Application of open Jackson networks for time and costs reduction in the quality control process in an electronic assembler

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Abstract

The queueing theory applied in the industry is very helpful when it is necessary to detect and eliminate production bottlenecks. There are processes that do not add value to the product, however, they are necessary, such is the case of quality inspection. In the electronics industry, this process is very important. The present study is focused on a company that assembles electronic products, whose final process is the quality inspection for car control centers, where the bottleneck of the assembly line takes place, raising the costs of the resources and workforce due to the long inspection process. The current state of the production line is analyzed, simulations are created, and a new model based on open Jackson networks is proposed, which allows the time and costs reduction in the assembly line. The comparison of the current process against the proposed new model is presented, the reduction of time and costs in the process is demonstrated, solving the initial problem.

Keywords
Queueing theory, Jackson Networks, Simulation, Quality control.

1. Introduction

Currently, the Mexican manufacturing sector is carrying out important innovations and investments that encourage organizations to apply strategies that allow them to perform better than their competitors, improving their productivity. This work was developed in a company dedicated to the manufacture of electrical products for control and distribution of energy. A recurring problem was the failure to comply with the production schedule during normal working hours, this forced the organization to work overtime to finish the production schedule, incurring in high operational costs in the manufacturing system.

The bottleneck was identified by top management, it was located in the product inspection area where long waiting lines were observed as well as the use of overtime to comply with production orders resulting in high operational costs as mentioned above. Currently the production area is made up of 11 work cells that count with three employees each, one of them assembles the unit, and the other two make the wiring. These cells deliver a total of 78 units on average per day to the quality inspection area. According to the original status there were 3 inspection stations in the area of quality inspection, in each of these there was an inspector, who is responsible of perform two operations, one of these is the inspection of the unit's wiring and the other one is the electrical test of the unit, at the end of which the unit is released. The average speed of both inspection operations together is 3 units per hour. All different models of units can be tested in any of the three stations. The work shift lasts 9 hours, but if the inspection operation is not finished, the quality inspectors have to stay overtime. Accumulation of extra time up to 18 extra hours per inspector per week was common in the original situation. Each inspector earns a salary of $ 390 pesos per day, the extra hours are paid according to the law. There are also other areas with inspectors trained to perform only visual inspections, they earn a salary of $ 290 pesos per day.

Figure 1 shows the average material quantity that is delivered to the quality inspection area on a daily basis, during the month of June 2017. As it can be seen, there are several days with quality inspection maximum capacity exceeded making thus pending work generates overtime costs.

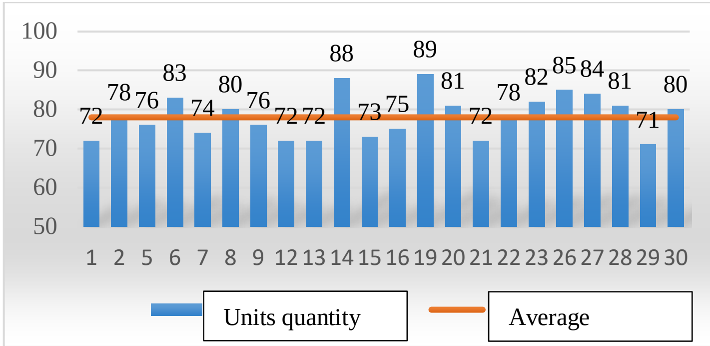

Figure 1. Production Units in June 2017

The objective of this analysis is to reduce the waiting time for product inspection in the quality inspection area, thus reducing costs and eliminating bottlenecks in the production line through queuing networks, so that the approximate waiting time will be known, and also the proposed new time.

There are several contributions in literature related to this work. According to Heizer and Render (1997) there must be a balance between the cost of providing a good service and the cost of the waiting time of a customer or a machine, in some cases the capacity of the service can vary having personnel and unoccupied machines that can be assigned to specific service stations to reduce excessively long lines. Performance evaluation plays a key role in manufacturing system design and productivity improvement (Wu & McGinnis, 2012), a model was developed to characterize the manufacturing system performance by applying queuing theory, this model decomposes system queue time and variability into bottleneck and non-bottleneck parts while capturing the dependence among workstations accurately with little information. Bretthauer (1995) presented capacity planning decisions modeled as a network of queues with emphasis on manufacturing applications; his model addresses the interaction between capacity and performance of the queuing network system. Korytkowski et al. (2009) developed a model of a make-to-order manufacturing system which considers quality assurance influence on performance, the model enables finding the optimal configuration of inspection stations allocation using the queuing networks theory, specifically an Open Jackson Network with multiple customer classes. Schick and Gershwin (2005) described work done under GM funding to analyze how production system design, quality and productivity are inter-related in production networks and developing analytical as well as numerical methods that make it possible to evaluate, compare, and optimize the performance of competing designs.
Regarding to queuing network, modeling of manufacturing systems has been addressed by a large number of researchers, contributions and application of queuing theory in manufacturing context have been analyzed in detail by Govill and Fu (1999). Another review of queuing network modeling of manufacturing systems was described by Papadopoulos and Heavy (1996) who reviewed the extant literature related to queuing theory in manufacturing.
In general terms, the queuing networks are systems represented by several nodes in which a customer finishes its process in a node and can be moved to next node or make backwards transitions e.g, for rework if it fails a quality test in a supply chain, (Jackson, 1957, 1963), (Cañadilla and Román, 2016), (Gross et al. 2008). In other words a Jackson network is a system of service nodes with the following characteristics:
1. An infinite queue.
2. Customers arriving from outside the system according to a Poisson entry process.
3. Servers with exponential distribution of service times.
Customers move from one node to another or leave the system. (Hillier and Lieberman, 2015).

