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# Integrated Simulation Modeling of Business, Maintenance and Production Systems for Concurrent Improvement of Lead Time, Cost and Production Rate

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**ABSTRACT**

The objective of this study is to integrate the business, maintenance and production processes of a manufacturing system by incorporating errors. First, the required functions are estimated according to the historical data. The system activities are simulated by Visual SLAM software and the required outputs are obtained. Several outputs including lead times in different dimensions, total cost and production rates are computed through simulation. Finally, data envelopment analysis (DEA) is utilized in order to select the best option between the defined scenarios due to the multi-criteria feature of the problem. This is the first study in which the lead times, cost and production rates are simultaneously considered in the integrated system imposed of business, maintenance and production processes by incorporating errors. In the current study, the major bottlenecks of the system being studied are identified and suggested different strategies to improve the system and make the best decision.

Keywords: Production Process, Business Process, Cost Estimation; Human Error, Maintenance Policy

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## 1. INTRODUCTION

Nowadays, the manufacturing companies need to adopt appropriate strategies to stay productive and profitable in the global competition market. The ubiquitous strategies are to minimize costs and lead times and maximize production rates. It is clear that minimizing the total cost results in more profit. In addition, minimizing the lead time leads to the customer satisfaction as well as increased production rates in a particular time period. The current study considers the integrated system imposed of business, maintenance and production processes by incorporating human error and machine error to minimize total cost and lead times and maximize production rates, simultaneously. It should be also given out that the complexity of the model will be intensified when the realistic assumptions are considered to be the model close to the real system. Thus, the other analytical models are either inefficient or insolvable in a reasonable period. But, the simulation model can be used to replace the actual system in order to analyze and improve the system. Unique feature of this study is to consider all the mentioned factors, simultaneously.

## 2. LITERATURE REVIEW

In the literature, the maintenance, production, business, error, cost, lead time and production rate have been individually investigated from different points of view. Also, some studies have attempted to combine some of them.

Chen and Papazafeiropouloa (2013) have investigated the supply chain integration in the Taiwan information technology industry. The aim of their study has been to explore how the suppliers adopt integration technology and improve efficiency of their organizations. Hashemi *et al*. (2014) have designed an integer linear programming model to minimize energy costs for the factory. Jahangirian *et al*. (2010) have reviewed the simulation applications in manufacturing and business according to peer-reviewed literature from 1997 to 2006. Their study reveals the raised trends in hybrid modeling in order to solve complicated problems. The integration of the production process, information system and business process has been investigated by Azadeh *et al*. (2008). They have attempted to evaluate the customer waiting times in different dimensions by using simulation modeling in the integrated system. The relationship between business and maintenance policies has been surveyed by Pinjala *et al*. (2006). They have considered about 150 companies in Belgium and several in Netherlands to authenticate their study. Oke and Charles-Owaba (2007) have presenteda model to schedule both operational activities and preventive maintenance by considering the uncertainty. They have applied the fuzzy logic to do this. Azadeh *et al*. (2012) have presented an approach to diagnose, simulate and improve the business process from a viewpoint of cybernetic. Kjaer (2003) has attempted to integrate the business and production processes. Roux *et al*. (2008) have analyzed the maintenance policies performances with random parameters by integrating the optimization algorithms and the simulation methods. The activities of business processes have been compared with manufacturing processes by Yelling and Machulack (1996). Law *et al*. (2010) have addressed post-implementation requirements to adopt successful enterprise resource planning (ERP). They have employed a case study approach to identify the critical success factors of ERP adoption.

Bouvard *et al*. (2011) have attempted to present a method to optimize the maintenance planning as well as grouping the dynamic maintenance operations. The main objective of their research has been to decrease the total maintenance cost. An integrated framework for costing availability type service contracts has been presented by Datta and Roy (2010). They have done this by focusing on the structured literature review and practice. Gulledge *et al*. (2010) have tried to integrate the product lifecycle management (PLM) and the condition-based maintenance (CBM). The integration has been done by employing composite applications in their paper. Kim and Park (2012) have proposed four human error analysis procedures to reduce test or maintenance (T&M) human errors. They have focused on task characteristics and work conditions to present procedures. Heo and Park (2010) have proposed a framework to evaluate the effects of human errors occurred in maintenance tasks of nuclear power plants. Azadeh *et al*. (2013) have proposed a new simulation-DEA approach to optimize maintenance policy and planning by incorporating learning effects. Azadeh *et al*. (2008) have presented an integrated simulation, multivariate analysis and multiple decision analysis to improve and optimize the railway system.

Liu *et al*. (2009) have presented a model to estimate human error cost in manufacturing environment. A model in order to simulate the human errors under different situations has been developed by Jin *et al*. (2003). Rooney *et al*. (2002) have investigated to reduce human error by determining root causes of errors. Kirwan (1992) has reviewed the available techniques of human error identification in human-machine systems.

According to the literature, there is no research to integrate the maintenance, production and business processes by incorporating errors. This paper fills the gap with the objective of minimizing cost and lead times and maximizing production rates, concurrently.

## 3. METHODOLOGY

As previously mentioned, the objective of this study is to present a computer simulation-DEA approach to integrate the production, maintenance and business process by incorporating errors. In addition, lead times, cost and production rates are considered as the evaluating criteria.

The overall goals of this research are summarized as follows:

1) Minimizing lead times in different dimensions (this study: 12 dimensions)
2) Maintaining or increasing the reliability of equipment
3) Identifying the major bottlenecks of the business process
4) obtaining the proper working hours
5) Reducing the errors
6) Maximizing the production rates (this study: 8 products)
7) Minimizing the total cost

According to the proposed approach, several techniques namely interview, questionnaire, visual observation, company's documents, and working standards and methods are used to collect data-set and understand the current situation of the system. The goodness of fit test is then used to estimate the functions. Selecting the best fitting distributions are done by STATISCA® and EASY FIT®. In the next step, the maintenance, production, business process and errors are simulated by the SLAM network. The simulation model is run and then verified and validated. Afterwards, various scenarios are defined and obtained the lead time in different dimensions, cost and production rates by simulation outputs. Consequen-

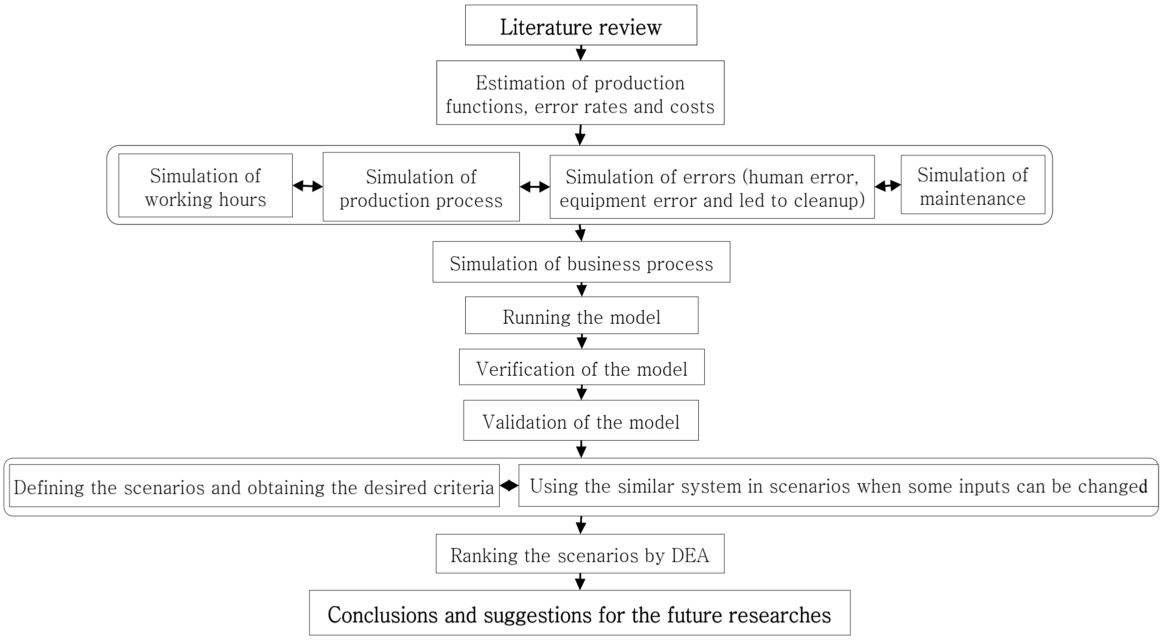



**Figure 1.** Research process.

tly, data envelopment analysis (DEA) is used to rank the various scenarios and select the best. Figure 1 shows a simple scheme of the research process.

It should be pointed out that the situation similar to the scenario is used to analyze the system when some inputs might be changed. For instance, the error rate change by changing the working hour. That is to say more working hour is caused more error as a result of more fatigue. In this case, a good estimation of the error rate is to use the collected error's data for the required hour (for less working hours).

## 4. CASE STUDY

A small order-based powder coating manufacturer is considered as the case study. The company uses three parallel machines to produce eight different coatings. The product request, sample request and complaint about a special product are three possible reasons to contact the company by the customers. The requests (local or out of state) are received through the general manager or deputy. If the request has been received through the deputy, the deputy transmits it to the general manager and customers follow their requests through the deputy.

Data flow diagrams (DFDs) presented in Figures 2 and 3explain the case study in which the corresponding numbers indicate the sequence of activities.

## 5. INTEGRATED SIMULATION

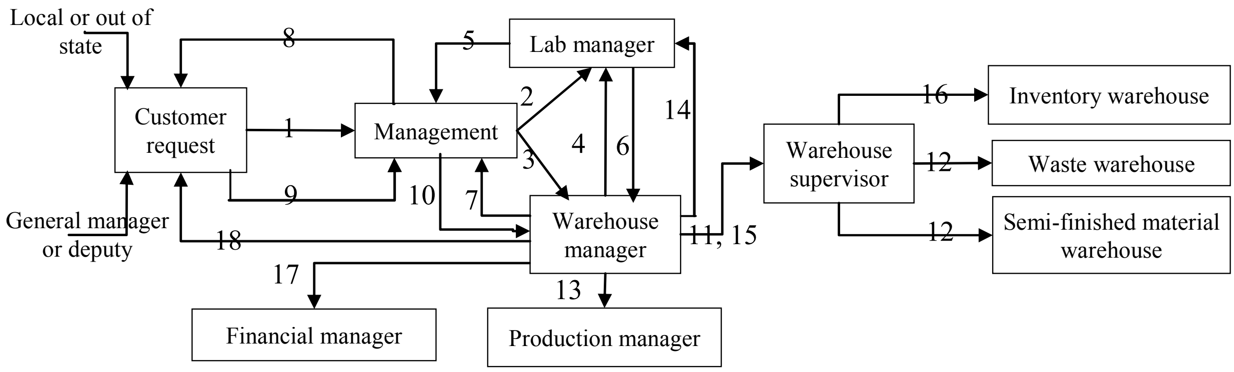
As previously mentioned, the Visual SLAM is used to simulate the model of system (Pritsker *et al*., 1989; Pritsker, 1990; Pritsker *et al*., 1997; Goldsman *et al*., 1999).

In order to simulate the integrated system, first, data flow diagrams have been drawn for modules and the modules are then simulated by the Visual SLAM network. These modules are including the arrival of requests to the company and customer complaint, production, sample request, maintenance (there is no preventive maintenance in the current system), manager interaction with the external entities (interaction might be related to their relationship with out of the organization or they might take a little time to rest and etc), working shift and errors [1. human error 2. machine error and 3. error caused to clean the equipment that the first and second errors exist in two forms: 1. caused to a complete failure product (waste material) 2. caused to a semi-failure product (return to the production line)]. The mentioned modules are linked each other through the business process module simulation. Functions and attributes used in the SLAM network are presented in the Tables 1 through 6.

### 5.1 Data Flow Diagrams for the Modules

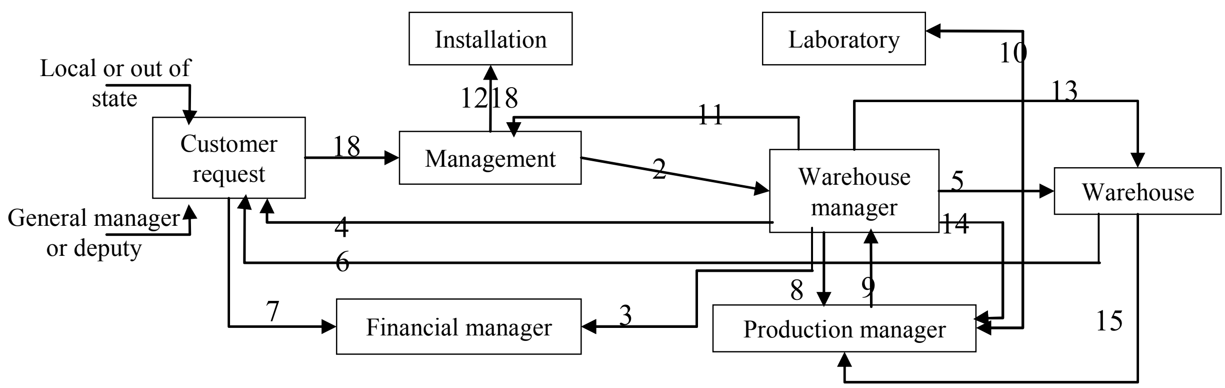
The DFD for the arrival of requests and customer complaint is described as follows:

The requests are received through the general manager and the deputy with probability 0.4 and 0.6, respectively. Also the requests are local or out of state with probability 0.45 and 0.55, respectively. The production request, sampling and customer complaint are placed with probability 0.57, 0.27 and 0.19, respectively. The general manager forwards the customer complaint to the lab and then lab manager reports the investigation results to the general manager. There are two kinds of results as the lab's investigation:




1) make complaint about a special product 2) forward a complaint form 3) forward three copies of the form(returned forms from warehouse) 4) forward three copies of the form(returned forms from warehouse) 5) Complaint assessment report 6) give all three returned forms from warehouse 7) give all three returned forms from warehouse 8) give the complaint assessment report to customer 9) Customer comment about the product 10) give all three returned forms from warehouse if either the product is defective and the customer wants to give back 11) forward the returned form as the permission of return of the product 12) forward the product according to the lab's comment 13) forward the first copy of the returned forms from warehouse if the product is identified modifiable by lab or the product is non-defective, but the customer wants to give back the product 14) forward the second copy of the returned forms from warehouse if the product is non-defective, but the customer wants to give back the product 15) forward the returned form as the permission of return of the product 16) send the product to inventory warehouse(because the product is non-defective) 17) give the second sheet of returned forms from warehouse to pay off to the customer 18) forward the third sheet of returned forms as the returned receipt

**Figure 2.** DFD for the customer complaints.




1) Customer product request 2) Forward the order rate to check if the inventory level is enough 3) forward the second copy to pay off by customer if the inventory is sufficient 4) forward the third copy as receipt when inventory is sufficient to customer order 5) forward the permission of exit of the product if the inventory is enough 6) forward the product and receipt to the customer 7) Pay off by customer 8) forward the amount of inventory shortage(inventory level is insufficient) 9) Forward the amounts of consumable materials and required raw materials 10) Forward the sample formula requested by the customer 11) permission form to provide consumable raw materials if it is insufficient 12) forward the permission to supply the raw materials 13) Completion of the material withdrawal form and forward it if there is enough inventory level from raw and consumables materials 14) Send back the warehouse report form 15) forward the warehouse report form according to the materials withdrawal.

**Figure 3.** DFD for the order and sample request by customers.

1) The product is non-defective or defect is solvable (with probability 0.75)

The result is forwarded to the customer as the received way of complaint (general manager or deputy).

2) The product is defective and defect is insolvable (with probability 0.25)

The result is forwarded to the customer as the received way of complaint (general manager or deputy) and also the warehouse supervisor is informed of accepting the return of defective products. Figure 4 shows the DFD for the arrival of requests and complaints of customer.

The reader should note that the DFDs for the remained modules are not illustrated in the paper.

**Table1.** Used functions

| Function | Description | Function | Description |
|---|---|---|---|
| F_1 | time between requests | F27 | Receiving the sample request by manager from Deputy |
| F1 | Conversation time between customer and deputy to receive the request | F28 | Conversation between general manager and customer to receive the sample request |
| F2 | Receiving the request by manager from deputy | | |
| F_3_1 | Conservation time between general manager and customer to receive the request | F_29_1 | Receiving the sample request by lab |
| | | F_29_2 | Prototyping |
| F_3_2 | Management approval to produce order | F30 | Receiving the result of prototyping by manager |
| F4 | Assessing inventory level by warehouse supervisor | F_31_1 | Receiving the result of prototyping by deputy |
| | | F_31_2 | the result report of prototyping by deputy |
| F5 | Reporting unavailability of final products | F_32_1 | the result report of prototyping by manager |
| F6 | Production order and exit permission | F33 | time between external activities of manager |
| F7 | Assessing availability of raw materials | | |
| F8 | material withdrawal instruction | F34 | external activity time of manager |
| F9 | cleaning time of machine 1 | F35 | time between external activities of warehouse Supervisor |
| F10 | cleaning time of machine 2 | | |
| F11 | cleaning time of machine 3 | F36 | external activity time of warehouse supervisor |
| F12 | materials withdrawal and production reports by production manager | F37 | time between external activities of production Manager |
| F13 | Recording of more product and less material | F38 | external activity time of production manager |
| F14 | Receiving the results of production by manager | F39 | time between external activities of deputy |
| F15 | Conversation between customer and deputy to receive the complaint | F40 | external activity time of deputy |
| | | F41 | time between external activities of lab manager |
| F16 | Receiving the complaint by manager from deputy | | |
| F17 | Conversation between customer and General manager to receive the complaint | F42 | external activity time of lab manager |
| | | F43 | Time between failure of machine 1 |
| F_18_1 | Receiving the complaint by laboratory from manager | F44 | repair time of machine 1 |
| | | F45 | Time between failure of machine 2 |
| F_18_2 | Complaint assessment by lab | F46 | Repair time of machine 2 |
| F19 | Receiving the complaint results if it is non-defective (from lab to manager) | F47 | Time between failure of machine 3 |
| | | F48 | Repair time of machine 3 |
| F_21_1 | Receiving the complaint results if it is non-defective (from manager to deputy) | F49 | time between errors of machine 1 |
| | | F50 | time between errors of machine 2 |
| F_21_2 | Complaint results report to customer by deputy | F51 | time between errors of machine 3 |
| F22 | Presenting the result of non-defective to customer by manager (receiving the defect if it is defective) | F52 | time between errors of operator 1 |
| | | F53 | time between errors of operator 2 |
| F_23_1 | Receiving the result from lab if the product is defective | F54 | time between errors of operator 3 |
| | | F55 | time between errors (both machine and operator 1) which lead to cleaning cost |
| F24 | Reporting the acceptance of defect by manager | | |
| F25 | Warehouse supervisor is informed of accepting the return of products | F56 | time between errors (both machine and operator 2) which lead to cleaning cost |
| F26 | Conservation between deputy and customer to receive the sample request | F57 | time between errors (both machine and operator 3) which lead to cleaning cost |

## 5.2 The Visual SLAM Network for the Modules

### 5.2.1 Recourse Allocation

Figure 5 shows resource allocation where EXCUTE, WARHOUSE, PRODUCER, LAB and REPRESENTATIVE stand for the resources general manager, warehouse manager, production manager, lab manager and deputy, respectively. In addition, MACHINE 1, MACHINE 2 and MACHINE 3 stand for machines 1 through 3, respectively.

