under all circumstances. For machine types M24&M27, the optimal policy recommends Fix on Phone under all circumstances except when a CRU was unsuccessful in fixing the issue, in which case the policy recommends an SSR.

The detailed LINDO report for the linear program has been provided in the Appendix figures B1 to B3

In order to ascertain the robustness of the policy, a range of sensitivity analysis was performed to understand the impact that parameters like cost and transition probabilities have on the final policy. A range of sensitivity analysis was done, which to summarize, shows that that the policy is not influenced by moderate changes in these parameters.

Limitations:

Though the current policy is a step in the right direction for Lenovo, we feel that the policy can be improved significantly if we had the following information

- Information about whether a service action helped resolve an issue – Currently the model is built on a strong assumption that only the final service action fixes an issue. The prior service actions are believed to have performed no part in resolving the issue. This assumption might not be valid in certain cases. In such situations, an input from Lenovo which states whether a service action was ultimately beneficial in fixing the issue would help improve the final policy
- Initial data gathered by the L1 associate about the issue – This would give us more information about the problem experienced by the customer. Certain service actions might not be suitable to fix certain type of issues. Providing more information about the issue will help us eliminate such service actions and provide a more relevant policy

Conclusion

In conclusion, the policy generated using Markov Decision Process recommends attempting a Fix on Phone before performing any other service action. Though the current policy is a step in the right direction, we feel that the recommendations could be further improved if we can address the limitations mentioned above.

Appendix

A. Natural evolution of the process

Asia Pacific Region

Transition Probabilities associated with moving from a broken state to an L3 escalation/ Fixed states are as shown below

Table A1: Overall Transition Probability matrix for Asia Pacific region

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	L3	F
B-NA	0.88	0.01	0.001	0.01	0.02	0	0.08
B-FOP	0.81	0.03	0.01	0.00	0.02	0.07	0.07
B-CRU	0.52	0	0.08	0	0	0.08	0.32
B-NPRA	0.60	0.01	0	0.00	0.09	0.21	0.10
B-ONS	0.19	0.01	0	0.01	0.32	0.10	0.37
L3	0	0	0	0	0	1	0
F	0	0	0	0	0	0	1

Using the transition matrix above, we calculated the amount of time spent in each of the transient states and the probabilities of getting absorbed in either the L3 or the fixed states.

The total time in epochs spent in the transient states are as shown below

Table A2: Number of epochs spent in transient states

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	Days to L3 / Resolution
B-NA	9.74	0.07	0.02	0.11	0.26	2.6
B-FOP	8.23	1.09	0.02	0.09	0.24	2.4
B-CRU	5.51	0.04	1.10	0.06	0.15	1.7
B-NPRA	6.10	0.05	0.01	1.07	0.29	1.9
B-ONS	2.89	0.03	0.00	0.05	1.55	1.1

The probabilities associated with getting absorbed in an L3/Fixed state is as shown below

Table A3: Absorption probabilities associated with being escalated to L3 or getting fixed

Current State \ Absorbing States	L3	F
B-NA	0.06	0.94
B-FOP	0.12	0.88
B-CRU	0.12	0.88
B-NPRA	0.26	0.74
B-ONS	0.17	0.83

PRC Region

Transition Probabilities associated with moving from a broken state to an L3 escalation/ Fixed states are as shown below

Table A4: Overall Transition Probability matrix for PRC region

Current State	Future State: B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	L3	F
B-NA	0.83	0.01	0	0.01	0.01	0	0.14
B-FOP	0.98	0.00	0	0.00	0.00	0.02	0.01
B-CRU	1	0	0	0	0	0	0
B-NPRA	0.72	0.00	0	0.00	0.05	0.05	0.19
B-ONS	0.27	0.00	0	0.00	0.17	0.04	0.53
L3	0	0	0	0	0	1	0
F	0	0	0	0	0	0	1

Using the transition matrix above, we calculated the amount of time spent in each of the transient states and the probabilities of getting absorbed in either the L3 or the fixed states.

