The Application of Spreadsheet Model Based on Queuing Network to Optimize Capacity Utilization in Product Development

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Abstract

Modeling of a manufacturing system enables one to identify the effects of key design parameters on the system performance and as a result make the correct decision. This paper proposes a manufacturing system modeling approach using computer spreadsheet software, in which a static capacity planning model and stochastic queuing model are integrated. The model was used to optimize the existing system utilization in relation to product design. The model incorporates a few parameters such as utilization, cycle time, throughput, and batch size. It is predicted that design changes initiated as a result of analysis using the model reduced subsequent manufacturing costs significantly and also can reduce the launch program by a few years, because confidence in the model justified the commissioning of full-scale manufacturing equipment when the product was still only at the concept stage.

Keywords: Manufacturing system, product design, spreadsheet model, utilization.

1. INTRODUCTION

Even though we have moved beyond the Industrial Age and into the information age, manufacturing remains an important part of the global economy. There is a need for the pervasive use of modeling and simulation for decision support in currentand future manufacturing systems, and several challenges need to be addressed by the simulation community to realize this vision [1].

Various factors should be considered before modeling manufacturing system. They are system complexity, degree of detail and accuracy, data and time availability, software availability, skill personnel, etc. Anyway, no single modeling tool is able to satisfy all these factors and for that reason several modeling approaches have been introduced. Generally there are two approaches used to model manufacturing system, they are simulation model and analytical model [2]. As shown on Fig. 1, the application of these two models can be differentiated based on data randomness time dependency. For the data randomness can be categorized into two models i.e. deterministic and stochastic. On the other hand for the time dependency it is also categorized as static models and dynamic models. The dynamic models are simulation models including deterministic models and stochastic models, and the static models are analytical models which include static capacity planning model and queuing network model.

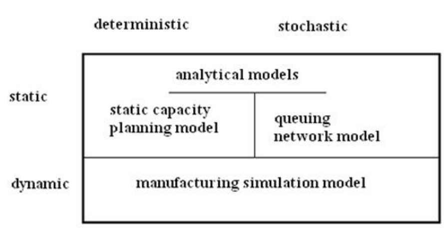

Fig. 1 Different modeling tools to model manufacturing system

Today, manufacturing systems modeling is often carried out according to the following steps [2].

1) Static capacity planning model: static and deterministic system behavior is examined quickly and roughly, using a spreadsheet model.
2) Stochastic model: stochastic features are described usually using a queuing network model.
3) Dynamic model: dynamic and detailed behavior of manufacturing systems is analyzed using a simulation model.

Each modeling approach mentioned above has its own strengthens and weaknesses; therefore the choosing of any model depends on mainly to the modeling objective.

Sometimes simulation model is also used as a tool for mathematical model validation. Koo et.al [2] used the estimated relative error parameter to measure the validity of mathematical model. He defined the estimated relative error as:

$$\text{Estimated relative error} = \frac{\text{spreadsheet value} - \text{simulation value}}{\text{simulation value}}$$

For a model validation purpose, Koe et. al [2] stated that a mathematical model is accepted if it has less than 32% of estimated relative error.

An example for spreadsheet model application has been presented by Shady et al. [3]. Their spreadsheet model based on program EXCEL Version 5 and be used to simulate the layout of electrical power transmission project in USA. Referring to their experience, they stated the benefits gained from the using of spreadsheet model:

- It is based on a software product that is widely used and readily accessible.
- It enables simplified modeling that is very easy to under stand.
- It facilitates the definition of data requirements.
- It has the potential to yield reduced data requirements.
- It allows quick turnaround which means quick feedback, and it provides a quick check for obvious data problems.

There were many studies about capacity analysis related to product development by using a certain mathematical model. These studies were conducted by a few researchers such as Koo et al. [2], Taylor et al. [4], Bermon et al. [5], Soundar and Bao [6]. However, these studies do not address the application in a multi-stage process which is the current trend in modern production lines. And also other than study by Shady et al. [3] that used only a spreadsheet model, the objective of this study is to describe a mathematical model which is as a result of combination between a spreadsheet and a complex queuing network model. The complex queuing network means a manufacturing system having multi-stage production line to produce assembling products. The mathematical model used in this study also considers the reliability factor. This reliability factor consists of normal yield, reduced yield and scrap yield parameters at a certain workstation. The assembling product of an automotive industry will be focus in this study.