**Table 2.** Attributes of the SLAM network

| Attribute | Description | Attribute | Description |
|---|---|---|---|
| ATRIB [1] | Arrival time of requests | XX (8) | Previous order code in line 1 |
| ATRIB [2] | who receives the request: management (ATRIB [2] = 1), deputy (ATRIB [2] = 2) | XX (9) | Production time of a specific order type in line 1 |
| | | XX (10) | Production time in line 1 (F59) |
| ATRIB [3] | request serial number | XX (11) | Order code in line 2 |
| ATRIB [4] | Request location: local (ATRIB [4] = 3), out of state (ATRIB [4] = 4) | XX (12) | Previous order code in line 2 |
| | | XX (13) | Production time of a specific order type in line 2 |
| ATRIB [5] | Request type: production (ATRIB [5] = 1), Sample (ATRIB [5] = 2), complaint (ATRIB [5] = 3) | XX (14) | Production time in line 2 (F60) |
| | | XX (15) | Order code in line 3 |
| ATRIB [6] | Color type (8 types) | XX (16) | Previous order code in line 3 |
| ATRIB [7] | Order rate | XX (17) | Production time of a specific order type in line 3 |
| ATRIB [8] | Manufacturing priority | XX (18) | Production time in line 3 (F61) |
| LTRIB [1] | utilized machine in production line 1 | XX [19] | Variable for order production rate of type 1 |
| LTRIB [2] | utilized machine in production line 2 | XX [20] | Variable for order production rate of type 2 |
| LTRIB [3] | utilized machine in production line 3 | XX [21] | Variable for order production rate of type 3 |
| XX (1) | Serial number of request | XX [22] | Variable for order production rate of type 4 |
| XX (4) | Order priority variable in production line 1 | XX [23] | Variable for order production rate of type 5 |
| XX (5) | Order priority variable in production line 2 | XX [24] | Variable for order production rate of type 6 |
| XX (6) | Order priority variable in production line 3 | XX [25] | Variable for order production rate of type 7 |
| XX (7) | Order code in line 1 | XX [26] | Variable for order production rate of type 8 |

**Table 3.** Variables

| Variable | Description | variable | Description |
|---|---|---|---|
| XX27 | Operator cost of machine 1 | XX42 | Raw materials costs of order type 7 |
| XX28 | Maintenance costs of machine 1 | XX43 | Raw materials costs of order type 8 |
| XX29 | Cleaning costs of machine 1 | XX44 | Costs of errors (both operator and machine 1) led to cleaning |
| XX30 | Operator cost of machine 2 | XX45 | Costs of errors (both operator and machine 2) led to cleaning |
| XX31 | Maintenance costs of machine 2 | XX46 | Costs of errors (both operator and machine 3) led to cleaning |
| XX32 | Cleaning costs of machine 2 | P_RATE1 | Production rate of type 1 |
| XX33 | Operator cost of machine 3 | P_RATE2 | Production rate of type 2 |
| XX34 | Maintenance costs of machine 3 | P_RATE3 | Production rate of type 3 |
| XX35 | Cleaning costs of machine 3 | P_RATE4 | Production rate of type 4 |
| XX36 | Raw materials costs of order type 1 | P_RATE5 | Production rate of type 5 |
| XX37 | Raw materials costs of order type 2 | P_RATE6 | Production rate of type 6 |
| XX38 | Raw materials costs of order type 3 | P_RATE7 | Production rate of type 7 |
| XX39 | Raw materials costs of order type 4 | P_RATE8 | Production rate of type 8 |
| XX40 | Raw materials costs of order type 5 | SFT1 | Working hours per day |
| XX41 | Raw materials costs of order type 6 | SFT2 | Non-working hours per day |

### 5.2.2 The Visual SLAM Network for the Arrival of Requests and Complaints of Customer

The CREATE node is used to the arrival of requests with the time between of F_1. ATRIB [1] is used as a variable for the arrival time of requests. The entities are routed to the GOON node with two branches and ASSIGN node and ATRIB [2] are used to determine who receives the request (general manager or deputy with probability 0.4 and 0.6, respectively (PROB (0.4) and PROB (0.6))) in the branches). ATRIB [4] is used to determine the request location like ATRIB [2]. The entities are routed to ASSIGN node to assign XX [1] as the entities counter and the other ASSIGN node is used to put entities counter as ATRIB [3].The entities are routed to one of the three nodes (21_production, 22_sampling, 23_error) with probability 0.57, 0.24 and 0.19, which are related to production request, sampling request and customer complaint, respectively. SLAM network for the customer complaint is started with the ASSIGN node and assigned the ATRIB [5] equals to 3 to identify the request type and ATRIB [7] equals to F58.

If the request have been received through the dep-

**Table 4.**Values of cost variables

| Variable | Value | | | | | Variable | Value | variable | Value |
|---|---|---|---|---|---|---|---|---|---|
| XX27 | SFT1×22×2×3,500 or [(sft1×22×2-176)×2×1.4+176×22×2]×3,500 | | | | | XX29 | 7,000 | XX36 | 13,000×F3 |
| XX30 | SFT1×22×2×3,500 or [(sft1×22×2-176)×2×1.4+176×22×2]×3,500 | | | | | XX32 | 4,000 | XX38 | 13,000×F3 |
| XX33 | SFT1×22×2×3,500 or [(sft1×22×2-176)×2×1.4+176×22×2]×3,500 | | | | | XX35 | 6,000 | XX40 | 13,000×F3 |
| SFT2 | 8×60(working hours for current system is 8) | | | | | XX37 | 13,000×F3 | XX42 | 13,000×F3 |
| XX44 | 7,000 | XX46 | 6,000 | XX39 | 13,000×F3 | XX41 | 13,000×F3 | XX43 | 13,000×F3 |
| XX45 | 4,000 | SFT1 | (24-SFT2)×60 | XX28 | 52,000 | XX31 | 63,000 | XX34 | 55,000 |

**Table 5.** Activities in SLAM network

| **Ac. No.** | **Function** | **Ac. No.** | **Function** | **Ac. No.** | **function** | **Ac. No.** | **Function** | **Ac. No.** | **Function** |
|---|---|---|---|---|---|---|---|---|---|
| 33 | F1 | 133 | F11 | 179 | F22 | 214 | F34 | 233 | F46 |
| 35 | F2 | 144 | F12 | 185 | F23 | 216, 218 | F35 | 236,239 | F47 |
| 36 | F3 | 146 | F13 | 187 | F24 | 217 | F36 | 237 | F48 |
| 39 | F4 | 148 | F14 | 189 | F25 | 221, 219 | F37 | 281,293 | F49 |
| 41 | F5 | 129 | XX [18] | 195 | F26 | 220 | F38 | 297,312 | F50 |
| 42 | F6 | 164 | F15 | 197 | F27 | 222, 224 | F39 | 316,327 | F51 |
| 48 | F7 | 166 | F16 | 198 | F28 | 223 | F40 | 331,342 | F52 |
| 49 | F8 | 168 | F17 | 201 | F29 | 225, 227 | F41 | 346,361 | F53 |
| 103 | F9 | 171 | F18 | 203 | F30 | 226 | F42 | 365,376 | F54 |
| 115 | F10 | 173 | F19 | 205 | F31 | 228,231 | F43 | 380,383 | F55 |
| 93 | XX [10] | 174 | F20 | 207 | F32 | 229 | F44 | 387,390 | F56 |
| 111, 139 | XX [14] | 177 | F21 | 213, 215 | F33 | 232,235 | F45 | 394,397 | F57 |

**Table 6.** Distribution functions

| Function | Distribution | Function | Distribution | Function | Distribution |
|---|---|---|---|---|---|
| F_1 | EXPON (61) | F_21_1 | UNFRM (17, 19) | F41 | EXPON (10.6) |
| F1 | RNORM (22.5, 6) | F_21_2 | RNORM (13.3, 6.8) | F42 | UNFRM (3, 6) |
| F2 | UNFRM (8, 10) | F22 | RNORM (10.9, 3.7) | F43 | WEIB (454, 8.26) |
| F_3_1 | RNORM (15, 5.1) | F_23_1 | UNFRM (18, 22) | F44 | RNORM (59.9, 127.8) |
| F_3_2 | UNFRM (5, 8) | F24 | RNORM (16.7, 4.9) | F45 | EXPON (714.2) |
| F4 | UNFRM (5, 8) | F25 | UNFRM (25, 27) | F46 | RNORM (45.7, 61.2) |
| F5 | UNFRM (9, 11) | F26 | RNORM (14.2, 6.9) | F47 | EXPON (416.6) |
| F6 | UNFRM (4, 6) | F27 | UNFRM (6, 8) | F48 | RNORM (86.5, 15.6) |
| F7 | UNFRM (6, 8) | F28 | RNORM (12.4, 5.2) | F49 | EXPON (150) |
| F8 | UNFRM (10, 14) | F_29_1 | UNFRM (6, 8) | F50 | EXPON (84) |
| F9 | UNFRM (14, 17) | F_29_2 | DPROBN (5, 6)* | F51 | EXPON (132) |
| F10 | UNFRM (11, 14) | | RNORM (71.2, 12) | F52 | EXPON (198) |
| F11 | UNFRM (19, 22) | F30 | UNFRM (7, 10) | F53 | EXPON (138) |
| F12 | UNFRM (5, 8) | F_31_1 | UNFRM (8, 11) | F54 | EXPON (168) |
| F13 | UNFRM (8, 10) | F_31_2 | UNFRM (10, 12) | F55 | EXPON (366) |
| F14 | UNFRM (3, 5) | F_32_1 | UNFRM (9, 11) | F56 | EXPON (336) |
| F15 | RNORM (25.8, 7.1) | F33 | EXPON (37) | F57 | EXPON (354) |
| F16 | UNFRM (11, 13) | F34 | RNORM (22, 7) | F58 | DPROBN (1, 2) |
| F17 | RNORM (18.6, 7.5) | F35 | EXPON (72) | F59 | ATRIB [7]* |
| F_18_2 | UNFRM (6, 9) | F36 | RNORM (52, 10.3) | | RNORM (109.7, 17.4) |
| F_18_1 | DPROBN (3, 4)* | F37 | EXPON (12) | F60 | ATRIB [7]*RNORM (97.7, 8.1) |
| | RNORM (45.3, 15.6) | F38 | UNFRM (4, 6) | F61 | ATRIB [7]* |
| F19 | UNFRM (13, 16) | F39 | EXPON (28) | | RNORM (124.7, 24.6) |
| F20 | UNFRM (15, 18) | F40 | RNORM (26, 11.3) | | |

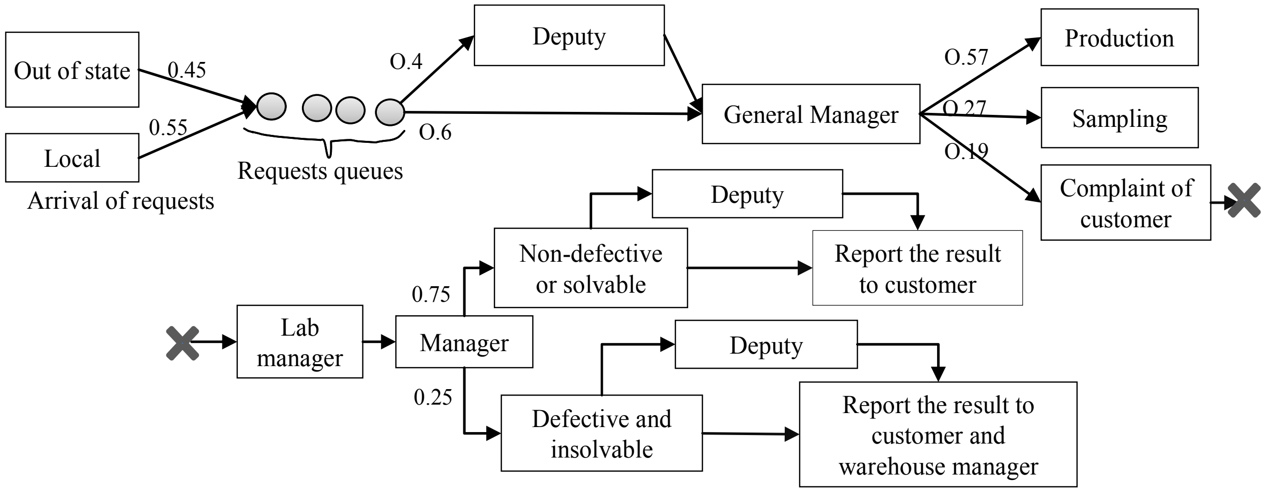



**Figure 4.** DFD for the arrival of requests and complaints.

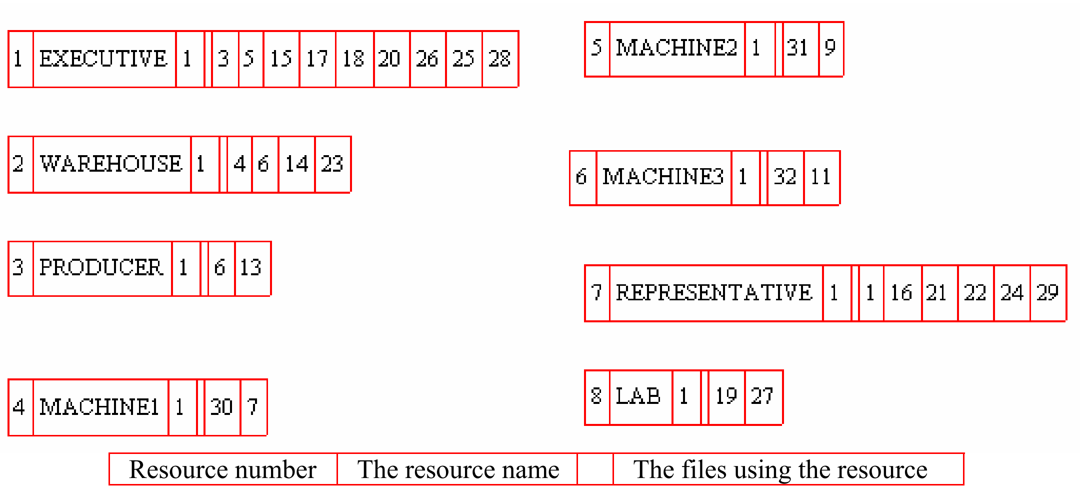



**Figure 5.** The SLAM network of resources.

uty (ATRIB [2] = 2), the entity is routed to the AWAIT (file number16) node and is waiting for the deputy. The deputy reports the customer request to the general manager in time of F15 (activity number 164) and is freed by FREE node. Entity is routed to another AWAIT node (file number 18) and is waiting for the manager. The manager forwards the customer complaint to the lab manager in time of F16 (activity number 166) and is freed. If the request have been received through the general manager (ATRIB [2] = 1), the entity is routed to the AWAIT node (file number 17) and is waiting for the manager. The manager reports the complaint to the laboratory in time of F16 (activity number 166) and is freed.

In both of them, the entity is routed to the AWAIT node (file number 19) and is waiting for the lab manager. The lab manager receives the complaint in time of F_18_1 and tests the defective of product in time of F_18_2 and is freed in time of F18 = F_18_1+F_18_2. The entity is then routed to the AWAIT node (file number 20) and is waiting for the general manager.

1) The product is non-defective or defect is solvable (PROB (0.75))

The manager receives the investigation result in time of F19 (activity number173) and is freed. If the complaint has been received through the deputy, the entity is routed to another AWAIT node (file number 21) and is waiting for the deputy. The deputy receives the investigation result in time of F_21_1 and reports to the customer in time of F_21_2 and is then freed in time of F21 = f_21_1+F_21_2 (activity number 177). If the complaint has been received through the general manager, the manager reports the investigation result to the customer in time of F22 (activity number179) and is freed. Finally, the entity is routed to the COLCT node for data collection and is then terminated by the TERMINATE node.

2) If the defect is insolvable (PROB (0.25))

If the complaint has been received through the general manager, the warehouse supervisor is informed of accepting the return of products in time of F24 (activity number 187) and manager is set free. If the complaint has been received through the deputy, the manager is set free and the entity is entered to the AWAIT node (file number 22) and is waiting for the deputy. The deputy receives the investigation result in time of F_23_1 and informs the warehouse supervisor of accepting the return of products in time of F_21_2 and is freed in time of F23 = F_21_2+F_23_1 (activity number 185) with the aim of FREE node.

In both of them, the entity is routed to the AWAIT node (file number 23) and is waiting for the warehouse supervisor. The warehouse supervisor receives the products in time of F25 (activity number 189) and is set free. The entity is entered to the COLCT node for data collection and is then terminated by the TERMINATE node (Figure 6).