The total time in epochs spent in the transient states are as shown below

Table A5: Number of epochs spent in transient states

Current State	Future State: B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	Days to L3 / Resolution
B-NA	6.46	0.06	0.00	0.04	0.10	1.7
B-FOP	6.31	1.06	0.00	0.04	0.10	1.9
B-CRU	6.46	0.06	1.00	0.04	0.10	1.9
B-NPRA	4.74	0.05	0.00	1.03	0.13	1.5
B-ONS	2.08	0.02	0.00	0.01	1.23	0.8

The probabilities associated with getting absorbed in an L3/Fixed state is as shown below

Table A6: Absorption probabilities associated with being escalated to L3 or getting fixed

Current State	Absorbing States: L3	F
B-NA	0.01	0.99
B-FOP	0.03	0.97
B-CRU	0.01	0.99
B-NPRA	0.05	0.95
B-ONS	0.05	0.95

B. Markov Decision Process

Transition Probability Matrix Calculations

The transition probability matrices were calculated using the number of transitions between two states A and B and the total number of transitions in the given data set. We provide the numbers below for both the Asia Pacific and the PRC regions

Asia Pacific Region

Number of transitions between states

Table B1: Total number of transitions between states in the Asia Pacific region

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	13579	111	22	169	260	367	89	593	264	0
B-FOP	96	3	1	0	2	5	0	2	1	8
B-CRU	13	0	2	0	0	4	4	0	0	2
B-NPRA	103	1	0	0	15	1	0	4	12	37
B-ONS	77	3	0	4	131	1	0	9	142	41
F-FOP	0	0	0	0	0	0	0	0	0	0
F-CRU	0	0	0	0	0	0	0	0	0	0
F-NPRA	0	0	0	0	0	0	0	0	0	0
F-ONS	0	0	0	0	0	0	0	0	0	0
F-L3	0	0	0	0	0	0	0	0	0	0

Using the above matrix, the likelihood of an action such as L1/L2, SSR and L3 were calculated

Transition Probability Matrices for each type of service action

L1/L2 service action

Table B2: Transition Probability matrix for L1/L2 action in Asia Pacific region

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0	0.19	0.04	0	0	0.62	0.15	0	0	0
B-FOP	0	0.33	0.11	0	0	0.56	0	0	0	0
B-CRU	0	0	0.2	0	0	0.4	0.4	0	0	0
B-NPRA	0	0.5	0	0	0	0.5	0	0	0	0
B-ONS	0	0.75	0	0	0	0.25	0	0	0	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

SSR service action

Table B3: Transition Probability matrix for SSR action in Asia Pacific region

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0	0	0	0.13	0.20	0	0	0.46	0.21	0
B-FOP	0	0	0	0	0.4	0	0	0.4	0.2	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	0	0	0	0	0.48	0	0	0.13	0.39	0
B-ONS	0	0	0	0.01	0.46	0	0	0.03	0.50	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

L3 service action

Table B4: Transition Probability matrix for L3 action in Asia Pacific region

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0.01	0	0	0	0	0	0	0	0	0.99
B-FOP	0.01	0	0	0	0	0	0	0	0	0.99
B-CRU	0.01	0	0	0	0	0	0	0	0	0.99
B-NPRA	0.01	0	0	0	0	0	0	0	0	0.99
B-ONS	0.01	0	0	0	0	0	0	0	0	0.99
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.01	0	0	0	0	0	0	0	0	0.99

Do Nothing

Table B5: Transition Probability matrix for Do Nothing action in Asia Pacific region

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	1	0	0	0	0	0	0	0	0	0
B-FOP	1	0	0	0	0	0	0	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	1	0	0	0	0	0	0	0	0	0
B-ONS	1	0	0	0	0	0	0	0	0	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

PRC Region

Machine Types (M23 and M26)

Number of transitions between states

Table B6: Total number of transitions between states in the PRC Region for M23&M26

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	16100	207	3	116	180	1103	5	799	1061	0
B-FOP	201	0	0	0	0	1	1	0	0	4
B-CRU	3	0	0	0	0	0	0	0	0	0
B-NPRA	97	0	0	0	4	1	0	0	8	6
B-ONS	76	0	0	0	34	1	0	2	92	13
F-FOP	0	0	0	0	0	0	0	0	0	0
F-CRU	0	0	0	0	0	0	0	0	0	0
F-NPRA	0	0	0	0	0	0	0	0	0	0
F-ONS	0	0	0	0	0	0	0	0	0	0
F-L3	0	0	0	0	0	0	0	0	0	0

Transition Probability Matrices for each service action

L1/L2 service action

Table B7: Transition Probability matrix for L1/L2 action in PRC region for M23&M26

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0	0.157	0.002	0	0	0.837	0.004	0	0	0
B-FOP	0	0	0	0	0	0.5	0.5	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	0	0	0	0	0	1	0	0	0	0
B-ONS	0	0	0	0	0	1	0	0	0	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

SSR service action

Table B8: Transition Probability matrix for SSR action in PRC region for M23&M26

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0	0	0	0.05	0.08	0	0	0.37	0.49	0
B-FOP	1	0	0	0	0	0	0	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	0	0	0	0	0.33	0	0	0	0.67	0
B-ONS	0	0	0	0	0.27	0	0	0.02	0.72	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