As mentioned before, there are extensive related research in the literature on queueing theory, Chen and Yao (2013) address the fundamentals of queueing networks, Chen and Xia (2017) studied a dynamic pricing and control problem in a service facility modelled as an open Jackson network to determine optimal admission prices and optimal service rates in order to maximize the long run average welfare of their system. Sigman (1990) studied stability of open Jackson networks, Bonald and Down (1999) studied stability of mixed (open and closed) Jackson networks

Hum et al. (2018) analyzed the probability of fulfilling customer orders within a promised lead time and study the problems of measuring and optimizing supply chain responsiveness using Jackson queuing network models. On the other hand, Mahdipour et al. (2013) analyzed a five-node open Jackson network and calculated the probabilities of total population overflow, individual buffer overflow and the average probability of missing the deadline.

By improving the current situation, the costs of extra time in the inspection area would be reduced in as well as the flow in the production line would not stop. There would be less work in process, and more space within the production line. These improvements would have a direct impact on the costs and delivery times of the product.

2. Methodology

As a first step, in order to understand the problem, plant tours to quality inspection area were carried out, additionally, staff interviews were conducted, and, furthermore, the production database was analyzed to confirm the bottleneck, noticeable by the large number of inspections pending units. At the end of the day, it was observed that the large number of units in queue was not reduced and even surpassed the space assigned for the inspection.

During the interviews with the operational staff, some employees mentioned the large amount of product stopped in quality inspection area, as well as the high cost of extra time used to comply with the production plan, they suggested some proposals to solve the problem in the inspection area.

Methodology used to solve the problem of waiting lines in quality inspection area is based on scientific method of operations research (Hillier and Lieberman, 2015) (Montufar et al., 2009), specifically queuing networks model of open Jackson networks (Jackson, 1957, 1963).

We want to reduce system cost C, thus we propose separating inspection tasks in two subprocesses, as first step a visual inspection is carried out at a cost k_2, consequently the electronic inspection is executed by specialized personnel with a cost k_3.

We propose a network model for the quality inspection process, which has two levels in the network, each node in the process has an arrival rate λ_i of units and a service rate μ_i with a probability ϕ_{ij} of move to the next process or exit the system. Figure 2 shows the proposed process, it starts through arrivals from the assembly process (E1), after that the product is visually inspected at station (E2) which is a queue $M/M/c$. As mentioned before, at E2 it is determined by a visual inspection if the unit is rejected or accepted with a probability ϕ_{24} of being rejected at station (E4). If the product is accepted in E2, then it is sent to E3 to carry out the inspection of electronic components, to determine if it leaves the system or it is sent to reprocess with a probability ϕ_{41}, regardless of whether the product passes the test or it is classified as scrap and finally leaves the system. It should be noted that the complementary probability of going from E2 to E3 is $\phi_{23} = 1 - \phi_{24}$.

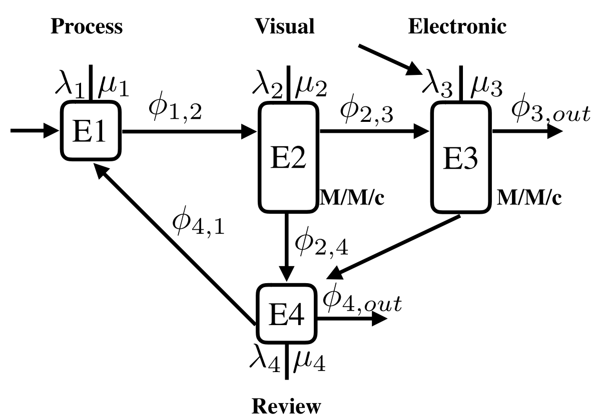

Figure 2 Network proposed for quality control process

Each node $i \in I$ is composed by c identical servers according to tasks separation in order to facilitate the analysis with service rate μ_i. There are external arrivals to the nodes 1 and 3 with arrival rates λ_2 and λ_3 while the arrival rates of λ_2 and λ_4 are internals from the network.