### 5.2.3 The production branch

The SLAM network is initiated with ASSIGN node (21_PRODUCTION) to determine the request type (ATRIB [5] = 1), order rate (ATRIB [7] = F58) and color

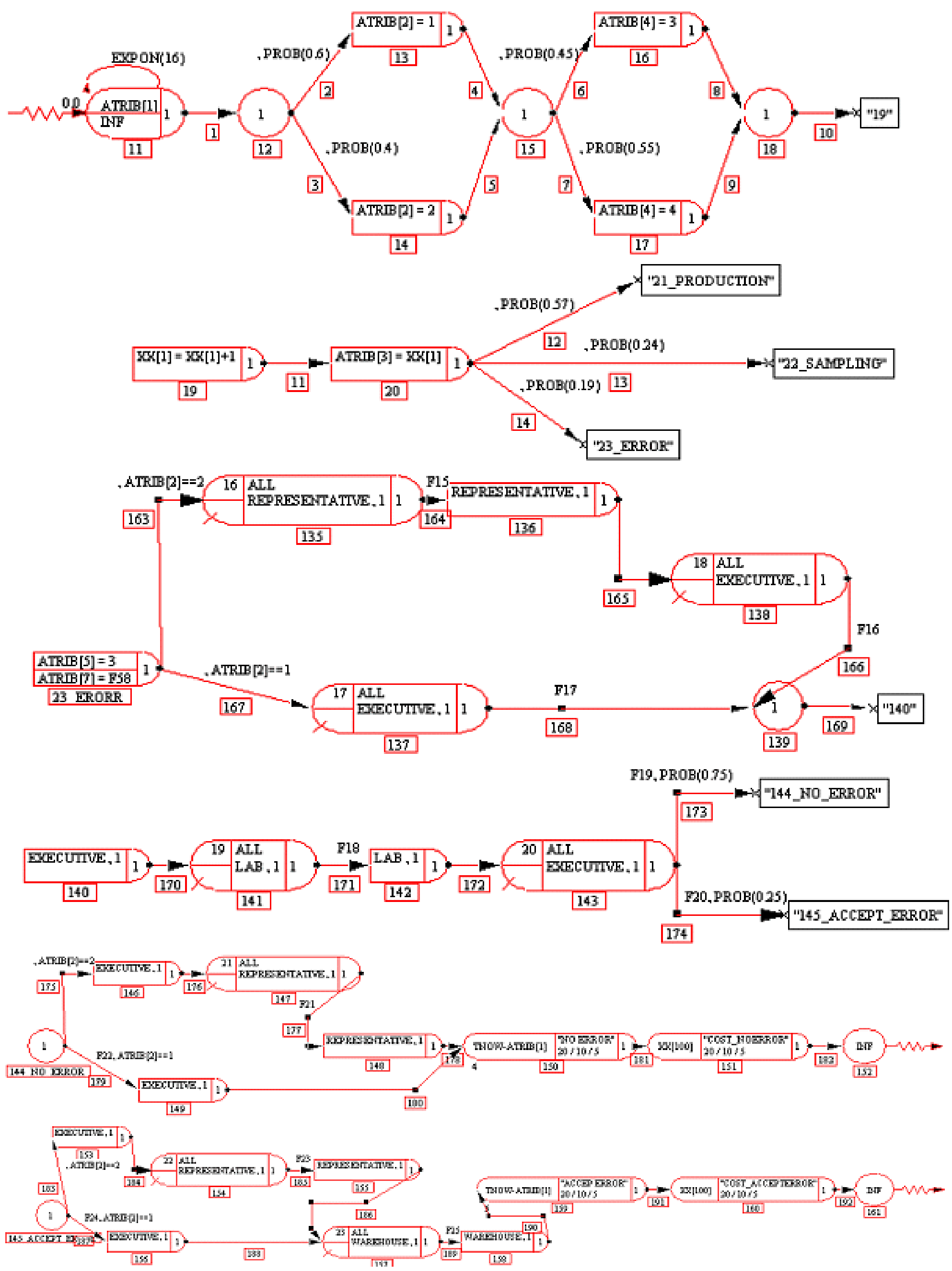



**Figure 6.** SLAM network for the arrival of requests and customer complaint.

type (ATRIB [6]). If the request is received through the deputy (ATRIB [2] = 2), the entity is routed to AWAIT node and is waiting for the deputy. The deputy forwards the request to the general manager and is freed in time of F1. The entity is entered to another AWAIT node and is waiting for the general manager. The general manager forwards a form to the warehouse manager to check the raw material inventory and is set free after time of F2. If the request is received through the central office, the general manager receives the request in time of F_3_1 and forwards it to the warehouse manager in time of F_3_2 and is freed after time of F3 (F_3_1+F_3_2). The entity is then routed to AWAIT node and is waiting for the warehouse manager.

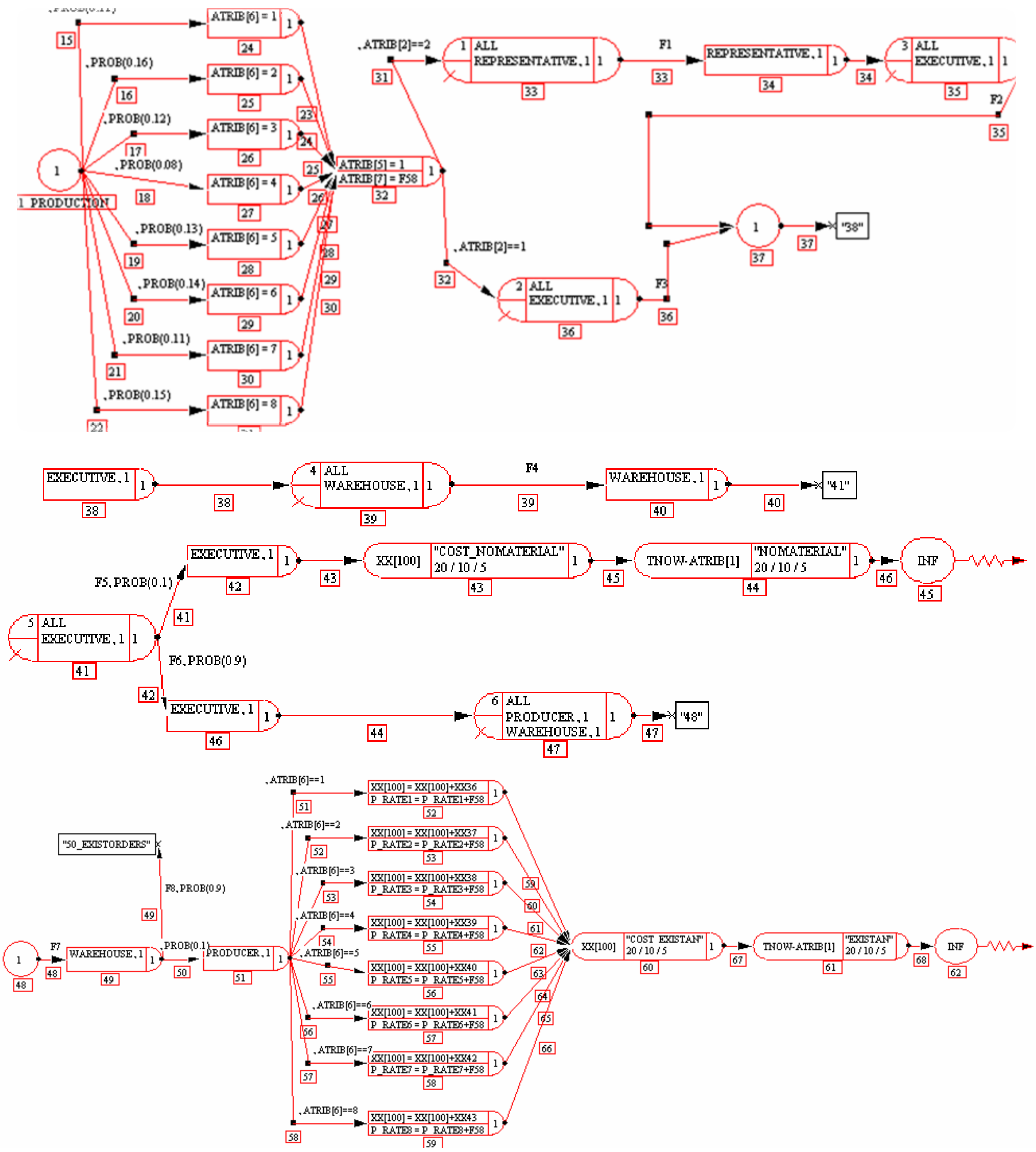



**Figure 7.** SLAM network for production process.

The warehouse manager checks the inventory and reports it to the general manager and is freed after time of F4. If the inventory is insufficient (with probability 0.1), the general manager reports it to the customer or the deputy (as the received way).

If the inventory level is sufficient (with probability 0.9), the general manager forwards the order rate to the production manager in time of F6 and is set free. At the same time, the production manager and the warehouse manager are busy informing the operators to get ready for producing and forwarding the needed production rate based on inventory level, respectively. The warehouse manager is freed after time of F7. If the inventory level is sufficient for the order rate based on warehouse manager's report (with probability 0.1), there is no need to produce any new product and the production manager is set free. The entity travels to ASSIGN node based on color type and adds the order rate and raw material cost to production rate and total cost, respectively. The entity is entered to COLLECT node for data collection and then terminated by TERMINATE node.

If the inventory level is not enough and the raw material is enough (with probability 0.9), the production manager forwards the order rate to the operator and is freed in time of F8 (Figure 7).

5.2.3.1 Raw Material Inventory is Sufficient and the Entity goes to the Production Process

The production process is started with FREE node (50_EXISTORDERS) to free the production manager.

The entity is then routed to ASSIGN node and adds the order rate to the production rate and raw material cost to the total cost, respectively. The entity is entered to another ASSIGN node to put ATRIB [8] = ATRIB [6] in order to determine color priority throughout the production process and then routed to one of three production lines based on color type (Figure 8).

5.2.3.2 The Production Process of Machine 1

The entity is routed to GOON node (72_MACHINE 1) and then entered to another GOON node (75) with two branches. If the received entity has a lower priority than the being serviced one (ATRIB [8] < XX [4]), the entity goes to the ASSIGN node to put the received entity priority equal to ATRIB [8]+2 (because there are two types of color to produce in the line 1) and it will then return to GOON node (75).

If the received entity has a higher priority than the being serviced one (ATRIB [8] > XX [4], the entity travels to AWAIT node and waits for MACHINE 1. The entity is then routed to ASSIGN node to assign XX [4] = ATRIB [8] and XX [7] = ATRIB [6] to determine the next priorities and the requested color type, respectively.

It also should be pointed out that if the waiting entities are more than 15, the received entity goes to COLLECT nodes labeled as Q1 and 87 in order to collect data and is then terminated. If the entity passes through AWAIT node, it travels to ASSIGN node after the production time (XX [10]) in order to determine its next priority and the requested color type by assigning XX [4] = ATRIB [8] and XX [7] = ATRIB [6], respectively. The entity is then routed to GOON node and if the manufactured color is the same rank as the previous color (XX [7] = XX [8]), the production time of a particular color will be equal to XX [9] = XX [9]+XX [10]. If the manufactured color isn't the same rank as the previous color, the entity goes to ASSIGN node in order to determine the previous color for the next entity, record the production time of the manufactured color and add cleaning cost of machine 1 by assigning XX [8] = XX

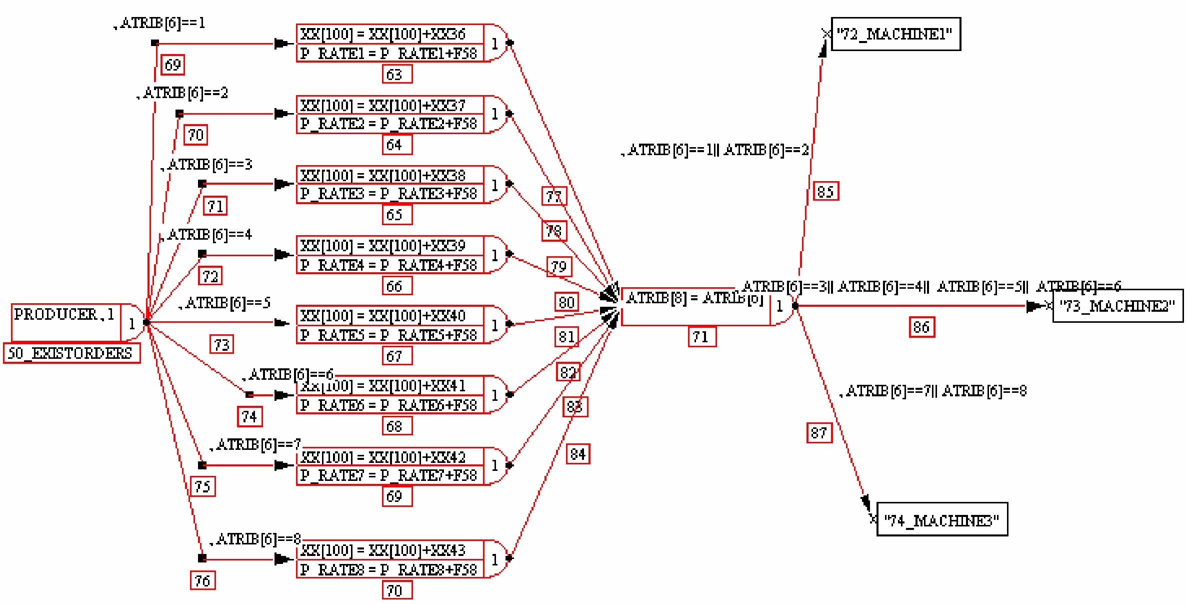



**Figure 8.** Raw material is sufficient and production order.

[7], XX [9] = XX [10] and XX [100] = XX [100] + XX [30], respectively.

The entity is entered to GOON node and if the production time of a particular color is less or equal to 20 hours (XX [9] <= 20h), MACHINE1 is freed and the entity goes to the production termination process. If XX [9] > 20h, then the entity travels to ASSIGN node in order to determine the priority of next color and add cleaning cost by assigning XX [4] = XX [4]+1 and XX [100] = XX [100]+XX [30]. The entity is then entered to FREE and FINDAR nodes to free machine 1 and remove all entities in file 25 after cleaning time, F9 (Figure 9).

5.2.3.3 The Production Process of Machines 2 and 3

The production process of machines 2 and 3 are similar as machine 1 with the following changes:

- F10, F45, F46, F50, F53, F56 and F60 for machine 2 and F11, F47, F48, F51, F54, F57 and F61 for machine 3 are applied instead of F9, F43, F44, F49, F52, F55 and F59, respectively.
- LTRIB [1] is replaced with LTRIB [2] and LTRIB [3] for machines 2 and 3, respectively.
- XX [5], XX [11], XX [12] and XX [13] for machine 2 and XX [6], XX [15], XX [16] and XX [17] for machine 3 are employed instead of XX [4], XX [7], XX [8] and XX [9].
- XX30, XX31 and XX32 and XX33, XX34 and XX35 are used instead of XX27, XX28, and XX29 for machines 2 and 3, respectively.
- The number 2 in the equation ATRIB [8] = ATRIB [8]+2 will be 4 for machines 2 and 3 (Figure 10).

5.2.3.4 The Production Termination Process

The entity is routed to ASSIGN node labeled as 89_PRODUCTION_END and is then entered to AWAIT node and is waiting for the production manager. The production manager reports the material withdrawal and the production to the warehouse manager in time of F12 and is set free.

The warehouse manager takes the new inventory and reports it to the general manager in time of F13. The general manager is informed from the production result and is freed after time of F14. The entity then travels to COLLECT node in order to collect the lead time, total cost and the production rate data and is then terminated (Figure 11).

### 5.2.4 The Sampling Process

The SLAM network is started with ASSIGN node to determine the request type (ATRIB [5] = 2). If the request is received through the deputy (ATRIB [2] = 2), the entity goes to AWAIT node (file number 24) and is waiting for the deputy. The deputy receives the request from the customer in time of F26 (activity 195) and is set free. The entity is then routed to another AWAIT node (file 25) and is waiting for the general manager. The general manager receives the request from the deputy in time of F27 (activity 197) and is freed.

If the request is received through the general man-

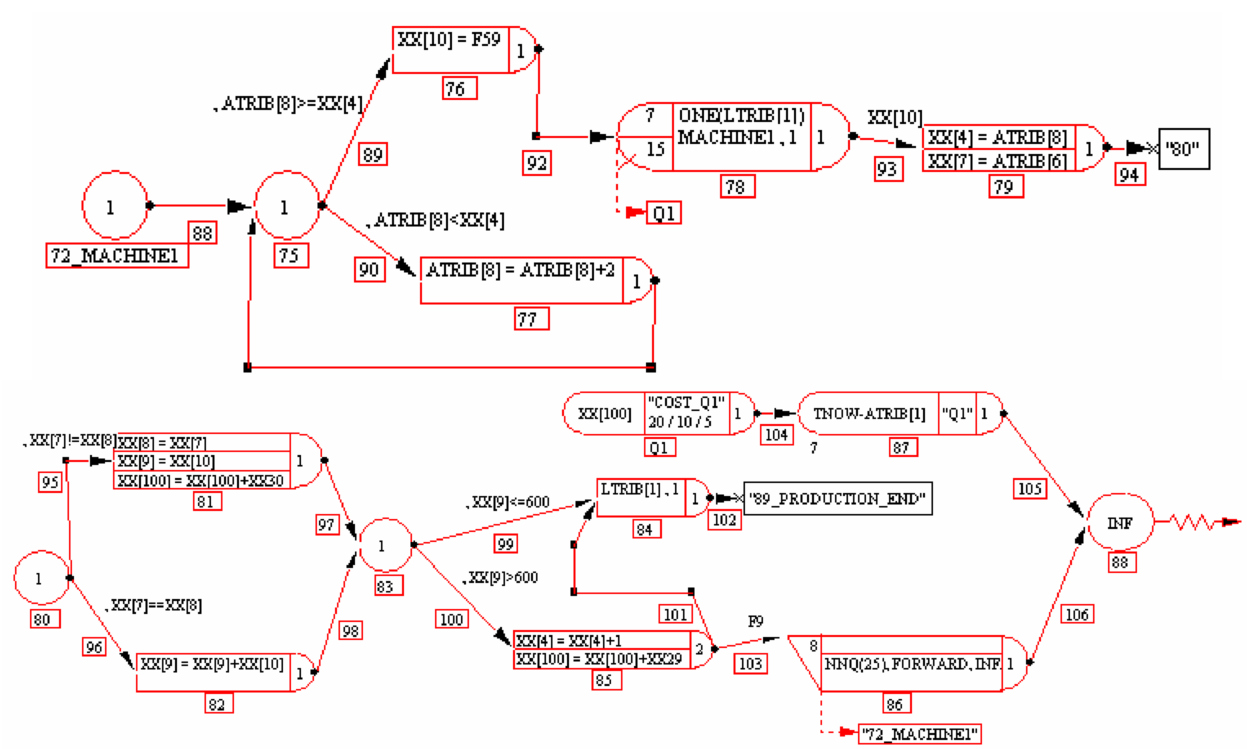



**Figure 9.** The production process of machine 1.

ager (ATRIB [2] = 1), the entity travels to the AWAIT node (file 26) and is waiting for the general manager. The general manager receives the request from the customer in time of F28 (activity 198) and is set free.

In both cases, the entity is entered to AWAIT node, file number 27 and queue capacity is 10 and the excess entities are routed to COLLECT nodes for collect dada and are terminated, and is waiting for the lab manager. The lab manager receives the formula in time of F_29_1 and makes the sample in time of F_29_2 and is then set free. The customer is informed from the result as the received way and the entity goes to COLLECT node for

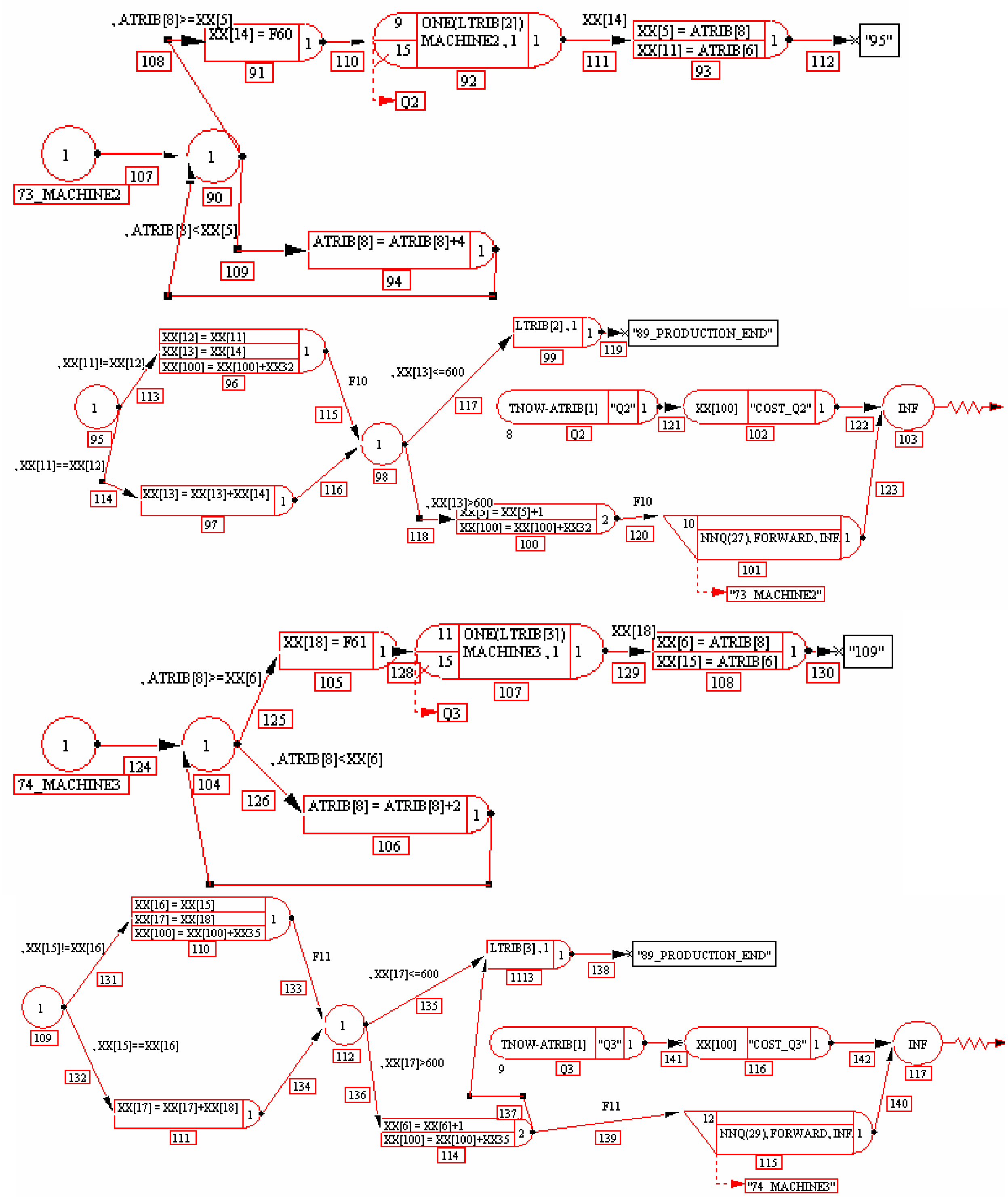



**Figure 10.** The production processes of machines 2 and 3.

data collection and is then terminated (Figure 12).