2. RELATED WORK

Developing successful new products requires the ability to predict the life cycle impact of design decisions at the early stage of product development. Downstream life cycle issues include considerations on how product will be made, shipped, installed, used, serviced, and retired or recycled. Ignoring downstream issues leads to poor product design that may cause unforeseen problems and excessive costs downstream [7].

Unfortunately, downstream life cycle needs are difficult to predict accurately during the early design phases. To overcome this problem, many researchers presented the results of their study using a certain approach during product design.

Taylor et al [4] used a capacity analysis model to determine the maximum product quantity at electronic assembling facilities. The analysis is conducted on a set of product that consists of existing products mixed with the detail design of new product. In the case where maximum production quantity is not enough, the design of the new product should be changed in order to avoid production process at critical or bottleneck resources. By taking this action, production quantity will be increased to an acceptable level. However, this capacity analysis model does not consider the manufacturing cycle time of the system.

Bermon et al. [5] have studied a capacity analysis model at a production line producingvarious products. The approach made was focused not only on product design but also to have a decision support that enables quick analysis. They defined available capacity as the number of operations that can accomplished by the equipment in a day. When information about available equipment, products, and required operation are known, the equipment capacities that conform to both required throughput and existing limitations are allocated. Cycle time data and capacity are allocated at level below the existing available capacity. The differences between the existing available capacity and allocated capacity are referred to as contingency factor. A good contingency factor will prevent the queuing time average of equipment groups from exceeding the processing time determined before. The queuing model approach was used to model the relationship between utilization and queuing time. By using this approach they can verify the capacity of manufacturing system in terms of capability toachieve the required throughput for a reasonable manufacturing cycle time.

A few researchers described capacity planning approaches as a part of planning andcontrol systems of traditional manufacturing [8, 9]. These approaches identify how many times, when, what type, and where manufacturing system should increase its capacity in order to obtain the required throughput. Therefore its general objective is to minimize equipment cost, inventory, and cycle time. There are many other models that are not very significant and also less accurate. Furthermore, these models do not include applications for multi-stage manufacturing system.

Soundar and Bao [6] presented a planning that relates product design effects to manufacturing system. They suggested the use of mathematical models and simulation to predict various performance parameters including manufacturing cycle time. The approach was however very general and no example were discussed in their paper.

Johnson and Montgomery as stated in [10] presented a mathematical formulation for the product-mix problem as a constrained LP

(Linear Programming) model. They found that many firms have benefited from the use of this LP model especially in making product-mix decision. In order to apply the LP model, many input data from the industry is required such as the minimum production level of each product type in the planning period, number of units of each resource that are required to produce one unit of each product type, and the amount of each resource available during the planning period.

Walid Abdul Kader [11] presented a study on certain parameters of modern production lines having a variety of product processes in a batch production environment, which is in relation to capacity estimation. These parameters include the set-up time, the product mix, and the reliability of the stations composing the systems.

Based on discussion above, it can be stated that previous studies have shown the importance of developing a tool that supports product development activities which relates to the use of a mathematical model. This model considered many parameters such as cycle time, throughput, batch size, capacity or utilization, cost, inventory, and product mix. However, these studies do not address the application in a multi-stage process which are very important to be studied.

Queuing models can represent a wide variety of manufacturing systems. Often, the model is a network of queues, where each node represents a different manufacturing resource or workstation. Given information about the probability distributions of job arrivals and job processing times at each node, one can determine the average time in system for a job. In general, the processing time distribution at one resource affects the interarrival time distribution at the resource that departing jobs visit next. A review of a large set of queuing system models for transfer lines, production lines, and flexible manufacturing systems has been conducted [12]. Many researchers have studied open queuing networks [13] who present queuing network models for manufacturing systems and for semiconductor wafer fabrication facilities [14]. Chincholkar et. al [15] present the analytical model for estimating the total manufacturing cycle time and throughput of the manufacturing system. The development of this model follows the standard decomposition approach for queuing network approximations [13]. Their goal is to analyze these facilities quickly by avoiding the effort and time needed to create and run simulation models. They present numerical results that show how the queuing network model yields results similar to those of a simulation model. Queuing models are also the mathematical foundation of manufacturing system analysis software like rapid modeling [16], and software that integrates a capacity planning model and queuing network approximations [2]. For this integration software, they report that the approximations are reasonable when variability is moderate. The production system performance evaluation of Boeing's aircraft tube manufacturing plant has been analyzed by using complex queuing network [17]. This complex queuing network also was used to analyze PCB (printed circuit boards) production line of an electronic industry [18]. Anyway, this complex queuing model need to be more examined its validity by applying the model to analyze different type of industry other than aircraft and PCB industries.