The company wants to avoid paying extra time, thus the waiting time w_i has to be reduced. It is important to note that the nodes 2 and 3 can be used as dummy nodes or integrated into the real process, node 1 is only a reference to the system and the cost of the node 4 is omitted.
We define c_i as the number of servers needed in each node i, then the total cost of the system is given by (1).

$$C = \sum_I c_i * k_i * w_i \tag{1}$$

Subject to

$$\sum_I c_i \leq m_i \tag{2}$$

$$w_i = \frac{L}{\lambda} = \frac{L}{\sum_I \lambda_i} \quad \forall\ i \in I \tag{3}$$

$$L = \sum_I L_i \tag{4}$$

$$\rho_i = \frac{\lambda_i}{c_i \mu_i} < 1 \tag{5}$$

$$L_i = \frac{C(r,c)\rho}{i - \rho} \quad \forall\, i \in I \tag{6}$$

Therefore (2) determines the limit of servers for each station according to the model, (3) determines the waiting time in the system, (4) the queue in the system, (5) limits the usage rate ρ_i and (6) determines the queue length, where $C(r,c)$ is C-Erlang function.

3. Experimentation

The data necessary for the analysis and formulation of the mathematical model were obtained from the database of finished product in the assembly line and from the areas prior to the quality inspection.

The arrival rate to the inspection process from the production department is 8.7 units per hour, it is estimated according to the proposal of the new network based on the task separation, the visual inspection and electronic inspection have service rates of 7 and 5 units per hour respectively and also these have a cost of $32.22 MXN and $43.3 MXN respectively.

The model was optimized through the use of R software supported by the *queueing* library for simulation and optimization. The optimum number of servers for the proposed model was found. Table 1 is a comparison of the current process against the proposed network and a summary of results of the new model in terms of server utilization, average of elements in the queue, average waiting time and cost. We can verify the cost reduction although the number of inspectors is increased, it is compensated by the waiting cost in the system.

	Actual (hrs)	Propossed (hrs)
Server utilization	0.9667	0.50
Average in the queue in system	27.1926	8.0478
Average waiting time in system	3.4589	0.829
Costs x hour	$ 151.00	$ 82.55

Table 1 Comparison between the traditional system and the proposed.

Table 2 shows the averages of the network, column 1 indicates the node or station, column 2 (L_i) indicates the average of clients queued for each node, column 3 indicates the average waiting (w_i) time for each node in the system, and column 4 (ρ_i) indicates the use of each server in the system. Note that the inspection nodes E2 and E3 greatly reduce waiting times and queue length.

Node	L_i	w_i	ρ_i
E1	0.2318678	0.02390390	0.1882246
E2	4.4095072	0.45458837	0.7986101
E3	2.9268176	0.30173377	0.6704912
E4	0.4796938	0.04945297	0.3241845

Table 2 System behavior of the proposed network

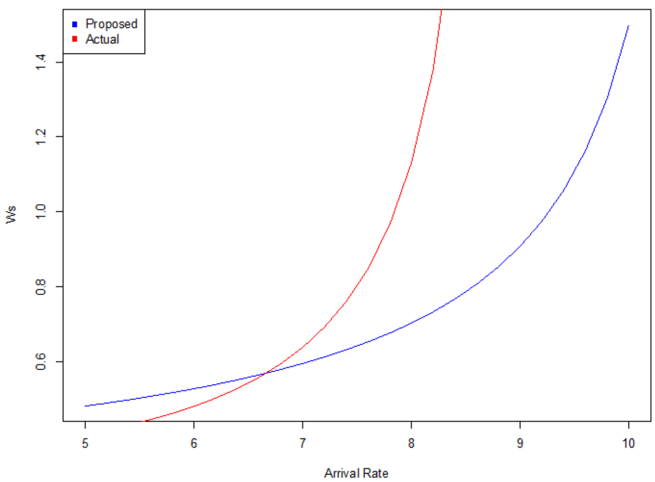

Figure 3. Comparison of the current state against the proposed model for the waiting time in the system