### 5.2.5 Maintenance Process and Interaction between Managers and External Entities

The SLAM network is begun with CREATE node to create only one entity which is divided into eight entities (there are three machines labeled as MACHINE 1, 2 and 3 and five managers labeled as EXCUTIVE, WAREHOUSE, PRODUCER, REPRESENTATIVE and LAB). The SLAM network for the maintenance of MACHINE 1 is as follows as:

The entity is routed to PREEMPT node (file number 30) to demonstrate the failure of MACHINE 1 in time of F43. The entity is then entered to ASSIGN node in order to calculate the maintenance cost of MACHINE 1 (XX28) after time of F44 (repair time of MACHINE 1)

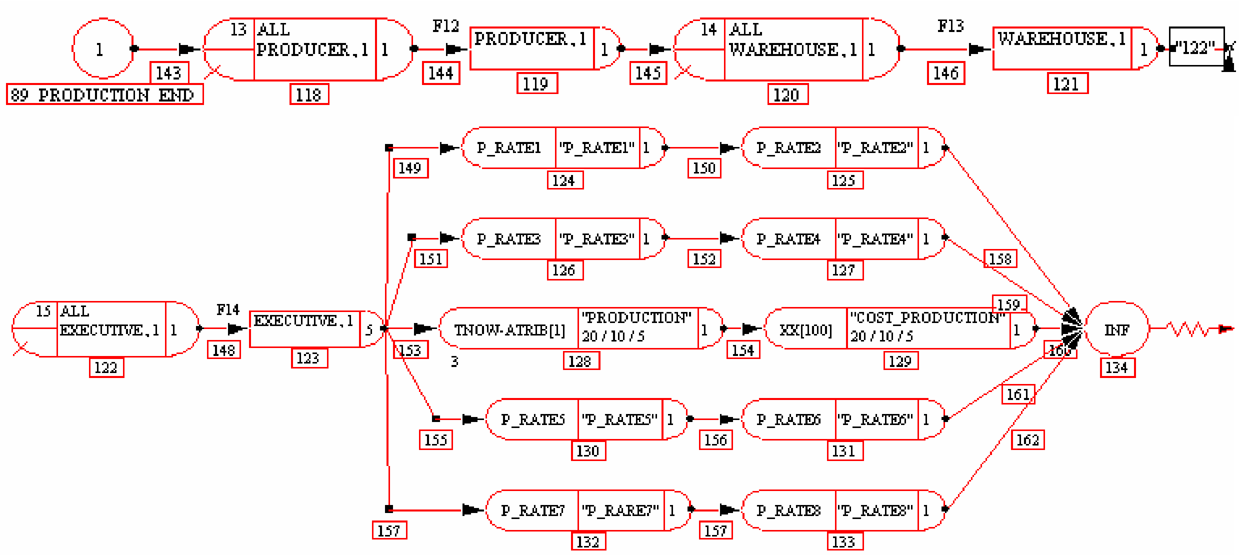



**Figure 11.** The end of production process.

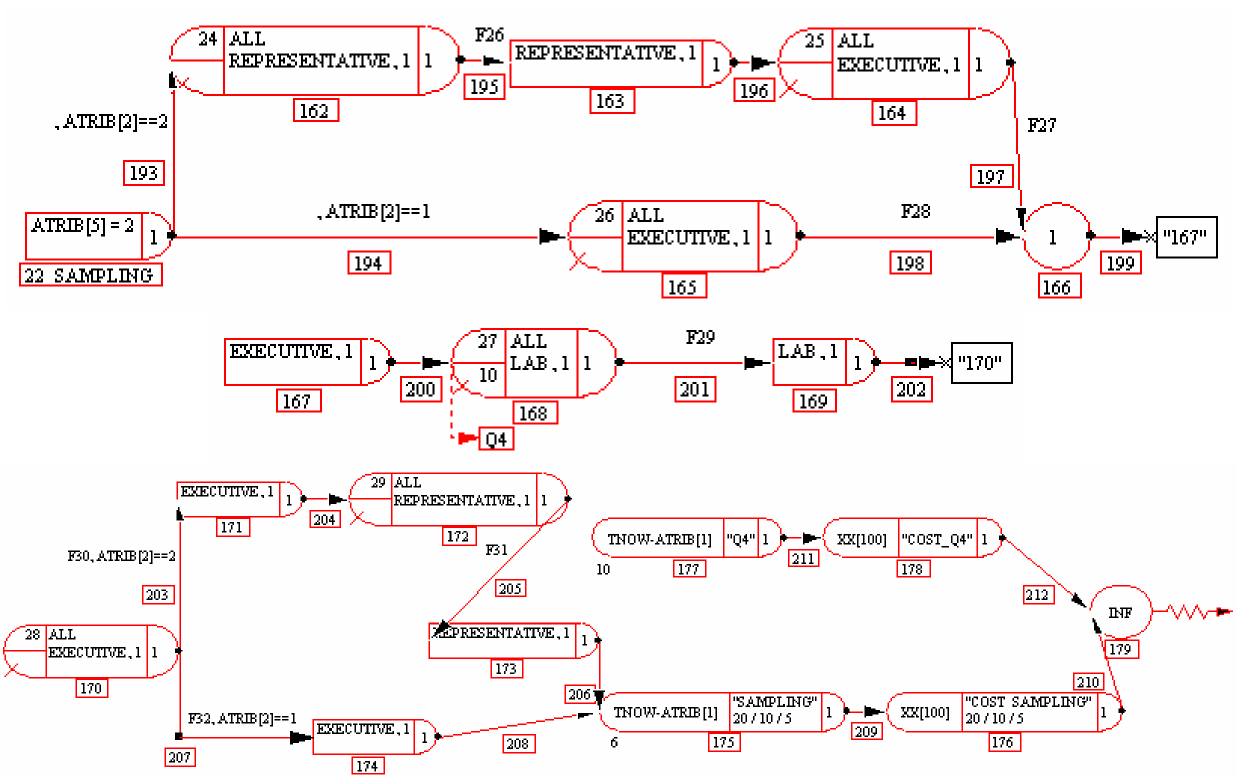



**Figure 12.** Sampling process.

and is then set free. The entity goes back to PREEMPT node after time of F43 and the process will be continued until the simulation time is met.

The maintenance SLAM of machines 2 and 3 are similar as machine 1 with the following exceptions:

1) Time between failures of machines 2 and 3 are F45 and F47 instead of F43.
2) Repair time of machines 2 and 3 are F46 and F48 instead of F44.
3) The maintenance costs for machines 2 and 3 are XX31 and XX34 instead of XX28.

The SLAM network for the external activities of general manager is as follows as:

The entity is routed to ALTER node in order to alter the resource general manager from 1 to 0 after time of F33. The entity is then entered to another ALTER node in order to alter the resource general manager from 0 to 1 after time of F34. The entity goes back to the ALTER node after time of F33 and the process will be repeated until the simulation time is terminated.

The SLAM network for the external activities of warehouse manager, producer manager, deputy and lab manager would be similar as the general manager by considering F36, F38, F40 and F42 instead of F34 and F35, F37, F39 and F41 instead of F33, respectively (Figure 13).

### 5.2.6 The SLAM Network of Working Shifts

By considering the working shifts, it is aimed to analyze the errors in different working shifts. The SLAM network is started with CREATE node to create only one entity which is divided into eight entities the same as the previous section. Then, the SLAM network of the general manager is as follows:

The entity goes to ALTER node in order to alter the resource general manager from 1 to 0 and is then routed to ASSIGN node in order to assign ATRIB [12] = TNOW (the current time of the entity). The entity is then entered to another ALTER node to alter the resource general manager from 0 to 1 after time of SFT2-((ATRIB [12]-ATRIB [11])-SFT1). The entity travels to ASSIGN node in order to assign ATRIB [11] = TNOW and then goes back to the ALTER node in order to set the recourse general manager equal to 0 in time of SFT1 and the cycle will be continued until the simulation time is met.

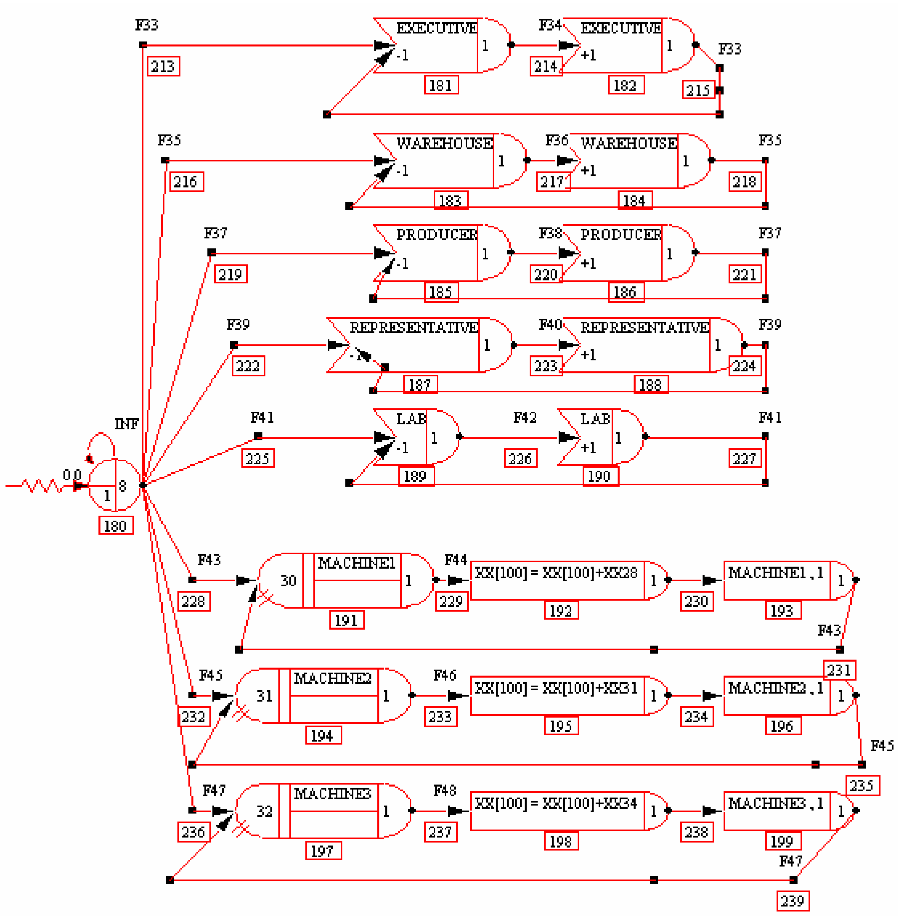



**Figure 13.** The maintenance process and interaction between managers and external entities.

The SLAM network of working shifts for the warehouse manager, deputy, production manager and lab manager are similar as the general manager in which ATRIB [13] and ATRIB [14], ATRIB [15] and ATRIB [16], ATRIB [17] and ATRIB [18] and ATRIB [19] and ATRIB [20] are employed instead of ATRIB [11] and ATRIB [12], respectively.

The SLAM network of machines 1 through 3 are similar as the general manager with some changes:

- The entity is routed to ASSIGN node in order to compute operator cost of machines 1 through 3 (XX27, XX28 and XX29, respectively) before going back to the ALTER node.
- ATRIB [21] and ATRIB [22], ATRIB [23] and ATRIB [24] and ATRIB [25] and ATRIB [26] are used instead of ATRIB [11] and ATRIB [12] for machines 1 through 3, respectively (Figure 14).

### 5.2.7 SLAM Network of Machine and Human Error

The SLAM network is initiated by CREATE node to create only one entity. The entity is then divided into six branches by considering machine type and working shifts. The route for machine 1 is drawn as follows:

The entity is routed to AWAIT node (file number 33) after time of F49 and is waiting for virtual resource (ERROR_MACHINE 1) in order to consider the error-rate. The entity is then entered to GOON node with two branches to determine the product is semi-defective or defective with probability 0.7 and 0.3, respectively.

1) If the product is semi-defective (PROB (0.7))
   The entity travels to GOON node with two branches to return the product to the production line (72_MACHINE 1) and free the virtual resource.
2) If the product is defective (PROB (0.3))

The entity goes to ASSIGN node and decreases the production rate. The entity is then routed to FREE node to free the virtual resource.

In both of them, the entity goes back to the AWAIT node in time of F49 (activity number 293). The process will be repeated until the simulation time is terminated. Moreover, one of the entities is routed to PREEMPT node to consider working hours and shifts. This entity causes to stop the resource ERROR_MACHINE1 and free it after time of SFT1. The intended entity goes back to PREEMPT node in time of SFT2 and the procedure will be continued.

The SLAM network of machines 2 and 3 as well as the operator error work similar as machine1 with the following exceptions:

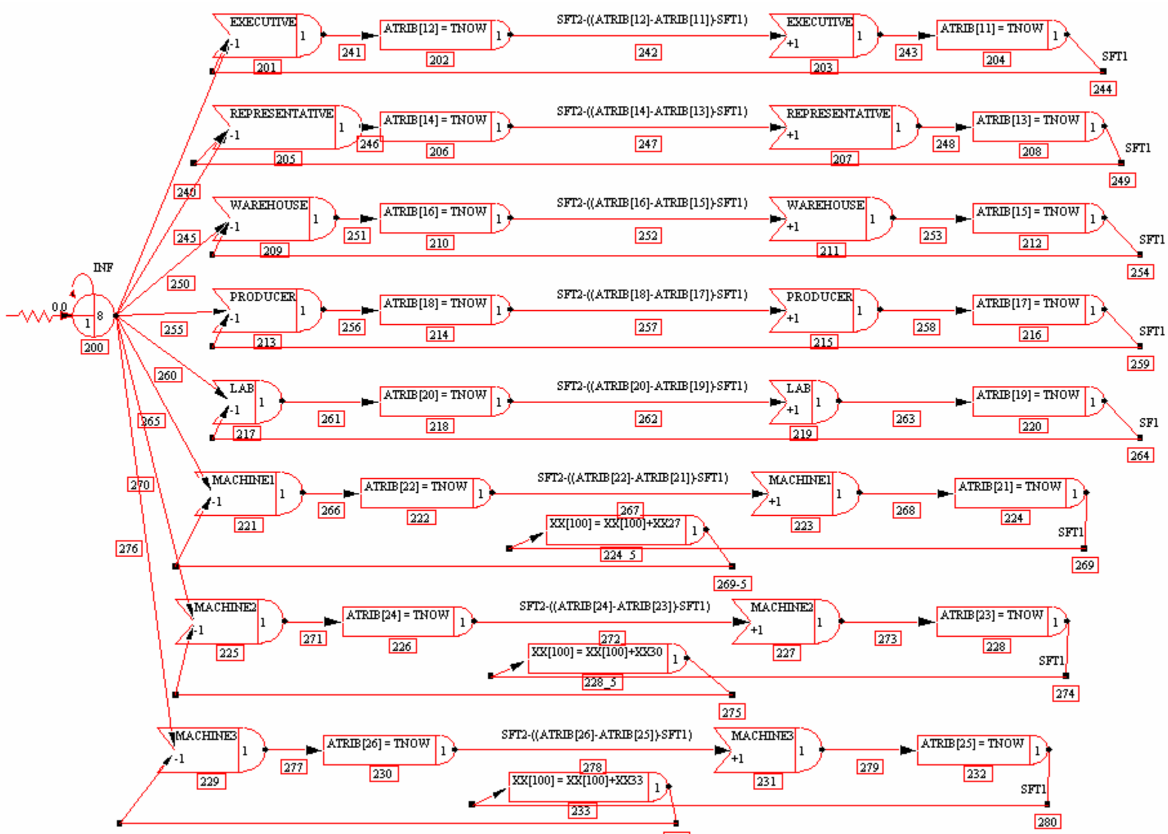



**Figure 14.** The SLAM network of working shifts.

- F49, ERROR_MACHINE1, file number 33 and 72_MACHINE1 are replaced with F50, ERROR_MACHINE2, file number 34 and 73_MACHINE2 for machine 2 and F51, ERROR_MACHINE3, file number 35 and 74_MACHINE3 for machine 3.
- F49, ERROR_MACHINE1, file number 33 and 72_MACHINE1 are replaced with F52, ERROR_HUMANE1 and file number 36, F53, ERROR_HUMANE2 and file number 37 and F54, ERROR_HUMANE3 and file number 38 for operators 1 through 3, respectively.
- 72_MACHINE1, 73_MACHINE2 and 74_MACHINE3 are the same as machines 1 through 3 for the operators 1 through 3, respectively (Figures 15 and 16).

### 5.2.8 The Error Caused to Cleaning

As stated before, the SLAM network is begun with a CREATE node in order to create only one entity which is divided into six branches by considering machine type and working shifts. The route for machine 1 is as follows as:

The entity is entered to the AWAIT node after time of F55 and is waiting for the virtual resource (ERROR_CLEANING_1, file number 39).

If there are any entities in the AWAIT node, the present entity goes to the TERMINATE node and is terminated, otherwise, the entity travels to the ASSIGN node in order to compute the cleaning cost (XX44) and is then entered to the FREE node to free the virtual resource. The entity goes back to the AWAIT node and the cycle will be continued until the simulation time is met.