L3 service action

Table B9: Transition Probability matrix for L3 action in PRC region for M23&M26

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0.01	0	0	0	0	0	0	0	0	0.99
B-FOP	0.01	0	0	0	0	0	0	0	0	0.99
B-CRU	0.01	0	0	0	0	0	0	0	0	0.99
B-NPRA	0.01	0	0	0	0	0	0	0	0	0.99
B-ONS	0.01	0	0	0	0	0	0	0	0	0.99
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.01	0	0	0	0	0	0	0	0	0.99

Do Nothing

Table B10: Transition Probability matrix for 'DN' action in PRC region for M23&M26

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	1	0	0	0	0	0	0	0	0	0
B-FOP	1	0	0	0	0	0	0	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	1	0	0	0	0	0	0	0	0	0
B-ONS	1	0	0	0	0	0	0	0	0	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

Machine Types (M24 and M27)

Number of transitions between states

Table B11: Total number of transitions between states in the PRC Region for M23&M26

Future State

Current State

	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	13433	144	0	137	296	535	6	522	1241	0
B-FOP	142	0	0	0	0	0	0	0	0	3
B-CRU	0	0	0	0	0	0	0	0	0	0
B-NPRA	82	0	0	0	9	1	0	1	39	5
B-ONS	81	1	0	0	66	0	0	1	215	7
F-FOP	0	0	0	0	0	0	0	0	0	0
F-CRU	0	0	0	0	0	0	0	0	0	0
F-NPRA	0	0	0	0	0	0	0	0	0	0
F-ONS	0	0	0	0	0	0	0	0	0	0
F-L3	0	0	0	0	0	0	0	0	0	0

L1/L2 service action

Table B12: Transition Probability matrix for L1/L2 action in PRC region for M24&M27

Future State

Current State

	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0	0.210	0	0	0	0.781	0.009	0	0	0
B-FOP	1	0	0	0	0	0	0	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	0	0	0	0	0	1	0	0	0	0
B-ONS	0	1	0	0	0	0	0	0	0	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

SSR service action

Table B13: Transition Probability matrix for SSR action in PRC region for M24&M27

Future State

Current State

	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0	0	0	0.06	0.13	0	0	0.24	0.57	0
B-FOP	1	0	0	0	0	0	0	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	0	0	0	0	0.18	0	0	0.020408	0.80	0
B-ONS	0	0	0	0	0.23	0	0	0.00	0.76	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

L3 service action

Table B14: Transition Probability matrix for L3 action in PRC region for M24&M27

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0.01	0	0	0	0	0	0	0	0	0.99
B-FOP	0.01	0	0	0	0	0	0	0	0	0.99
B-CRU	0.01	0	0	0	0	0	0	0	0	0.99
B-NPRA	0.01	0	0	0	0	0	0	0	0	0.99
B-ONS	0.01	0	0	0	0	0	0	0	0	0.99
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.01	0	0	0	0	0	0	0	0	0.99

Do Nothing

Table B15: Transition Probability matrix for 'DN' action in PRC region for M24&M27

Future State

Current State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	1	0	0	0	0	0	0	0	0	0
B-FOP	1	0	0	0	0	0	0	0	0	0
B-CRU	1	0	0	0	0	0	0	0	0	0
B-NPRA	1	0	0	0	0	0	0	0	0	0
B-ONS	1	0	0	0	0	0	0	0	0	0
F-FOP	0.05	0	0	0	0	0.95	0	0	0	0
F-CRU	0.05	0	0	0	0	0	0.95	0	0	0
F-NPRA	0.05	0	0	0	0	0	0	0.95	0	0
F-ONS	0.05	0	0	0	0	0	0	0	0.95	0
F-L3	0.05	0	0	0	0	0	0	0	0	0.95

Cost Matrix Calculations

Lenovo provided us with the normalized costs for both the service actions performed and the replaceable parts of each machine. The costs provided were as below.

Cost of service actions

- FOP = 0.5
- CRU = 0.5 + Cost of part * Number of parts
- ONS = 2 + Cost of part * Number of parts
- NPRA = 2.125
- L3 = 10

Cost of parts

- System Board = 2.25
- Processor = 7.5
- Hard Drives = 0.75
- Memory = 0.75
- Power Supplies = 0.75
- All other parts = 1.5

In addition to the above-mentioned costs, we imposed a penalty of 0.2 on each epoch spent without any attempt being made to fix the issue.

The resulting cost matrices for both the Asia Pacific and PRC regions are provided below.