In this paper, the manufacturing system is considered as a queuing network in which machines, products and buffers can be modeled as servers, customers, and queues, respectively. A work centre is composed of one or more machines and a buffer with unlimited capacity. Some machines are subject to down-time due to machine breakdowns, maintenance, or other such cases. Each job processing at work centre follows a first-come first-serve (FCFS) queue discipline. No re-entrant flow of job exists in the system, and batch size is the type of production type analyzed.

3. MATHEMATICAL MODELING

In this section, we describe the underlying computational algorithms used in the spreadsheet model. The algorithm, based on the queuing network, is the same as Wei-Thornton [17] used but we modify the original algorithms by considering reliability factor at each work station.

The proposed spreadsheet model in this paper has the fundamental procedure for evaluating performance measures as it is shown in Fig. 2. The procedure is adapted from that one developed by Koo et al. [2] although a few adaptation need to be done.

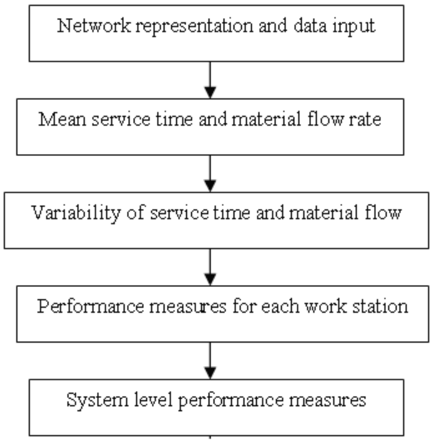

Fig. 2 Procedure to calculate performance measures on spreadsheet model

3.1 Input Data and Notation

In this study the input data and notations used are listed below.

B_i - job size of product i at release

c^s_{ij} - SCV (*squared coefficient of variation*) of the set up time

c^t_{ij} - SCV of the part process time

- SCV of job interarrival times for product i

c^d_j - SCV of interdeparture times at station j

m^f_j - mean time to failure for a resource at station j

m^r_j - mean time to repair for a resource at station *j*

n_j - the number of resources at station *j*

s_{ij} - mean job setup time of product *i* at station *j*

T_i - desired throughput of product *i* (parts per hour)

t_{ij} - mean part process time of product *i* at station *j*

y^n_{ij} - normal yield of product *i* at station *j*

y^r_{ij} - reduced yield of product *i* at station *j*

y^s_{ij} - scrap yield of product *i* at station *j*

Both s_{ij} and t_{ij} are based on the design parameters of product *i*.

3.2 Parameters for Material Flow

Release rate of product *i* (jobs per hour) x_i includes three parameters. These parameters are desired throughput, job size, and cumulative yield of product *i* (Y_i) through R_i. This R_i refers to the sequence of stations that product *i* must visit.

$$x_i = \frac{T_i}{B_i Y_i} \quad (1)$$

where $Y_i = (Y^n_i)(Y^r_i)(Y^s_i)$ (2)

for $Y^n_i = \prod_{k \in R_i} y^n_{ik}$ (3)

$$Y^r_i = \prod_{k \in R_i} y^r_{ik} \quad (4)$$

$$Y^s_i = \prod_{k \in R_i} y^s_{ik} \quad (5)$$

3.3 Parameters for Service Time

The mean and variability of the process time for an individual product are given in the input data. However there are many factors that affect this process time and therefore the adjustment of process time of a product *i* at a workstation *j* should be done. These factors for example are product mix, batch size, setup time, and design parameters of product.