Another one of six entities is routed to the PREEMPT node in order to consider the working shifts of machine 1 and causes to stop the virtual resource ERROR_CLEANING_1. The entity travels to the FREE node to free ERROR_CLEANING_1 after time of SFT1 and then goes back to the PREEMPT node after time of SFT2.

The SLAM network of machines 2 and 3 are similar as machine 1 in which F56, ERROR_CLEANING_2, file number 40 and XX45 for machine 2 and F57, ERROR_CLEANING_3, file number 41& XX46 are applied instead of F55, ERROR_CLEANING_1, file number 39 and XX44 (Figure 17).

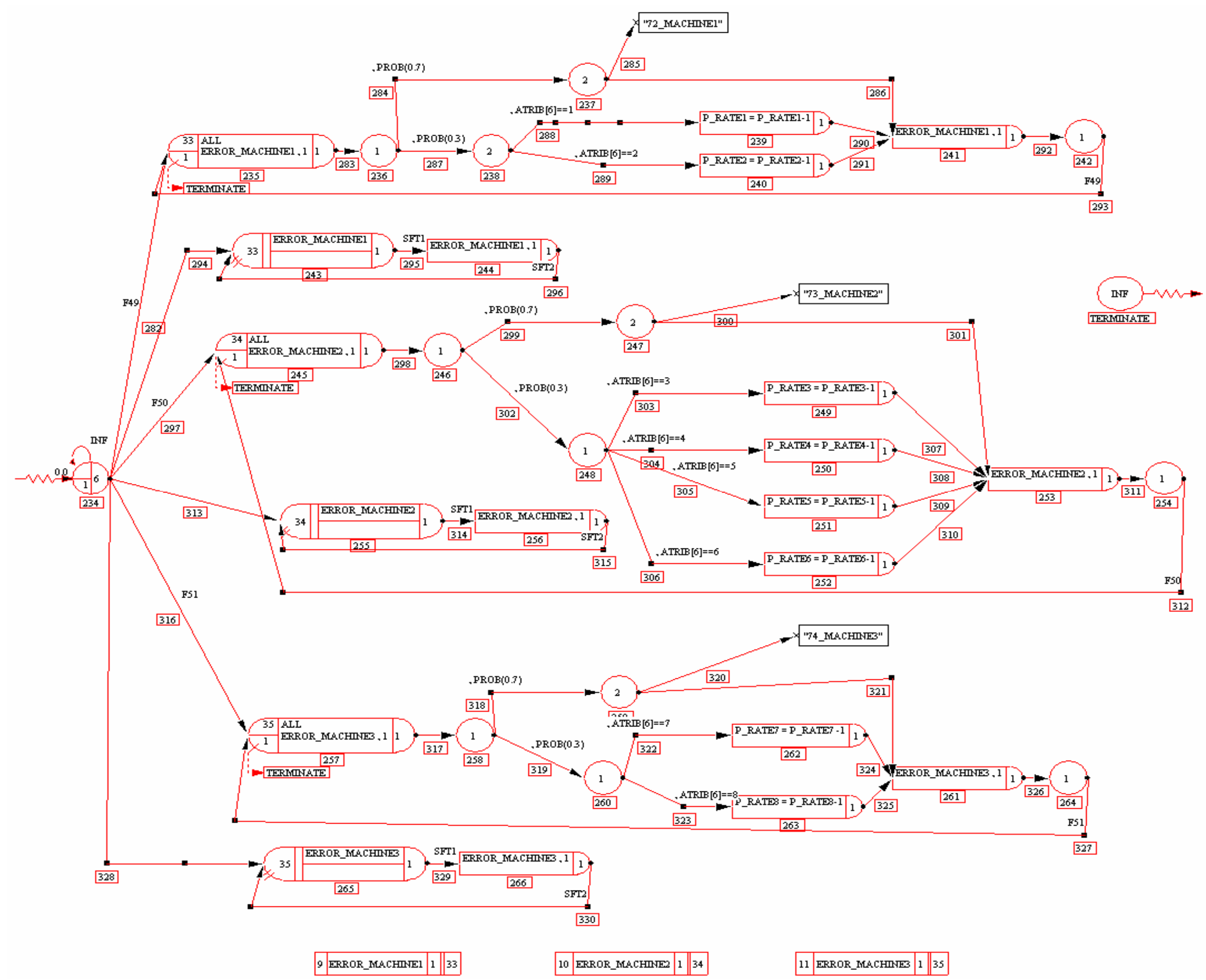



**Figure 15.** The SLAM network of machine error.

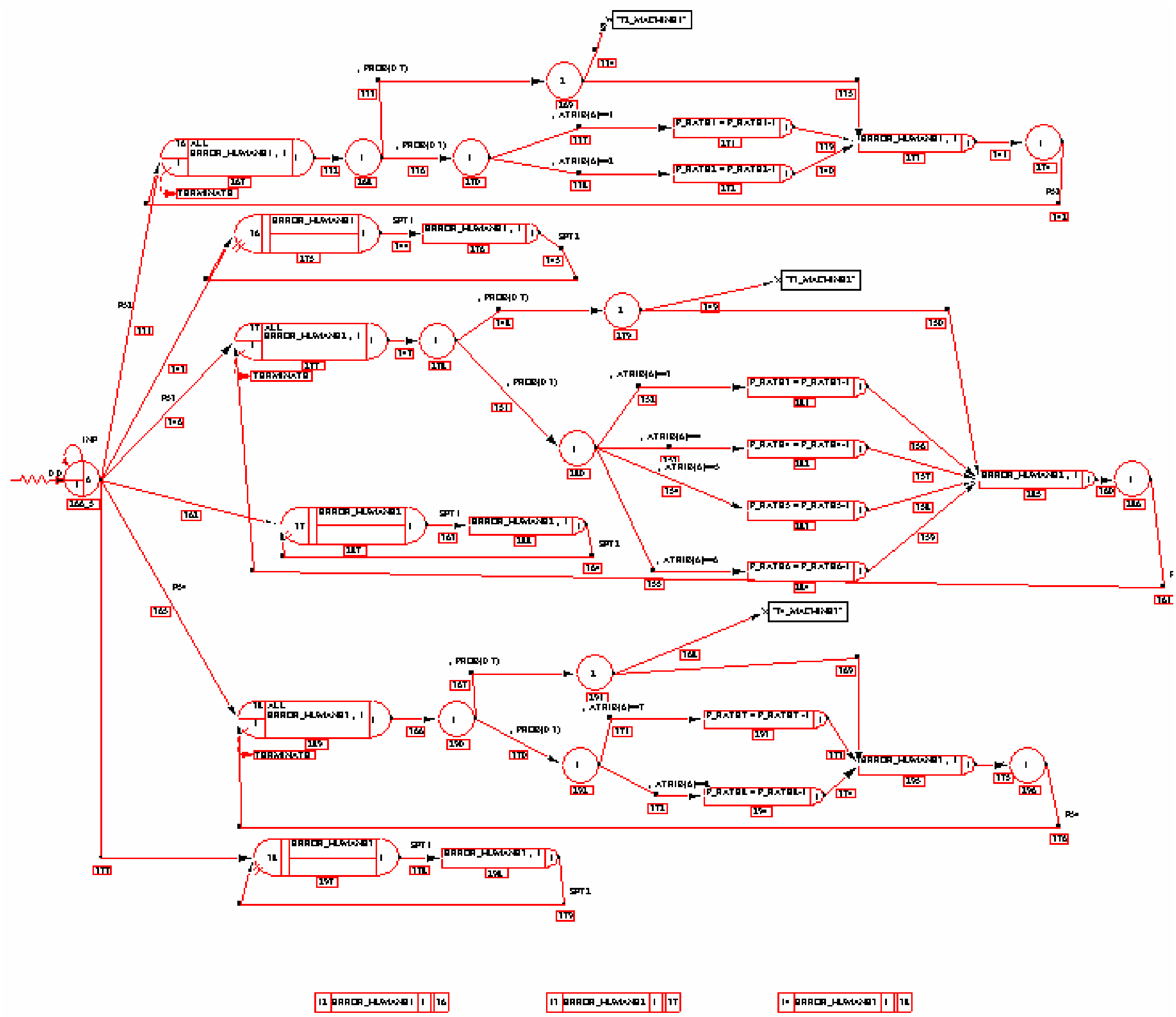


**Figure 16.** The SLAM network of humane error.

### 5.3 Verification and Validation

The SLAM model has been run for 30 working days (1.5 working month) and replicated 100 times.

*Simulation time (minutes) = (working hours) 8 ×(minute) 60×(working day) 30*

The judgment and objective tests are used in order to verification and validation of the model. In The judgment tests, the experts express their views about the simulation model and its behavior. The objective tests compare the actual behavior of the system and the obtained relevant data by the simulation model. The model is verified by using two methods: 1) gradually and in the early stages of modeling 2) tracing some entities to monitor the entity path by the node monitoring in the SLAM network. The received numbers of requests in eight different dimensions are used to validate the simulation model. The results of 30 replications are compared with 30 random samples of the actual system for the eight discussed performance criterion. It should be pointed out that the independent *t*-test is done to compare the mean of number of requests in the actual system and the simulation model by the SPSS software. Results of validation are presented in the Table 7. According to the results of validation, the simulation model behaves as good as the actual system.

## 6. SENSITIVITY ANALYSIS AND DISCUSSION

This paper considers 101 various scenarios to ana-

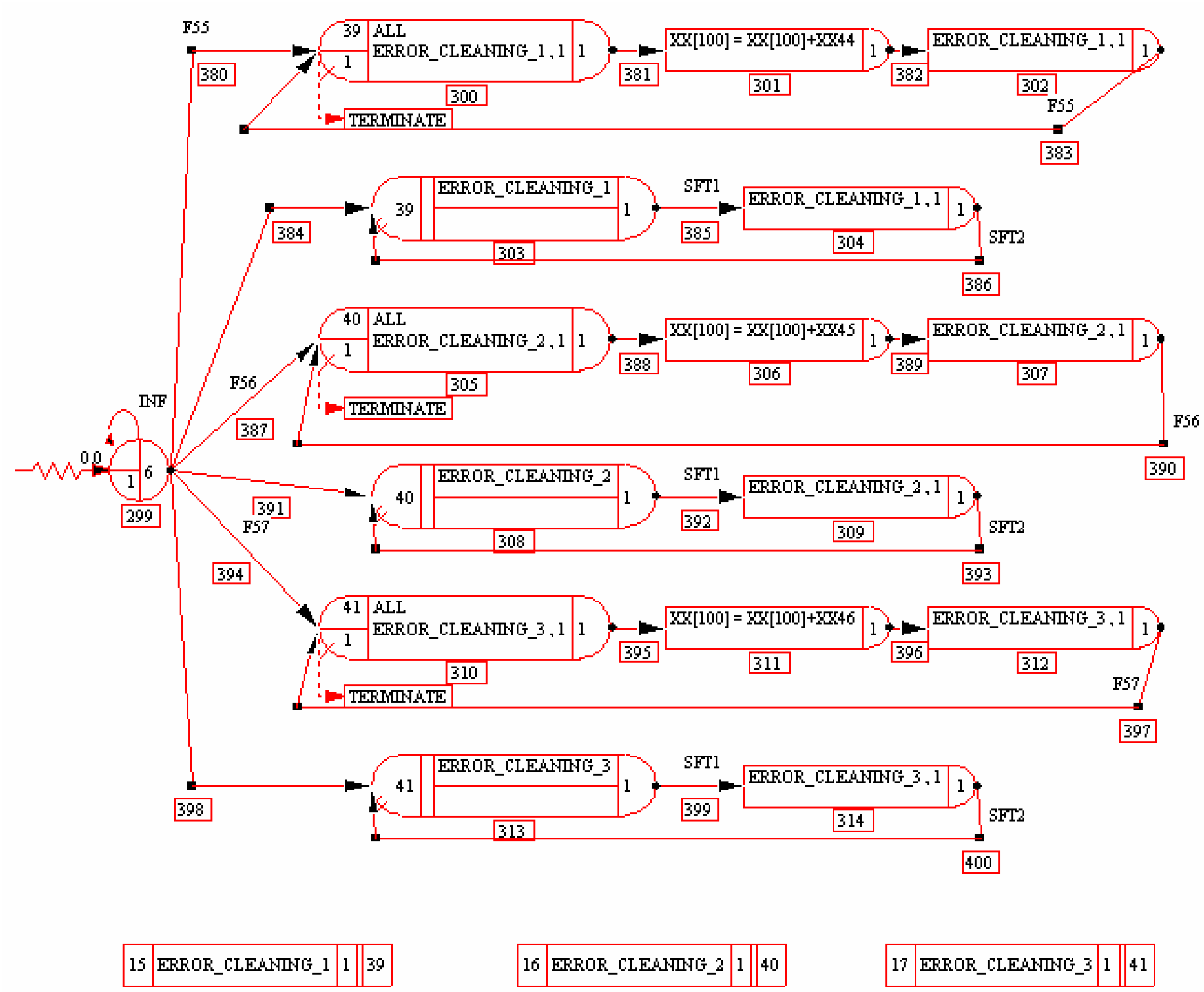



**Figure 17.** The SLAM network of error caused to cleaning.

lyze the system. The major bottlenecks are identified by Awe Sim summary report in the Visual SLAM. Inputs and outputs of the DEA model for the current system and scenarios are shown in Tables 8 and 9. In addition, the results have been drawn in Figure 18. Results show under the same conditions, the lead time for the lab manager considerably decreases by adding the assistant to the lab manager (*D7, D15, D21, D26, D30,* ⋯). This might be due to the high waiting time for the lab manager in the current system. By considering the results shown in Figure 18, it could be inferred that under the same conditions, the lead times and the production rates increase as the machines are added (*D89, D90, D91, D92,* ⋯). The improvements in production rates are clear, however, increased lead times might be due to the fact that more requests are placed in the production line instead of the transition to the external queue (it means missing the request). Therefore, more requests cause more busy time for the resources and increased lead times for customers. As a result, the lead time could be reduced by adding the machines if the production rates would be controlled. It can be seen that in the same conditions as the lead times increase, the production rates increase and vice versa. However, it can be observed that improvements (i.e. increase in production rates and decrease in lead times) are less in comparison with improvement in only one of them. In some scenarios, lead times increase in some dimensions and reduce in the remained dimensions byadding the assistant. This can be due to assistants' correlation in the mentioned dimensions. The results in Figure 18 show that total cost increases in all the scenarios. In most the scenarios, improvement percent for lead times reduce by adding more assistants and machines (sequence numbers in DMUs). This can be due to the fact that the resulted system behaves similar to two systems instead of a single system.

## 6.1 Data Envelopment Analysis (DEA) results

As mentioned before, in this study, the DEA is used

**Table 7.** Results of simulation and actual system in order to validate

| | Run N. | raw material isn't sufficient | | Inventory is sufficient to customer order | | Production of machine 1 | | Production of machine 2 | | Production of machine 3 | | Product is non-defective or defect is solvable | | Defect is acceptable | | sampling | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1[a] | 2[b] | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| | 1 | 3 | 14 | 5 | 11 | 25 | 26 | 37 | 38 | 22 | 23 | 33 | 41 | 16 | 14 | 57 | 68 |
| | 2 | 14 | 11 | 5 | 14 | 24 | 18 | 34 | 26 | 21 | 16 | 35 | 44 | 11 | 11 | 74 | 60 |
| | 3 | 11 | 8 | 3 | 16 | 31 | 20 | 45 | 30 | 27 | 18 | 41 | 30 | 14 | 16 | 55 | 57 |
| | 4 | 14 | 19 | 20 | 19 | 28 | 22 | 40 | 32 | 24 | 19 | 35 | 33 | 19 | 19 | 60 | 49 |
| | 5 | 16 | 16 | 17 | 22 | 29 | 23 | 41 | 33 | 25 | 20 | 22 | 27 | 11 | 14 | 52 | 49 |
| | 6 | 11 | 14 | 20 | 16 | 34 | 20 | 48 | 30 | 29 | 18 | 35 | 30 | 11 | 8 | 52 | 63 |
| | 7 | 8 | 20 | 11 | 14 | 23 | 33 | 33 | 47 | 20 | 29 | 25 | 35 | 11 | 14 | 68 | 60 |
| | 8 | 22 | 11 | 6 | 11 | 26 | 25 | 38 | 35 | 23 | 22 | 38 | 46 | 5 | 19 | 35 | 30 |
| | 9 | 11 | 9 | 9 | 17 | 33 | 27 | 47 | 40 | 29 | 24 | 30 | 46 | 5 | 25 | 46 | 46 |
| | 10 | 11 | 23 | 20 | 9 | 23 | 29 | 34 | 42 | 24 | 26 | 49 | 49 | 26 | 14 | 49 | 40 |
| | 11 | 11 | 20 | 11 | 11 | 27 | 20 | 40 | 29 | 28 | 17 | 32 | 52 | 11 | 8 | 69 | 69 |
| | 12 | 14 | 11 | 17 | 14 | 32 | 31 | 46 | 45 | 21 | 27 | 54 | 37 | 3 | 5 | 54 | 54 |
| | 13 | 30 | 26 | 3 | 17 | 24 | 33 | 35 | 47 | 24 | 29 | 37 | 34 | 9 | 8 | 46 | 46 |
| | 14 | 16 | 11 | 19 | 20 | 27 | 21 | 40 | 31 | 27 | 19 | 46 | 32 | 6 | 11 | 60 | 63 |
| | 15 | 14 | 9 | 16 | 17 | 31 | 24 | 45 | 35 | 35 | 21 | 40 | 29 | 11 | 14 | 69 | 57 |
| | 16 | 11 | 14 | 19 | 14 | 40 | 18 | 57 | 26 | 27 | 16 | 43 | 32 | 3 | 16 | 57 | 54 |
| | 17 | 14 | 19 | 11 | 14 | 31 | 37 | 45 | 53 | 21 | 32 | 43 | 52 | 9 | 8 | 43 | 49 |
| | 18 | 17 | 11 | 5 | 11 | 24 | 34 | 35 | 50 | 27 | 30 | 34 | 34 | 6 | 14 | 57 | 52 |
| | 19 | 20 | 8 | 8 | 16 | 31 | 26 | 45 | 38 | 19 | 23 | 42 | 44 | 11 | 11 | 44 | 46 |
| | 20 | 6 | 22 | 19 | 8 | 22 | 28 | 32 | 40 | 23 | 24 | 37 | 46 | 9 | 17 | 46 | 49 |
| | 21 | 11 | 19 | 11 | 11 | 26 | 19 | 38 | 27 | 27 | 17 | 30 | 49 | 6 | 20 | 65 | 60 |
| | 22 | 11 | 11 | 16 | 14 | 30 | 29 | 44 | 43 | 20 | 26 | 52 | 35 | 9 | 14 | 52 | 65 |
| | 23 | 11 | 25 | 11 | 16 | 23 | 31 | 33 | 45 | 23 | 27 | 35 | 33 | 14 | 9 | 44 | 68 |
| | 24 | 14 | 11 | 8 | 19 | 26 | 20 | 38 | 30 | 26 | 18 | 44 | 30 | 25 | 6 | 57 | 60 |
| | 25 | 14 | 8 | 16 | 16 | 29 | 23 | 43 | 33 | 33 | 20 | 38 | 27 | 11 | 9 | 65 | 57 |
| | 26 | 11 | 19 | 16 | 14 | 38 | 17 | 54 | 25 | 26 | 15 | 41 | 30 | 7 | 11 | 55 | 49 |
| | 27 | 14 | 5 | 8 | 11 | 29 | 35 | 43 | 51 | 20 | 31 | 41 | 49 | 14 | 14 | 41 | 43 |
| | 28 | 16 | 16 | 14 | 8 | 23 | 33 | 33 | 47 | 27 | 29 | 33 | 33 | 17 | 19 | 55 | 49 |
| | 29 | 19 | 25 | 16 | 5 | 31 | 32 | 45 | 46 | 18 | 28 | 41 | 33 | 19 | 17 | 49 | 55 |
| | 30 | 5 | 16 | 11 | 8 | 20 | 29 | 30 | 41 | 22 | 25 | 35 | 30 | 19 | 18 | 68 | 63 |
| **Independent t-Test** | **T** | **-1.193** | | **-1.128** | | **1.384** | | **1.433** | | **1.383** | | **0.322** | | **-1.337** | | **0.193** | |
| | **Sig. (2-tailed)** | **0.238** | | **0.264** | | **0.172** | | **0.157** | | **0.172** | | **0.749** | | **0.187** | | **0.847** | |

[a] simulation result [b] actual system.

in order to evaluate the different scenarios according to the criteria of production rates (8 products), lead times in 13 different dimensions and cost obtained through the simulation. DEA is a useful tool to measure the relative efficiencies a homogenous set of decision making units (DMUs), when multiple inputs and multiple outputs attend. Farrell (1957) considered a method including the one input and one output to measure the efficiency. Charnes *et al*. (1978) developed the Farrell's perspective and presented the CCR model which was able to measure the efficiency with multiple input and output. The model BCC was developed by Banker *et al*. (1984) that was variable returns to scale in contrast with CCR (constant returns to scale). Adler *et al*. (2002) have reviewed the ranking methods in the DEA. Also, some researchers have attempted to improve and develop the DEA model (Meilin *et al*., 2010; Minh *et al*., 2012; Tone, 2002; Liu and Tsai, 2004; Anderson and Peterson, 1993).