Cost Matrix for the Asia Pacific region

Table B16: Cost matrix associated with transition between states in the Asia Pacific state

Current State \ Future State	B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
B-NA	0.2	0.7	1.684	2.325	4.249	0.5	1.513	2.125	3.646	10
B-FOP	0.2	0.7	1.684	2.325	4.249	0.5	1.513	2.125	3.646	10
B-CRU	0.2	0.7	1.684	2.325	4.249	0.5	1.513	2.125	3.646	10
B-NPRA	0.2	0.7	1.684	2.325	4.249	0.5	1.513	2.125	3.646	10
B-ONS	0.2	0.7	1.684	2.325	4.249	0.5	1.513	2.125	3.646	10
F-FOP	0	0	0	0	0	0	0	0	0	0
F-CRU	0	0	0	0	0	0	0	0	0	0
F-NPRA	0	0	0	0	0	0	0	0	0	0
F-ONS	0	0	0	0	0	0	0	0	0	0
F-L3	0	0	0	0	0	0	0	0	0	0

Cost Matrix for the PRC region

Machine types M23 and M26

Table B17: Cost associated with transition between states in the PRC state for M23&M26

Current State		Future State									
		B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
	B-NA	0.2	0.7	1.450	2.325	3.907	0.5	1.375	2.125	3.183	10
	B-FOP	0.2	0.7	1.450	2.325	3.907	0.5	1.375	2.125	3.183	10
	B-CRU	0.2	0.7	1.450	2.325	3.907	0.5	1.375	2.125	3.183	10
	B-NPRA	0.2	0.7	1.450	2.325	3.907	0.5	1.375	2.125	3.183	10
	B-ONS	0.2	0.7	1.450	2.325	3.907	0.5	1.375	2.125	3.183	10
	F-FOP	0	0	0	0	0	0	0	0	0	0
	F-CRU	0	0	0	0	0	0	0	0	0	0
	F-NPRA	0	0	0	0	0	0	0	0	0	0
	F-ONS	0	0	0	0	0	0	0	0	0	0
	F-L3	0	0	0	0	0	0	0	0	0	0

Machine types M24 and M27

Table B18: Cost associated with transition between states in the PRC state for M24&M27

Current State		Future State									
		B-NA	B-FOP	B-CRU	B-NPRA	B-ONS	F-FOP	F-CRU	F-NPRA	F-ONS	F-L3
	B-NA	0.2	0.7	1.450	2.325	4.277	0.5	1.625	2.125	3.307	10
	B-FOP	0.2	0.7	1.450	2.325	4.277	0.5	1.625	2.125	3.307	10
	B-CRU	0.2	0.7	1.450	2.325	4.277	0.5	1.625	2.125	3.307	10
	B-NPRA	0.2	0.7	1.450	2.325	4.277	0.5	1.625	2.125	3.307	10
	B-ONS	0.2	0.7	1.450	2.325	4.277	0.5	1.625	2.125	3.307	10
	F-FOP	0	0	0	0	0	0	0	0	0	0
	F-CRU	0	0	0	0	0	0	0	0	0	0
	F-NPRA	0	0	0	0	0	0	0	0	0	0
	F-ONS	0	0	0	0	0	0	0	0	0	0
	F-L3	0	0	0	0	0	0	0	0	0	0

Results of the Markov Decision Process

Asia Pacific Region

We used LINDO to solve the linear programming problem developed to generate the optimal policy. The variables were defined as Y_{jk} where 'j' indicates the state of the machine and 'k' indicates the service action.