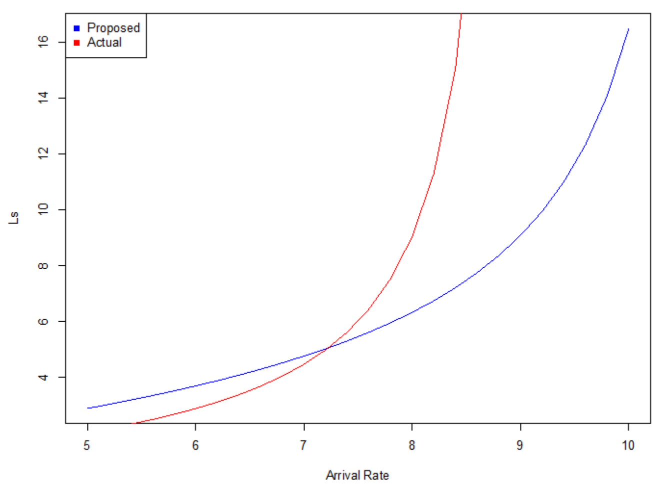

Figure 4. Comparison of the current state against the proposed model for the system queue

We can graphically see the improvement using the proposed model, Figure 3 shows the improvement of waiting times in the system even when the arrival rate is increased is much more efficient the proposed model and can support 3 or more additional units per hour. Figure 4 shows the queue in the system and we can see a lower exponential growth compared to the current state of the system.

4. Conclusions

The proposed system of separating the inspection tasks has shown great efficiency to avoid the product long waiting queues in the system, in addition the inspection costs are reduced. The cost is reduced significantly, and the overtime cost is almost eliminated, which considerably increased the quality inspection total cost. Additionally to the cost reduction, the bottleneck observed in this area is also reduced. Since concentrating specific tasks per worker, service rate efficiency is increased.

In order to maintain the efficiency of the inspection process, it is suggested that the following conditions be met: The number of electronic inspectors should not be less than the number of visual inspectors. Inspection tasks should not be combined, that is, specific tasks improve the speed of the inspection process. In case production increases, a re-evaluation of the model should be considered to find the right amount of quality inspectors.

In general, the industry does not run the risk of increasing some resources to improve the process, because there is a lot of uncertainty about cost reduction, however, when using appropriate simulation and optimization tools as shown in this document, there is a lot of certainty about the final result.

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Biographies

Leonardo G. Hernandez-Landa holds a BSc. in Industrial Engineering from ITSPe in Veracruz, México and earned his PhD in Engineering from the graduate program in System Engineering at Department of Mechanical and Electrical Engineering, Universidad Autónoma de Nuevo León (UANL). Leonardo is currently a Professor of operations management at Department of Industrial Engineering, UANL in San Nicolás de los Garza, México, where he joined in 2016. Dr. Hernandez' research has primarily focused on methods for solving difficult discrete optimization problems arising in logistic, routing and transportation systems. Previously, he has conducted funded research on vehicle routing problems with accessibility and route design. Dr. Hernandez is a SNI Fellow second highest country-wide distinction granted by the Mexican System of Research Scientists, where he has been a member since 2017. Dr Hernandez live very happily with his wife and family in Apodaca Nuevo León, México.

Argelia Vargas-Moreno. BSc. in Industrial Engineering with minor in Management and Master of Industrial Engineering by the UANL. Chair of department of Industrial engineering and management. Full time professor and taught undergraduate and graduate courses such as Industrial Engineering, Methods engineering and Operations research. Worked as project engineer at Hylsa, at TUBACERO and IMSA. She has been recognized by the SEP with the PRODEP certification; Professor Vargas-Moreno is Member of the IISE and is the faculty advisor of student chapter # 358. Her academic publications include books on the following topics: Industrial Engineering, methods engineering, statistics, probability and accounting.

Elva Patricia Puente Aguilar is a Professor of Industrial Engineering and Management area in the Universidad Autónoma de Nuevo León since 2010, teaching courses such as Industrial Engineering, Work Study, Manufacturing Processes, Quality Culture and Production Control. She earned B.Sc. in Industrial Engineering with minor in Management and Master in Business Administration degree from Universidad Autónoma de Nuevo León. Currently she is a PhD student in Project Engineering at Universidad Internacional Iberoamericana. She has got ten years experience in manufacturing industry with expertise in the areas of material and production planning, manufacturing engineering, quality engineering and new products engineering. She has participated as co-author and speaker in conferences in Mexico and USA. Her research interests include design and optimization of operations and education and engineering linkage in production systems.

Patricia Gómez Fuentes. Industrial Engineer Manager earned the Master degree in Industrial Engineering Productivity specialty in 2011. She has 5 years of experience in the manufacturing sector in the area of training and instruction. From 2005 to date is a professor on the Chemical Sciences of the Universidad Autónoma de Nuevo León, giving the chair of Operations Research, currently holds the position of Coordinator of Student and Academic Affairs, Industrial Engineer Manager.