There are two different approaches in the DEA: input-oriented approach (the inputs are decision variables

**Table 8.** Lead times in different dimensions for the current system and scenarios

| DMUs | Inputs | Undesirable outputs | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Unavailability of raw material | Production rate of machine1 | Capacity of machine1 is full | Production rate of machine2 | Capacity of machine2 is full | Production rate of machine3 | Capacity of machine3is full | Non defective | Defective | Sampling | Capacity of lab is full | Sufficient inventory |
| 1 | Current system | 103.042 | 5211.376 | 141.694 | 6825.650 | 136.818 | 6513.339 | 68.733 | 426.517 | 480.663 | 1184.290 | 55.110 | 124.510 |
| 2 | M1: 2 | 103.798 | 7720.059 | 119.526 | 6825.334 | 136.812 | 6513.144 | 67.465 | 426.509 | 480.668 | 1185.112 | 55.111 | 124.500 |
| 3 | M1: 3 | 103.128 | 7275.262 | 131.259 | 6825.990 | 136.734 | 6512.897 | 68.345 | 425.984 | 479.981 | 1184.785 | 55.213 | 124.654 |
| 4 | M2: 2 | 102.489 | 5210.432 | 142.867 | 7056.908 | 145.909 | 6511.687 | 67.985 | 423.634 | 481.872 | 1183.857 | 55.342 | 124.978 |
| 5 | M2: 3 | 102.043 | 5214.653 | 141.938 | 6659.735 | 192.031 | 6517.127 | 68.876 | 427.342 | 477.871 | 1181.984 | 55.112 | 124.432 |
| 6 | M3: 2 | 102.912 | 5215.113 | 140.879 | 6821.876 | 136.123 | 5225.689 | 57.462 | 424.345 | 482.435 | 1182.657 | 55.300 | 124.379 |
| 7 | M3: 3 | 101.943 | 5219.311 | 143.173 | 6820.324 | 135.765 | 5263.031 | 42.427 | 425.654 | 480.546 | 1185.754 | 54.977 | 123.876 |
| 8 | L: 2 | 93.721 | 5051.933 | 129.876 | 6679.173 | 90.557 | 6316.115 | 62.515 | 387.933 | 457.757 | 301.868 | 1.106 | 113.462 |
| 9 | G: 2 | 86.632 | 4821.569 | 128.462 | 7694.653 | 22.091 | 3477.985 | 37.563 | 398.000 | 450.143 | 1166.155 | 49.448 | 106.377 |
| 10 | W: 2 | 95.284 | 5688.274 | 156.001 | 5628.635 | 24.998 | 5628.127 | 35.465 | 394.602 | 443.697 | 1095.673 | 48.987 | 103.385 |
| 11 | P: 2 | 92.707 | 7763.551 | 169.278 | 7663.845 | 34.896 | 4871.635 | 160.777 | 387.719 | 431.939 | 1076.559 | 50.097 | 123.467 |
| 12 | D: 2 | 94.950 | 5670.629 | 161.974 | 7132.644 | 25.110 | 6078.025 | 62.140 | 396.790 | 448.488 | 1070.860 | 52.764 | 116.190 |
| 13 | G: 2, W: 2 | 79.908 | 5658.235 | 122.116 | 5972.010 | 19.404 | 4340.549 | 65.783 | 366.715 | 414.755 | 1074.490 | 45.561 | 88.337 |
| 14 | G: 2, P: 2 | 79.682 | 7886.712 | 146.406 | 9368.971 | 31.170 | 6836.135 | 81.309 | 359.968 | 407.128 | 1054.719 | 44.723 | 88.460 |
| 15 | D: 2, G: 2 | 80.596 | 5535.613 | 122.494 | 6057.083 | 21.531 | 3443.751 | 22.923 | 370.858 | 423.505 | 1020.570 | 46.455 | 110.411 |
| 16 | L: 2, G: 2 | 78.399 | 4363.372 | 116.254 | 6963.343 | 19.992 | 3147.464 | 33.993 | 299.959 | 341.009 | 253.887 | 1.013 | 96.268 |
| 17 | G: 2, M1: 2 | 86.908 | 4989.421 | 179.609 | 7694.543 | 22.091 | 3477.979 | 37.563 | 398.000 | 450.143 | 1166.155 | 49.448 | 106.377 |
| 18 | G: 2, M2: 2 | 86.095 | 3782.617 | 216.189 | 8092.980 | 22.033 | 3479.876 | 36.765 | 396.876 | 447.987 | 1163.879 | 47.876 | 108.356 |
| 19 | G3: 2, M3: 2 | 85.073 | 3787.876 | 209.987 | 7694.563 | 23.091 | 6268.274 | 32.207 | 391.754 | 452.875 | 1169.483 | 52.987 | 103.878 |
| 20 | W: 2, P: 2 | 86.234 | 7240.524 | 167.653 | 9028.926 | 33.891 | 7233.886 | 56.010 | 355.804 | 403.972 | 981.942 | 45.973 | 111.862 |
| 21 | D: 2, W: 2 | 87.296 | 5499.613 | 143.940 | 5946.855 | 78.427 | 3775.686 | 59.247 | 364.973 | 412.526 | 984.993 | 48.533 | 97.101 |
| 22 | W: 2, L: 2 | 85.967 | 5132.070 | 140.747 | 5078.263 | 22.554 | 4473.317 | 31.997 | 297.228 | 332.697 | 251.972 | 0.923 | 85.326 |
| 23 | W: 2, M1: 2 | 95.361 | 6869.396 | 143.228 | 5618.635 | 24.198 | 4958.127 | 34.876 | 391.767 | 443.876 | 1092.334 | 59.763 | 92.456 |
| 24 | M2: 2, W: 2 | 95.284 | 5688.274 | 156.001 | 6959.308 | 22.404 | 4948.654 | 34.653 | 396.659 | 445.765 | 1093.765 | 51.348 | 93.835 |
| 25 | W: 2, M3: 2 | 95.244 | 5689.435 | 151.654 | 5629.826 | 23.987 | 3519.654 | 25.221 | 394.876 | 448.876 | 1090.216 | 45.236 | 90.734 |
| 26 | P: 2, D: 2 | 85.865 | 8460.065 | 155.412 | 10505.484 | 34.694 | 6060.844 | 69.782 | 358.111 | 404.769 | 966.473 | 47.620 | 116.602 |
| 27 | L: 2, P: 2 | 83.455 | 6990.946 | 152.432 | 8438.558 | 31.423 | 7629.044 | 144.777 | 284.584 | 326.154 | 247.100 | 0.905 | 111.180 |
| 28 | P: 2, M1: 2 | 89.586 | 8590.642 | 157.978 | 9373.275 | 33.298 | 8471.863 | 158.265 | 389.193 | 435.183 | 1071.276 | 52.876 | 125.872 |
| 29 | M2: 2, P: 2 | 92.707 | 7769.876 | 161.162 | 9893.999 | 31.006 | 8479.123 | 154.762 | 381.983 | 429.987 | 1069.873 | 48.267 | 121.273 |
| 30 | P: 2, M3: 2 | 91.239 | 7758.287 | 157.293 | 9376.333 | 34.286 | 7726.999 | 67.753 | 372.239 | 416.927 | 1059.592 | 49.391 | 118.274 |
| 31 | L: 2, D: 2 | 85.745 | 5120.907 | 146.272 | 6441.191 | 22.676 | 4171.392 | 25.569 | 291.902 | 334.102 | 254.526 | 1.409 | 101.675 |
| 32 | D: 2, M1: 2 | 96.456 | 6452.560 | 128.496 | 7123.873 | 24.982 | 4612.293 | 29.183 | 391.284 | 443.277 | 1061.234 | 54.236 | 114.522 |
| 33 | M2: 2, D: 2 | 94.950 | 6443.876 | 124.981 | 7248.102 | 23.702 | 4624.274 | 29.382 | 385.546 | 439.283 | 1065.425 | 51.273 | 113.231 |
| 34 | D: 2, M3: 2 | 94.950 | 6438.193 | 124.125 | 7113.526 | 25.110 | 3834.153 | 24.620 | 382.342 | 439.284 | 1071.268 | 51.143 | 108.953 |
| 35 | L: 2, M1: 2 | 94.408 | 5488.079 | 108.713 | 6201.623 | 22.872 | 5921.154 | 61.353 | 315.452 | 359.717 | 271.465 | 1.006 | 111.479 |
| 36 | L: 2, M2: 2 | 93.721 | 4730.357 | 126.951 | 6418.510 | 23.217 | 5917.836 | 60.285 | 313.284 | 357.927 | 268.295 | 1.019 | 109.876 |
| 37 | M3: 2, L: 2 | 92.733 | 4728.184 | 131.384 | 6199.983 | 19.987 | 4752.951 | 52.655 | 309.876 | 365.164 | 279.987 | 0.997 | 114.387 |
| 38 | M1: 2, M2: 2 | 103.873 | 6029.286 | 139.174 | 7038.285 | 25.983 | 6514.387 | 67.179 | 423.286 | 486.176 | 1175.234 | 55.298 | 126.253 |
| 39 | M1: 2, M3: 2 | 104.012 | 6028.165 | 142.175 | 6817.191 | 24.946 | 5224.542 | 57.275 | 425.873 | 482.365 | 1183.586 | 54.954 | 125.011 |
| 40 | M2: 2, M3: 2 | 103.798 | 6032.184 | 139.564 | 7054.274 | 25.275 | 5222.375 | 57.433 | 427.231 | 480.274 | 1180.173 | 54.197 | 124.198 |
| 41 | G: 2, W: 2, P: 2 | 71.653 | 5893.166 | 140.495 | 7593.803 | 26.303 | 4108.196 | 99.696 | 328.683 | 371.741 | 963.055 | 40.836 | 91.890 |
| 42 | G: 2, W: 2, D: 2 | 73.622 | 3938.135 | 88.612 | 5798.159 | 18.905 | 4420.233 | 40.446 | 339.506 | 387.680 | 934.293 | 42.527 | 67.139 |
| 43 | G: 2, W: 2, L: 2 | 71.666 | 5074.747 | 109.521 | 5356.070 | 17.403 | 3892.874 | 57.998 | 269.151 | 312.478 | 231.835 | 0.925 | 79.226 |
| 44 | G: 2, W: 2, M1: 2 | 79.687 | 5866.745 | 112.380 | 5961.754 | 18.755 | 4332.246 | 64.234 | 362.097 | 409.023 | 1060.107 | 44.509 | 87.345 |
| 45 | G: 2, W: 2, M2: 2 | 79.908 | 5651.642 | 120.199 | 6669.165 | 21.928 | 4332.913 | 61.876 | 361.372 | 412.906 | 1078.432 | 44.383 | 87.734 |
| 46 | G: 2, W: 2, M3: 2 | 78.973 | 5651.836 | 118.274 | 5974.298 | 19.404 | 3751.423 | 35.189 | 355.723 | 415.337 | 1068.922 | 46.823 | 88.337 |
| 47 | G: 2, P: 2,D: 2 | 71.730 | 8794.949 | 141.058 | 6833.468 | 24.637 | 6353.032 | 71.932 | 332.744 | 379.981 | 915.684 | 41.680 | 97.948 |
| 48 | L: 2, G: 2,P: 2 | 71.309 | 7058.048 | 131.023 | 8384.563 | 27.895 | 6117.855 | 72.765 | 268.285 | 305.001 | 227.078 | 0.906 | 79.166 |
| 49 | P: 2, G: 2, M1: 2 | 79.296 | 7953.276 | 154.947 | 9359.139 | 30.538 | 6831.287 | 79.537 | 357.265 | 402.762 | 1049.765 | 43.646 | 85.503 |
| 50 | G: 2, P: 2, M2: 2 | 78.253 | 7881.276 | 145.297 | 8748.236 | 23.588 | 6825.762 | 78.360 | 356.280 | 402.289 | 1053.298 | 43.877 | 89.283 |
| 51 | G: 2, P: 2, M3: 2 | 79.982 | 7886.713 | 31.170 | 9368.971 | 28.491 | 8701.516 | 100.483 | 359.968 | 407.128 | 1054.719 | 44.723 | 88.460 |