The mappings associated with j and k are as shown below

Table B19: Mapping between states and service actions

State	j
B-NA	1
B-FOP	2
B-CRU	3
B-NPRA	4
B-ONS	5
F-FOP	6
F-CRU	7
F-NPRA	8
F-ONS	9
F-L3	10

Service Action	K
L1/L2	1
SSR	2
L3	3
Do Nothing	4

The results from LINDO report as shown below

```
LP OPTIMUM FOUND AT STEP     10

      OBJECTIVE FUNCTION VALUE

      1)     0.4691427

 VARIABLE        VALUE          REDUCED COST
      Y11         0.122655          0.000000
      Y21         0.122655          0.000000
      Y31         0.122655          0.000000
      Y41         0.122655          0.000000
      Y51         0.122655          0.000000
      Y61         0.122655          0.000000
      Y71         0.116829          0.000000
      Y81         0.111280          0.000000
      Y91         0.105994          0.000000
     Y101         0.000000          0.178274
      Y12         0.000000          2.158099
      Y22         0.000000          2.580660
      Y32         0.000000          3.515061
      Y42         0.000000          3.141633
      Y52         0.000000          3.206035
      Y62         0.000000          0.032100
      Y72         0.000000          0.022588
      Y82         0.000000          0.012601
      Y92         0.000000          0.002117
     Y102         0.000000          0.178274
      Y13         0.000000          9.211648
      Y23         0.000000          9.248391
      Y33         0.000000          8.804773
      Y43         0.000000          9.346569
      Y53         0.000000          9.296569
      Y63         0.000000          0.032100
      Y73         0.000000          0.022588
      Y83         0.000000          0.012601
      Y93         0.000000          0.002117
     Y103         0.100959          0.000000
      Y14         0.000000          3.921935
      Y24         0.000000          3.958678
      Y34         0.000000          3.515061
      Y44         0.000000          4.056856
      Y54         0.000000          4.006856
      Y64         0.000000          0.032100
      Y74         0.000000          0.022588
      Y84         0.000000          0.012601
      Y94         0.000000          0.002117
     Y104         0.000000          0.178274
```

Figure B1: Results from the LINDO Report for Asia Pacific region

PRC Region

Machine Type (M23 and M26)

Results from LINDO report is as shown below

```
LP OPTIMUM FOUND AT STEP      0

       OBJECTIVE FUNCTION VALUE

       1)      1.540640

 VARIABLE        VALUE          REDUCED COST
      Y11         0.124101          0.000000
      Y21         0.124101          0.000000
      Y31         0.000000          4.896355
      Y41         0.124101          0.000000
      Y51         0.124101          0.000000
      Y61         0.124101          0.000000
      Y71         0.118206          0.000000
      Y81         0.112592          0.000000
      Y91         0.107243          0.000000
     Y101         0.000000          0.585443
      Y12         0.000000          2.268451
      Y22         0.000000         17.698584
      Y32         0.000000          8.549723
      Y42         0.000000          2.924611
      Y52         0.000000          2.859049
      Y62         0.000000          0.105415
      Y72         0.000000          0.074178
      Y82         0.000000          0.041383
      Y92         0.000000          0.006952
     Y102         0.000000          0.585443
      Y13         0.000000          9.549467
      Y23         0.000000          9.148860
      Y33         0.124101          0.000000
      Y43         0.000000          9.586360
      Y53         0.000000          9.586360
      Y63         0.000000          0.105415
      Y73         0.000000          0.074178
      Y83         0.000000          0.041383
      Y93         0.000000          0.006952
     Y103         0.102149          0.000000
      Y14         0.000000         18.099192
      Y24         0.000000         17.698584
      Y34         0.000000          8.549723
      Y44         0.000000         18.136084
      Y54         0.000000         18.136084
      Y64         0.000000          0.105415
      Y74         0.000000          0.074178
      Y84         0.000000          0.041383
      Y94         0.000000          0.006952
     Y104         0.000000          0.585443
```

Figure B2: Results from the LINDO Report for PRC region for M23&M26

Machine Types M24 and M27

The results from the LINDO report is as shown below

```
LP OPTIMUM FOUND AT STEP      1

       OBJECTIVE FUNCTION VALUE

       1)      2.707027

 VARIABLE        VALUE          REDUCED COST
      Y11         0.125582          0.000000
      Y21         0.125582          0.216344
      Y31         0.000000          9.867554
      Y41         0.125582          0.000000
      Y51         0.125582          0.000000
      Y61         0.125582          0.000000
      Y71         0.119617          0.000000
      Y81         0.113935          0.000000
      Y91         0.108523          0.000000
     Y101         0.000000          1.028670
      Y12         0.000000          2.543598
      Y22         0.000000         15.757585
      Y32         0.125682         15.757585
      Y42         0.000000          2.961011
      Y52         0.000000          2.829811
      Y62         0.000000          0.185222
      Y72         0.000000          0.130336
      Y82         0.000000          0.072713
      Y92         0.000000          0.012215
     Y102         0.000000          1.028670
      Y13         0.000000          9.607270
      Y23         0.000000          0.000000
      Y33         0.000000          0.000000
      Y43         0.000000          9.659168
      Y53         0.000000          9.459168
      Y63         0.000000          0.185222
      Y73         0.000000          0.130336
      Y83         0.000000          0.072713
      Y93         0.000000          0.012215
     Y103         0.103368          0.000000
      Y14         0.000000         25.364855
      Y24         0.000000         15.757585
      Y34         0.000000         15.757585
      Y44         0.000000         25.416752
      Y54         0.000000         25.216753
      Y64         0.000000          0.185222
      Y74         0.000000          0.130336
      Y84         0.000000          0.072713
      Y94         0.000000          0.012215
     Y104         0.000000          1.028670
```

Figure B3: Results from the LINDO Report for PRC region for M24&M27