**Table 8.** (continued)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 52 | G: 2, D: 2, L: 2 | 72.359 | 4969.846 | 109.975 | 5438.020 | 19.394 | 3100.741 | 20.580 | 274.295 | 315.714 | 241.889 | 0.518 | 99.127 |
| 53 | G: 2, D: 2, M1: 2 | 79.784 | 5702.830 | 112.137 | 6048.274 | 21.285 | 3433.102 | 22.398 | 375.541 | 413.182 | 1017.183 | 46.298 | 109.111 |
| 54 | M2: 2, G: 2, D: 2 | 80.596 | 5710.105 | 121.271 | 7524.092 | 19.802 | 3449.183 | 22.190 | 368.555 | 424.290 | 1023.872 | 47.129 | 108.419 |
| 55 | G: 2, D: 2, M3: 2 | 81.937 | 5698.265 | 120.244 | 6061.276 | 21.900 | 5138.133 | 44.112 | 374.193 | 419.267 | 1022.222 | 45.118 | 111.362 |
| 56 | M1: 2, G: 2, L: 2 | 78.169 | 4940.325 | 108.195 | 6954.677 | 19.532 | 3155.465 | 33.177 | 297.763 | 339.099 | 254.205 | 1.019 | 97.191 |
| 57 | G: 2, L: 2, M2: 2 | 77.276 | 4359.387 | 115.291 | 7323.898 | 19.939 | 3144.233 | 34.442 | 295.262 | 338.457 | 255.251 | 0.997 | 93.844 |
| 58 | G: 2, L: 2, M3: 2 | 76.101 | 4369.273 | 118.645 | 6949.374 | 18.999 | 5672.596 | 29.146 | 293.343 | 342.266 | 250.626 | 1.039 | 96.372 |
| 59 | M1: 1, M2: 2, G: 2 | 85.626 | 5455.909 | 118.033 | 809.575 | 22.489 | 3477.016 | 37.610 | 397.894 | 451.500 | 1163.527 | 48.352 | 107.137 |
| 60 | M1: 2, M3: 2, G: 2 | 87.157 | 5451.698 | 121.050 | 7694.318 | 22.448 | 6268.366 | 32.723 | 398.972 | 452.378 | 1159.500 | 49.545 | 105.223 |
| 61 | G: 2, M2: 2, M3: 2 | 86.632 | 4816.512 | 127.289 | 8091.546 | 22.133 | 6262.022 | 32.207 | 396.000 | 450.318 | 1168.366 | 49.333 | 102.517 |
| 62 | W: 2, P: 2, D: 2 | 78.115 | 6586.808 | 158.888 | 6771.474 | 25.801 | 6569.335 | 80.851 | 326.294 | 368.807 | 880.606 | 43.390 | 82.731 |
| 63 | W: 2, P: 2, L: 2 | 76.883 | 6455.337 | 149.472 | 8049.799 | 30.130 | 6449.339 | 49.936 | 264.836 | 296.440 | 224.512 | 0.822 | 99.731 |
| 64 | M1: 2, W: 2, P: 2 | 85.006 | 7242.922 | 131.108 | 9020.042 | 33.560 | 7229.942 | 55.993 | 353.232 | 401.293 | 985.006 | 46.763 | 110.801 |
| 65 | P: 2, W: 2, M2: 2 | 86.489 | 7241.754 | 166.263 | 8943.147 | 24.767 | 7232.654 | 55.102 | 352.525 | 398.463 | 981.284 | 43.985 | 109.216 |
| 66 | P: 2, W: 2, M3: 2 | 83.911 | 724.971 | 164.566 | 9019.489 | 32.223 | 8806.776 | 108.735 | 348.891 | 404.094 | 979.804 | 45.973 | 111.862 |
| 67 | W: 2, D: 2, L: 2 | 78.096 | 4919.992 | 128.769 | 5320.099 | 19.756 | 3377.755 | 53.002 | 265.983 | 304.364 | 231.926 | 1.284 | 86.868 |
| 68 | W: 2, D: 2, M1: 2 | 89.057 | 5638.944 | 126.270 | 5944.243 | 22.111 | 3769.195 | 58.081 | 362.093 | 410.984 | 981.198 | 47.274 | 96.154 |
| 69 | W: 2, D: 2, M2: 2 | 87.296 | 5498.720 | 142.900 | 5839.039 | 24.065 | 3776.311 | 59.962 | 364.289 | 412.727 | 984.678 | 48.765 | 97.187 |
| 70 | M3: 2, D: 2, W: 2 | 87.391 | 5500.273 | 144.183 | 5950.437 | 23.196 | 6238.654 | 30.987 | 365.874 | 413.486 | 982.367 | 49.649 | 98.098 |
| 71 | W: 2, L: 2, M1: 2 | 86.037 | 6197.700 | 129.223 | 5071.184 | 22.324 | 4466.295 | 30.271 | 291.193 | 338.928 | 254.961 | 0.933 | 83.919 |
| 72 | L: 2, M2: 2, W: 2 | 84.305 | 5134.298 | 139.873 | 6278.489 | 20.213 | 4477.763 | 31.193 | 296.287 | 333.276 | 251.287 | 1.008 | 86.735 |
| 73 | L: 2, M3: 2, W: 2 | 86.997 | 5136.119 | 141.186 | 5059.174 | 22.501 | 3175.736 | 23.156 | 299.255 | 336.232 | 248.217 | 0.899 | 84.777 |
| 74 | W: 2, M1: 2, M2: 2 | 95.361 | 6859.336 | 145.398 | 6953.384 | 20.517 | 4962.982 | 37.215 | 397.671 | 440.697 | 1098.551 | 48.175 | 91.557 |
| 75 | W: 2, M1: 2, M3: 2 | 95.701 | 6869.396 | 143.228 | 5632.002 | 25.875 | 3522.874 | 23.187 | 398.278 | 442.155 | 1093.942 | 51.761 | 96.146 |
| 76 | M2: 2, M3: 2, W: 2 | 94.708 | 5683.196 | 155.603 | 6950.894 | 21.955 | 3510.197 | 25.306 | 390.779 | 444.497 | 1095.487 | 50.177 | 94.293 |
| 77 | P: 2, D: 2, L: 2 | 76.642 | 7551.348 | 138.719 | 9377.063 | 30.968 | 5409.833 | 62.287 | 260.393 | 298.037 | 227.051 | 1.257 | 104.077 |
| 78 | P: 2, D: 2, M1: 2 | 87.733 | 8562.911 | 168.111 | 10510.516 | 33.441 | 6065.545 | 67.414 | 361.984 | 409.391 | 959.904 | 48.516 | 117.442 |
| 79 | M2: 2, D: 2, P: 2 | 84.333 | 8467.885 | 153.164 | 9177.541 | 31.716 | 6072.984 | 71.047 | 361.547 | 399.761 | 955.294 | 48.897 | 115.931 |
| 80 | P: 2, D: 2, M3: 2 | 85.899 | 8460.065 | 169.137 | 10505.484 | 31.111 | 8341.187 | 107.671 | 358.274 | 404.047 | 966.391 | 47.851 | 116.142 |
| 81 | L: 2, P: 2, M1: 2 | 81.572 | 7740.942 | 141.323 | 8427.982 | 32.273 | 7619.335 | 139.503 | 283.417 | 318.004 | 248.449 | 0.917 | 112.125 |
| 82 | P: 2, L: 2, M2: 2 | 83.129 | 6987.163 | 149.194 | 8990.946 | 27.921 | 7631.593 | 145.918 | 288.197 | 331.302 | 249.643 | 0.884 | 108.998 |
| 83 | M3: 2, L: 2, P: 2 | 83.060 | 6990.946 | 152.423 | 8437.835 | 31.437 | 6958.032 | 61.011 | 284.584 | 326.164 | 247.284 | 0.907 | 111.180 |
| 84 | M1: 2, M2: 2, P: 2 | 90.894 | 8590.393 | 153.746 | 9896.655 | 29.998 | 8476.018 | 158.004 | 391.761 | 430.720 | 1079.610 | 52.023 | 120.654 |
| 85 | M1: 2, M3: 2, P: 2 | 91.703 | 8601.184 | 157.174 | 9363.544 | 34.275 | 7737.746 | 69.765 | 382.999 | 429.378 | 1072.193 | 52.097 | 124.654 |
| 86 | M2: 2, M3: 2, P: 2 | 92.707 | 7763.765 | 169.119 | 9893.091 | 31.006 | 7726.785 | 67.114 | 387.417 | 436.176 | 1076.649 | 50.843 | 123.005 |
| 87 | D: 2, L: 2, M1: 2 | 87.173 | 5827.036 | 116.039 | 6435.755 | 22.876 | 4167.226 | 24.347 | 289.294 | 332.864 | 252.398 | 1.302 | 102.397 |
| 88 | M2: 2, D: 2, L: 2 | 85.876 | 5129.877 | 148.309 | 6542.176 | 21.044 | 4161.173 | 26.374 | 292.107 | 338.590 | 257.993 | 1.509 | 99.981 |
| 89 | M3: 2, L: 2, D: 2 | 84.653 | 5120.278 | 146.876 | 6442.376 | 22.775 | 3458.596 | 22.101 | 288.759 | 340.297 | 247.019 | 1.561 | 103.256 |
| 90 | L: 2, M1: 2, M2: 2 | 94.650 | 5482.779 | 109.061 | 6409.090 | 23.645 | 4739.568 | 53.194 | 313.098 | 358.937 | 272.217 | 1.009 | 115.018 |
| 91 | L: 2, M1: 2, M3: 2 | 94.765 | 5493.987 | 107.537 | 6208.232 | 22.435 | 4774.465 | 53.976 | 317.086 | 355.853 | 275.006 | 1.100 | 114.543 |
| 92 | L: 2, M2: 2, M3: 2 | 94.408 | 4738.251 | 128.263 | 6419.173 | 23.171 | 4751.164 | 51.646 | 317.765 | 362.165 | 274.963 | 0.902 | 113.759 |
| 93 | M1: 2, M2: 2, M3: 2 | 102.287 | 5201.982 | 119.556 | 7044.217 | 25.548 | 5316.879 | 57.665 | 426.402 | 480.104 | 1184.365 | 55.110 | 124.236 |
| 94 | G: 2, W: 2, P: 2, D: 2 | 64.459 | 6581.069 | 131.175 | 6534.389 | 17.582 | 7497.997 | 85.515 | 301.393 | 344.158 | 829.407 | 37.753 | 75.942 |
| 95 | G: 2, W: 2, P: 2, L: 2 | 62.340 | 5215.028 | 124.328 | 6719.970 | 23.277 | 5573.241 | 88.224 | 238.027 | 276.344 | 205.026 | 0.818 | 81.316 |
| 96 | G: 2, P: 2, D: 2, L: 2 | 63.559 | 7793.100 | 124.990 | 6055.055 | 21.830 | 5629.347 | 63.738 | 242.896 | 279.574 | 214.199 | 0.459 | 86.791 |
| 97 | W: 2, P: 2, D: 2, L: 2 | 68.906 | 5810.314 | 140.157 | 5973.210 | 22.760 | 5794.901 | 71.320 | 234.474 | 268.308 | 204.451 | 1.132 | 72.978 |
| 98 | G: 2, W: 2, P: 2, D: 2, L: 2 | 56.352 | 5753.426 | 114.678 | 5712.616 | 15.371 | 6555.120 | 74.760 | 216.696 | 250.336 | 191.423 | 0.410 | 66.392 |
| 99 | Change of working hours: 6 hours, one-shift | 103.439 | 5797.820 | 150.019 | 7449.523 | 30.993 | 4736.617 | 39.304 | 431.090 | 486.512 | 1005.095 | 44.557 | 108.931 |
| 100 | Change of working ：hours 6 hours, two-shifts | 101.999 | 6234.723 | 183.604 | 7381.195 | 30.095 | 6762.197 | 87.608 | 425.665 | 489.358 | 1354.055 | 60.356 | 110.190 |
| 101 | Preventive maintenance (time between of 400 min) | 102.012 | 4898.693 | 130.358 | 6143.085 | 129.977 | 5536.338 | 69.420 | 423.387 | 482.284 | 1173.209 | 52.198 | 117.238 |

M: machine, D: deputy, G: general manager, L: lab manager, W: warehouse, P: production manager.

**Table 9.** Results of production rates and total cost for the current system and scenarios

| DMU | desirable outputs | | | | | | | | Undesirable output |
|---|---|---|---|---|---|---|---|---|---|
| | Production rate 1 | Production rate 2 | Production rate 3 | Production rate 4 | Production rate 5 | Production rate 6 | Production rate 7 | Production rate 8 | Total cost |
| 1 | 229.195 | 183.512 | 128.268 | 86.857 | 138.115 | 160.827 | 115.433 | 173.608 | 37748411.357 |
| 2 | 266.526 | 236.726 | 150.328 | 96.243 | 171.381 | 183.356 | 138.027 | 194.023 | 43096783.844 |
| 3 | 320.371 | 264.519 | 203.389 | 134.193 | 203.368 | 206.113 | 179.004 | 217.876 | 48350251.849 |
| 4 | 234.339 | 202.995 | 151.964 | 94.962 | 135.024 | 167.331 | 137.878 | 166.702 | 39457709.974 |
| 5 | 224.080 | 205.162 | 122.258 | 85.427 | 140.996 | 172.708 | 120.525 | 147.178 | 36070177.570 |
| 6 | 201.283 | 168.890 | 104.114 | 79.463 | 110.595 | 139.171 | 88.336 | 142.685 | 39230958.266 |
| 7 | 192.678 | 154.817 | 99.808 | 61.853 | 102.914 | 117.226 | 97.406 | 132.529 | 34349168.575 |
| 8 | 226.781 | 201.123 | 139.234 | 91.856 | 148.128 | 178.675 | 145.765 | 197.876 | 42400672.589 |
| 9 | 236.959 | 218.691 | 139.304 | 93.835 | 141.372 | 161.359 | 116.130 | 153.421 | 43238042.000 |
| 10 | 271.913 | 205.463 | 172.508 | 87.968 | 169.102 | 181.079 | 125.363 | 180.861 | 39630382.380 |
| 11 | 376.247 | 291.298 | 227.454 | 137.347 | 239.126 | 249.218 | 200.780 | 279.787 | 44175060.679 |
| 12 | 269.910 | 203.668 | 156.858 | 107.830 | 167.601 | 189.519 | 144.492 | 185.758 | 39933024.823 |
| 13 | 286.025 | 255.140 | 150.839 | 126.009 | 174.958 | 170.279 | 151.093 | 237.784 | 46937690.251 |
| 14 | 405.716 | 323.618 | 242.574 | 156.948 | 263.247 | 257.223 | 222.015 | 261.277 | 52798389.757 |
| 15 | 277.503 | 225.575 | 168.974 | 104.029 | 172.296 | 186.171 | 152.712 | 186.644 | 48003557.864 |
| 16 | 223.546 | 206.312 | 131.419 | 88.524 | 133.370 | 152.225 | 109.557 | 144.737 | 43087420.905 |
| 17 | 233.162 | 174.083 | 119.500 | 80.425 | 142.408 | 127.900 | 114.717 | 162.917 | 44087420.905 |
| 18 | 299.932 | 245.458 | 165.496 | 106.497 | 175.452 | 213.662 | 160.982 | 192.873 | 45463310.504 |
| 19 | 233.550 | 183.860 | 128.711 | 99.826 | 140.806 | 142.264 | 125.323 | 169.075 | 46400141.493 |
| 20 | 382.621 | 318.049 | 207.571 | 141.533 | 237.566 | 258.470 | 288.593 | 110.125 | 46932945.865 |
| 21 | 281.810 | 219.127 | 154.066 | 103.035 | 176.522 | 188.239 | 144.450 | 186.312 | 41733987.877 |
| 22 | 271.913 | 205.463 | 172.508 | 87.968 | 169.102 | 181.079 | 125.363 | 180.861 | 42561976.437 |
| 23 | 326.787 | 247.114 | 198.863 | 142.347 | 213.879 | 230.202 | 167.612 | 246.202 | 42180318.817 |
| 24 | 256.323 | 204.754 | 157.915 | 93.471 | 159.370 | 183.486 | 122.125 | 187.019 | 41961976.437 |
| 25 | 208.664 | 164.257 | 119.276 | 71.765 | 124.872 | 130.872 | 102.963 | 145.875 | 42561976.437 |
| 26 | 442.344 | 338.147 | 254.986 | 160.910 | 272.177 | 320.011 | 225.789 | 338.387 | 47368461.976 |
| 27 | 376.247 | 291.298 | 227.254 | 137.347 | 239.126 | 249.218 | 200.780 | 279.787 | 47175060.679 |
| 28 | 415.814 | 346.582 | 239.708 | 169.719 | 288.684 | 282.869 | 216.278 | 295.344 | 46175060.679 |
| 29 | 383.427 | 292.834 | 222.668 | 138.416 | 232.555 | 266.853 | 198.757 | 275.519 | 46675060.679 |
| 30 | 351.326 | 266.201 | 187.807 | 133.786 | 208.040 | 228.661 | 182.743 | 251.055 | 47001959.738 |
| 31 | 269.910 | 203.663 | 156.858 | 107.830 | 167.601 | 189.519 | 144.492 | 185.758 | 46002813.960 |
| 32 | 307.770 | 265.147 | 185.943 | 121.002 | 231.415 | 196.831 | 154.734 | 208.914 | 42091603.077 |
| 33 | 276.298 | 212.021 | 152.724 | 97.893 | 172.364 | 183.809 | 136.150 | 187.650 | 42360202.702 |
| 34 | 219.532 | 158.877 | 119.682 | 81.668 | 121.910 | 151.424 | 108.957 | 141.999 | 42360202.702 |
| 35 | 264.004 | 236.726 | 150.328 | 96.243 | 171.381 | 183.356 | 138.027 | 194.023 | 43248411.357 |
| 36 | 231.767 | 193.253 | 140.116 | 90.909 | 136.569 | 164.079 | 126.655 | 170.155 | 43117363.232 |
| 37 | 235.596 | 186.279 | 130.486 | 93.647 | 139.098 | 164.345 | 116.414 | 164.221 | 43248411.357 |
| 38 | 249.800 | 211.503 | 140.407 | 94.945 | 155.240 | 173.850 | 127.221 | 179.122 | 42617363.232 |
| 39 | 232.643 | 202.808 | 127.221 | 87.853 | 140.988 | 161.263 | 113.182 | 168.354 | 43248411.357 |
| 40 | 217.811 | 185.942 | 128.039 | 87.213 | 122.810 | 153.251 | 113.107 | 154.694 | 42720986.492 |
| 41 | 331.369 | 238.537 | 184.133 | 120.474 | 202.703 | 198.461 | 157.369 | 228.849 | 53416593.141 |
| 42 | 214.835 | 159.596 | 109.233 | 86.635 | 138.882 | 137.149 | 115.074 | 150.153 | 47584488.817 |
| 43 | 286.025 | 225.140 | 150.839 | 126.009 | 174.958 | 170.279 | 151.093 | 237.784 | 51937690.251 |
| 44 | 297.647 | 250.389 | 174.204 | 109.687 | 177.080 | 182.216 | 138.413 | 209.449 | 50437690.251 |
| 45 | 279.233 | 227.287 | 152.248 | 110.842 | 171.588 | 185.082 | 142.538 | 210.459 | 49437690.251 |
| 46 | 212.451 | 178.826 | 112.460 | 94.941 | 124.747 | 147.828 | 113.121 | 172.795 | 47920508.941 |
| 47 | 488.352 | 363.992 | 303.105 | 193.267 | 315.994 | 334.751 | 248.953 | 356.446 | 53325022.924 |
| 48 | 405.716 | 323.618 | 242.574 | 156.948 | 263.247 | 257.223 | 222.015 | 261.277 | 54798389.757 |
| 49 | 409.625 | 336.016 | 251.725 | 153.582 | 262.206 | 254.613 | 230.531 | 288.353 | 54298389.757 |
| 50 | 380.822 | 306.822 | 222.065 | 139.599 | 240.066 | 258.084 | 209.063 | 261.893 | 53561325.234 |
| 51 | 402.968 | 308.907 | 223.667 | 144.744 | 231.586 | 258.290 | 209.316 | 268.493 | 54298367.876 |
| 52 | 277.503 | 225.575 | 168.974 | 104.029 | 172.296 | 186.171 | 152.712 | 186.644 | 48387112.109 |
| 53 | 285.600 | 217.276 | 161.444 | 102.375 | 196.542 | 197.693 | 137.348 | 197.890 | 49237655.998 |
| 54 | 289.899 | 237.486 | 167.500 | 102.441 | 174.226 | 198.203 | 151.932 | 200.731 | 48238265.298 |

**Table 9.** (continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 55 | 254.920 | 204.673 | 140.051 | 92.380 | 141.454 | 169.745 | 131.281 | 168.182 | 48298447.264 |
| 56 | 254.596 | 200.329 | 148.616 | 99.643 | 159.236 | 154.038 | 140.882 | 200.167 | 48323341.876 |
| 57 | 261.739 | 225.885 | 148.458 | 97.511 | 154.411 | 182.944 | 135.269 | 168.805 | 46396088.916 |
| 58 | 228.548 | 195.086 | 130.065 | 94.175 | 137.088 | 147.244 | 117.440 | 156.906 | 49900141.493 |
| 59 | 276.639 | 222.894 | 157.056 | 103.070 | 167.344 | 183.850 | 150.932 | 196.520 | 47823341.183 |
| 60 | 243.448 | 192.095 | 138.664 | 99.735 | 150.021 | 148.151 | 133.102 | 184.621 | 49400141.493 |
| 61 | 266.741 | 214.659 | 147.104 | 103.162 | 158.129 | 177.963 | 143.152 | 180.974 | 49400141.493 |
| 62 | 378.737 | 304.096 | 240.916 | 144.512 | 251.728 | 257.399 | 198.921 | 264.182 | 47916451.649 |
| 63 | 382.621 | 318.049 | 207.571 | 141.533 | 237.566 | 258.470 | 187.215 | 288.593 | 49932945.865 |
| 64 | 381.977 | 304.266 | 228.818 | 160.783 | 246.896 | 253.007 | 199.440 | 285.209 | 49432945.865 |
| 65 | 370.472 | 319.002 | 205.665 | 132.258 | 224.005 | 257.657 | 195.081 | 278.157 | 49778697.802 |
| 66 | 378.523 | 303.405 | 195.472 | 136.929 | 232.051 | 264.169 | 190.559 | 302.936 | 50800383.694 |
| 67 | 281.810 | 219.127 | 154.066 | 103.035 | 176.522 | 188.239 | 144.450 | 186.312 | 43733987.877 |
| 68 | 290.989 | 235.615 | 165.718 | 100.537 | 183.756 | 214.902 | 146.952 | 225.193 | 43917366.275 |
| 69 | 257.434 | 202.835 | 143.729 | 91.831 | 167.151 | 168.497 | 130.339 | 174.842 | 43895855.175 |
| 70 | 278.582 | 208.122 | 140.623 | 102.162 | 161.133 | 185.598 | 139.342 | 187.753 | 44106094.206 |
| 71 | 326.787 | 247.114 | 198.863 | 142.347 | 213.879 | 230.202 | 167.612 | 246.202 | 45680318.817 |
| 72 | 256.323 | 204.011 | 156.732 | 93.073 | 159.983 | 183.486 | 121.127 | 182.464 | 45061976.437 |
| 73 | 213.612 | 171.324 | 111.062 | 79.935 | 127.763 | 134.770 | 111.818 | 147.960 | 45061976.117 |
| 74 | 283.760 | 224.836 | 169.909 | 120.262 | 182.371 | 208.047 | 142.251 | 215.134 | 45180318.817 |
| 75 | 236.101 | 185.318 | 133.461 | 99.591 | 146.375 | 155.751 | 123.399 | 177.905 | 45817451.754 |
| 76 | 193.074 | 163.040 | 104.507 | 77.507 | 114.867 | 133.597 | 98.038 | 146.837 | 44561988.140 |
| 77 | 442.344 | 338.147 | 254.986 | 160.910 | 213.879 | 320.011 | 225.789 | 338.387 | 50368461.029 |
| 78 | 449.630 | 351.326 | 304.198 | 180.346 | 294.230 | 311.358 | 267.835 | 327.077 | 51712310.904 |
| 79 | 402.594 | 318.133 | 233.651 | 145.422 | 252.437 | 281.623 | 209.872 | 304.276 | 49637684.787 |
| 80 | 402.403 | 317.238 | 220.012 | 136.817 | 235.174 | 277.363 | 201.175 | 303.047 | 50435185.920 |
| 81 | 415.814 | 346.582 | 239.708 | 169.719 | 288.684 | 282.869 | 216.278 | 295.344 | 49675060.679 |
| 82 | 403.211 | 320.476 | 228.795 | 154.602 | 257.334 | 283.679 | 206.506 | 283.297 | 50358765.066 |
| 83 | 371.109 | 293.843 | 193.934 | 149.972 | 232.819 | 245.486 | 190.492 | 258.833 | 50019159.738 |
| 84 | 403.211 | 320.476 | 228.795 | 154.602 | 257.334 | 283.679 | 206.506 | 283.297 | 49858765.066 |
| 85 | 358.609 | 294.843 | 213.934 | 139.972 | 228.819 | 220.486 | 180.492 | 248.833 | 49501959.738 |
| 86 | 358.506 | 267.738 | 183.021 | 134.854 | 201.469 | 246.296 | 180.720 | 246.787 | 49865367.983 |
| 87 | 307.770 | 265.147 | 185.943 | 121.002 | 231.415 | 196.831 | 154.734 | 208.914 | 45591603.077 |
| 88 | 276.298 | 212.021 | 152.724 | 97.893 | 172.364 | 183.809 | 136.150 | 187.650 | 45376568.098 |
| 89 | 219.532 | 158.877 | 119.682 | 81.668 | 121.910 | 151.424 | 108.957 | 141.999 | 45498764.754 |
| 90 | 249.172 | 219.860 | 151.146 | 95.602 | 153.202 | 175.343 | 137.952 | 180.363 | 45720986.492 |
| 91 | 232.643 | 202.808 | 127.221 | 87.853 | 140.988 | 161.263 | 113.182 | 168.354 | 45786754.087 |
| 92 | 217.811 | 185.942 | 128.039 | 87.213 | 122.810 | 153.251 | 113.107 | 154.694 | 45720986.492 |
| 93 | 233.209 | 202.870 | 135.469 | 90.223 | 139.000 | 163.286 | 121.414 | 167.803 | 45220344.287 |
| 94 | 406.342 | 304.457 | 237.952 | 152.320 | 266.576 | 250.253 | 216.274 | 308.230 | 56361266.772 |
| 95 | 331.369 | 238.537 | 184.133 | 120.474 | 202.703 | 198.461 | 157.369 | 228.849 | 57551091.427 |
| 96 | 488.352 | 363.992 | 303.105 | 193.267 | 315.994 | 334.751 | 248.953 | 356.446 | 56325022.924 |
| 97 | 378.737 | 304.096 | 240.916 | 144.512 | 251.728 | 257.399 | 198.921 | 264.182 | 50916451.649 |
| 98 | 406.342 | 304.457 | 237.952 | 152.320 | 266.576 | 250.253 | 216.274 | 308.230 | 59361266.772 |
| 98 | 340.530 | 288.981 | 210.623 | 133.653 | 217.161 | 246.971 | 181.388 | 256.329 | 65167965.990 |
| 99 | 255.278 | 189.616 | 140.601 | 83.417 | 147.976 | 161.744 | 126.149 | 184.878 | 3334302.635 |
| 100 | 272.441 | 235.202 | 172.022 | 113.339 | 181.602 | 196.748 | 147.089 | 195.994 | 46358231.239 |
| 101 | 239.655 | 191.394 | 136.681 | 93.194 | 140.021 | 169.493 | 121.203 | 182.489 | 44349187.021 |

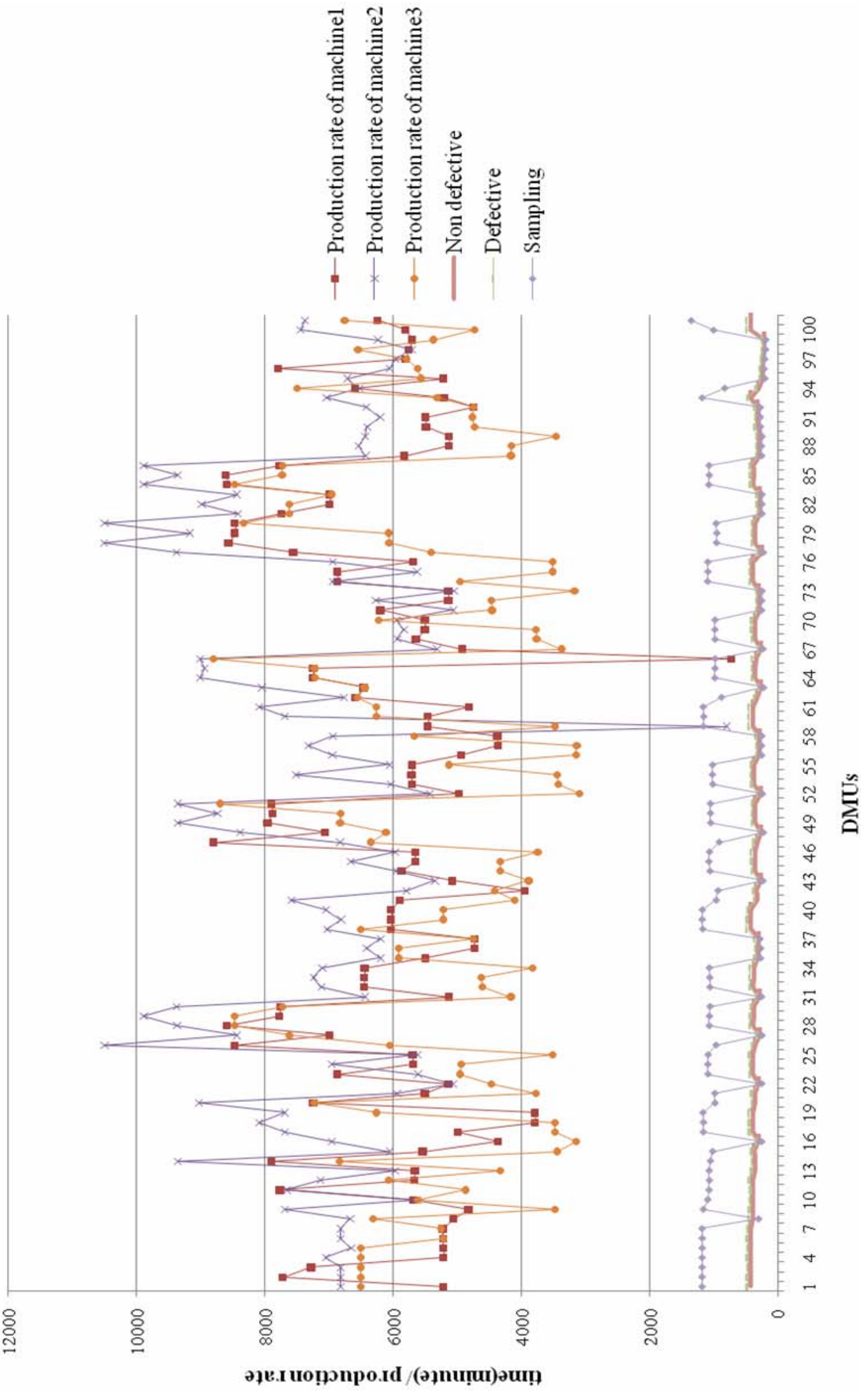



**Figure 18.** simulation results for makespan, cost, and waiting times.

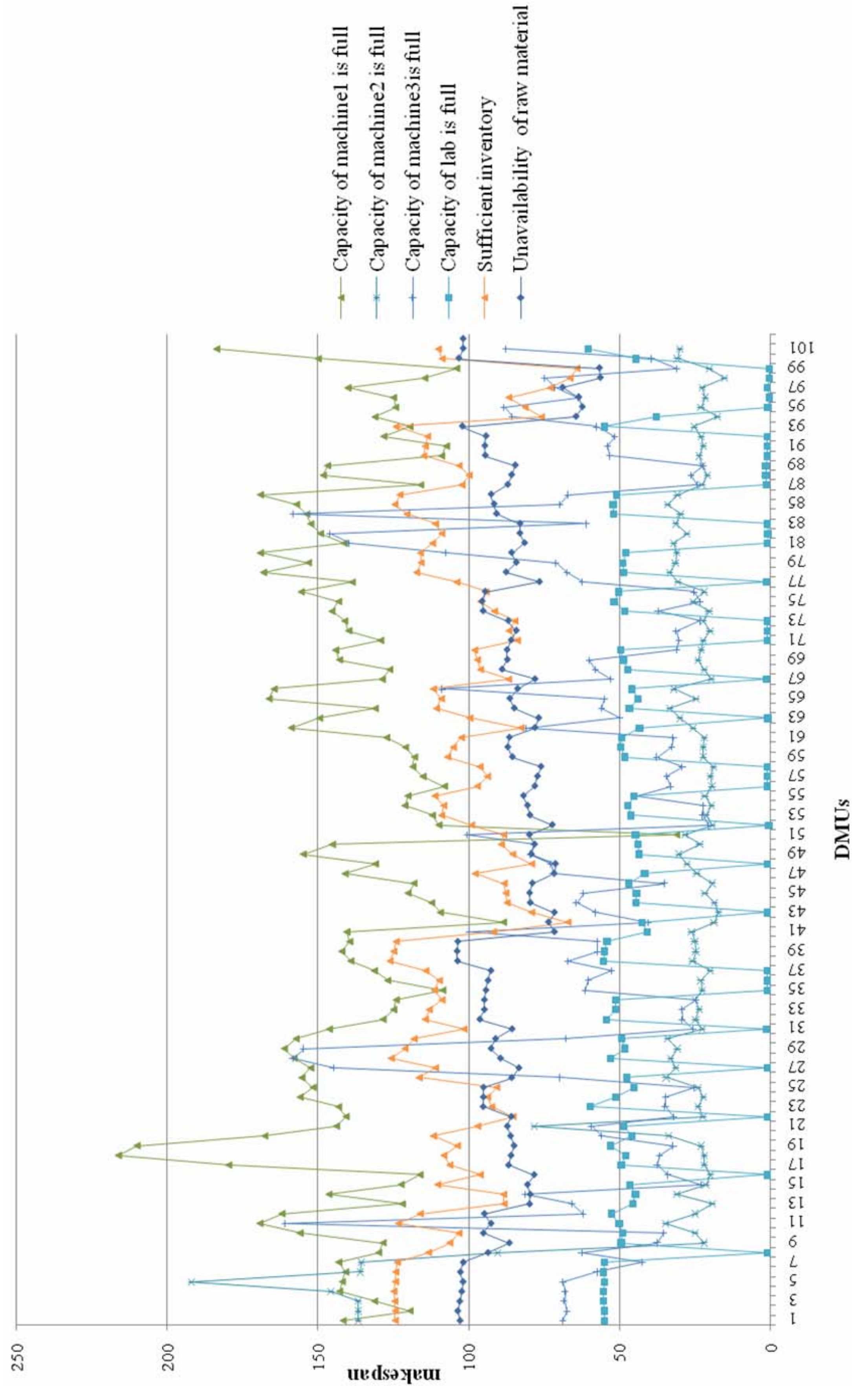



**Figure 18.** (continued).

and the outputs are constant and pre-determined) and output-oriented approach (the inputs are constant and outputs are decision variables). Selecting an approach depends on control extent of inputs and outputs by managers (Battese and Coelli, 1998). Sueyoshi and Goto (2010) have combined operational and environmental efficiency measurements (desirable and undesirable variables) and presented two types of unified efficiency model. The first unified output-oriented model proposed by them is formulated as follows:

$$\max \sum_{i=1}^{e} R_i^x s_i^{xy} + \sum_{r=1}^{t} R_r^y s_r^y + \sum_{i=1}^{e} R_i^x s_i^{xz} + \sum_{f=1}^{h} R_f^z s_f^z$$

s.t.

$$\begin{aligned} & \sum_{j=1}^{n} x_{ij}\lambda_j^y + s_i^{xy} = x_{ik}, \quad k\text{th organization} \\ & \sum_{j=1}^{n} y_{rj}\lambda_j^y - s_r^z = y_{rk} \qquad (1) \\ & \sum_{j=1}^{n} \lambda_j^y = 1 \\ & \sum_{j=1}^{n} x_{ij}\lambda_j^z - s_i^{xz} = x_{ik} \\ & \sum_{j=1}^{n} z_{fj}\lambda_j^z + s_f^z = z_{fk} \\ & \sum_{j=1}^{n} \lambda_j^z = 1 \\ & \lambda_j^y, \lambda_j^z, s_i^{xy}, s_i^{xz}, s_r^y, s_f^z \geq 0, \\ & \quad j = 1, \cdots, n;\ i = 1, \cdots, e;\ f = 1, \cdots, h;\ r = 1, \cdots, t; \end{aligned}$$

In which, $X_j = (x_{1j}, x_{2j}, \cdots, x_{ej})^T$, $Y_j = (y_{1j}, y_{2j}, \cdots, y_{tj})^T$, $Z_j = (z_{1j}, z_{2j}, \cdots, z_{hj})$, $\lambda_j^y$, $\lambda_j^z$ and $\lambda = (\lambda_1, \cdots, \lambda_n)^T$ stand for column vector of inputs, desirable(good) outputs, undesirable (bad) outputs, the $j$th unknown variable for desirable outputs, the $j$th unknown variable for undesirable outputs and unknown variables, respectively. Also, $s_i^x$, $s_r^y$, $s_f^z$, $s_i^{xy}$ and $s_i^{xz}$ indicate slack variables related to inputs, desirable outputs, undesirable outputs, the $i$th input-related variable on desirable outputs and the $i$th input-related variable on undesirable outputs, respectively. Moreover, $n$ organizations is considered and it is assumed that $X_j$, $Y_j$ and $Z_j > 0$ for all $j = 1, \cdots, n$.

$Rs$ indicate the ranges and are computed as follows:

$$R_i^x = \frac{1}{\left[(e+t+h)\left(UB_i^x - LB_i^x\right)\right]},\ R_r^y = \frac{1}{\left[(e+t+h)\left(UB_r^y - LB_r^y\right)\right]}$$

and $R_f^z = \dfrac{1}{\left[(e+h+t)\left(UB_f^z - LB_f^z\right)\right]}$

In which, $UB_i^x = \max_j\{x_{ij}\}$, $UB_r^y = \max_j\{y_{rj}\}$, $LB_i^x = \min_j\{x_{ij}\}$, $LB_r^y = \min_j\{y_{rj}\}$, $UB_f^y = \max_j\{z_{fj}\}$, and $LB_f^z = \min_j\{z_{fj}\}$.

In this study, the best DMU is selected by using model (1) and considering the number of machines, the number of assistants of deputy, the general manager, the lab manager, the warehouse manager and the production manager and working hours as inputs, the production rates (to maximize) as desirable outputs and the lead times and cost (to minimize) as undesirable outputs (Tables 8 and 9).

The results of DEA are given in the Table 10.

The features of this study compared to the previous studies are indicated in the Table 11.

## 7. CONCLUSION

Companies need different strategies to achieve their business goals. The common strategies are to minimize the costs and lead times and maximize the production rates. The current study considers the integrated system imposed of business, maintenance and production process by incorporating errors to minimize total cost and lead

**Table 10.** DEA results (output-oriented unified model)

| DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank | DMU | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d37 | 1 | d18 | 11 | d68 | 21 | d39 | 31 | d53 | 41 | d100 | 51 | d95 | 61 | d48 | 71 | d21 | 81 | d67 | 91 | d45 | 101 |
| d23 | 2 | d96 | 12 | d1 | 22 | d38 | 32 | d82 | 42 | d77 | 52 | d36 | 62 | d10 | 72 | d25 | 82 | d91 | 92 | | |
| d83 | 3 | d58 | 13 | d8 | 23 | d22 | 33 | d47 | 43 | d13 | 53 | d88 | 63 | d70 | 73 | d41 | 83 | d16 | 93 | | |
| d98 | 4 | d42 | 14 | d89 | 24 | d64 | 34 | d60 | 44 | d5 | 54 | d50 | 64 | d24 | 74 | d15 | 84 | d102 | 94 | | |
| d51 | 5 | d87 | 15 | d7 | 25 | d44 | 35 | d74 | 45 | d4 | 55 | d101 | 65 | d30 | 75 | d11 | 85 | d31 | 95 | | |
| d94 | 6 | d20 | 16 | d78 | 26 | d69 | 36 | d93 | 46 | d66 | 56 | d52 | 66 | d62 | 76 | d27 | 86 | d14 | 96 | | |
| d85 | 7 | d54 | 17 | d90 | 27 | d97 | 37 | d72 | 47 | d84 | 57 | d3 | 67 | d55 | 77 | d2 | 87 | d17 | 97 | | |
| d73 | 8 | d63 | 18 | d9 | 28 | d71 | 38 | d57 | 48 | d32 | 58 | d6 | 68 | d79 | 78 | d35 | 88 | d26 | 98 | | |
| d86 | 9 | d92 | 19s | d75 | 29 | d61 | 39 | d34 | 49 | d59 | 59 | d46 | 69 | d65 | 79 | d80 | 89 | d12 | 99 | | |
| d43 | 10 | d81 | 20 | d19 | 30 | d33 | 40 | d76 | 50 | d29 | 60 | d28 | 70 | d65 | 80 | d40 | 90 | d56 | 100 | | |

**Table 11.** Features of this study compared to the previous studies

| | business | Maintenance | Production | Objective | | Human error | Information system |
|---|---|---|---|---|---|---|---|
| | | | | single | multi | | |
| Azadeh *et al*. (2008) | √ | | √ | √ | | | √ |
| Pinjala *et al*. (2006) | √ | √ | | | | | |
| Oke and Charles-Owaba (2007) | | √ | √ | √ | | | |
| Kjaer (2003) | √ | | | | | | |
| Bouvard *et al*. (2011) | | √ | √ | | | | |
| Gulledge *et al*. (2010) | √ | √ | | √ | | | |
| Kim and Park (2012) | | √ | | | | √ | |
| Heo and Park (2010) | | √ | | | | √ | |
| Liu *et al*. (2009) | | | √ | √ | | √ | |
| This study | √ | √ | √ | | √ | √ | |

times and maximize production rates, simultaneously.

Unique features of this study led to obtain a good and optimized system. Some causes of human error were identified and proposed methods to rectify them. Also, the optimal scenario for time between preventive maintenance was found by considering the other factors for the system being studied. Moreover, the methods were presented to remove the major bottlenecks of the integrated system.

## 8. SUGGESTION FOR FUTURE RESEARCHES

There are several extensions to this study which can be investigated in future researches:

- Preventive maintenance (PM) inspection period could be investigated in more details. Also the type and number of maintenance activities could be changed.
- It is possible to consider other multi-criteria functions. For example, average utilization of equipment, availability, average queue length and etc. could be added to the criteria of this research.
- It could be extended by considering extensive ergonomics factors like facility layout design.
- Also, the safety factor could provide another field for research.

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