Mean part process time of product *i* at station *j* is differentiated based on the type of station. These types are categorized into work station and inspection station. If a station is a work station, the adjusted process time is shown on formula (6). On the other hand, we use formula (7) if that station is an inspection station.

$$t^+_{ij} = B_i(Y_{ij})(t_{ij}) + s_{ij} + (1 - y^s_{ij})(s_{ij}) \quad (6)$$

$$t^+_{ij} = B_i(Y_{ij})(t_{ij}) + \{2 - y^s_{ij}\}s_{ij} \quad (7)$$

Another parameters for service time are aggregate process time (t_j^+) and modified aggregate process time (t_j^*) at station j. The formulas for these parameters are as follows:

$$t_j^+ = \frac{\sum_{i \in V_j} x_i t_{ij}^+}{\sum_{i \in V_j} x_i} \qquad (8)$$

$$t_j^* = \frac{t_j^+}{A_j} \qquad (9)$$

In this case V_j is the set of products that visit station j, and A_j is availability of a resource at station j which is formulated as:

$$A_j = \frac{m_j^f}{m_j^f + m_j^r} \qquad (10)$$

3.4 Approximation of Performance Measures

Given all parameters described in the previous sections, static performance such as resource utilization can be calculated. The resource utilization is one of the performance measures commonly used in manufacturing systems. Sometimes, it is the most important factor for decision making, especially when a large capital investment is needed. The average resource utilization at station j (u_j) is:

$$u_j = \frac{t_j^*}{n_j} \sum x_i \qquad (11)$$

Other than static performance above, we can also calculate stochastic performance which is cycle time parameter. The average cycle time at station j (CT_j^*), and the average cycle time of jobs of product i (CT_i) are formulated as follows:

$$CT_j^* = \frac{1}{2}(c_j^a + c_j^*)\frac{u_j^{(\sqrt{2n_j+2}-1)}}{n_j(1-u_j)} t_j^* + t_j^* \qquad (12)$$

$$CT_i = \sum_{j \in R_i} CT_j^* \qquad (13)$$

where is SCV of interarrival times at station j, and is SCV of the modified aggregate process time:

$$c_j^a = c_{j-1}^d \rightarrow 2 \le j \le J \qquad (14)$$

$$c_j^* = c_j^+ + 2A_j(1 - A_j)\frac{m_j^r}{t_j^+} \qquad (15)$$

Referring to the discussion above, the flowchart on Fig. 3 is used as a guidance to optimize the resource utilization:

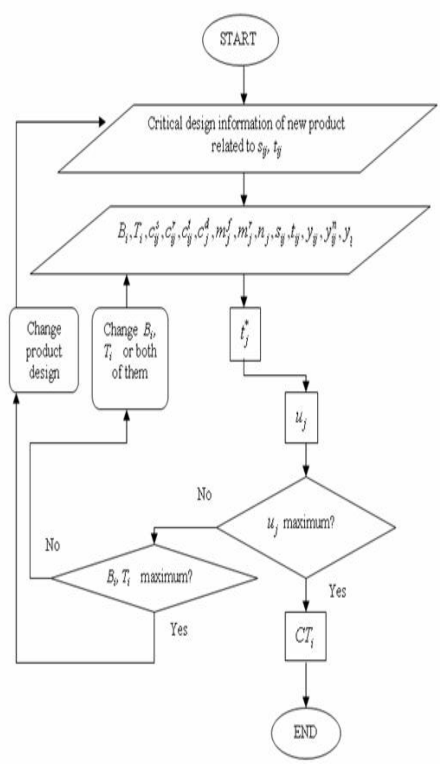

Fig. 3 The framework for optimizing resource utilization

4. IMPLEMENTATION MODEL

The spreadsheet model here is constructed using Microsoft Excel. To implement the proposed model on the spreadsheet, a spreadsheet program should be configured so that both its data structure and its computational methodology conform to spreadsheet characteristics. The spreadsheet program proposed consists of three main parts which are input block, intermediate result block, and output block. Another part is graph section which is related directly to output block. The function of the graph section is to show output results from output block in the form of graph performance. All the calculation procedures and formulas described in the previous section will be encoded to the intermediate result block and output block. On the other hand, all data

required for modeling a system are entered in the input block. Clearly, once the data are entered in the input block, intermediate calculations are performed before finding final performance measures displayed on the output block. These calculations are carried out in the intermediate result block. Intermediate calculations include parameters such as the mean and variability of interarrival time and service time for product *i* at each workstation. Figure 4 and 5 shows spreadsheet model for input block and output block - graph section,
respectively.

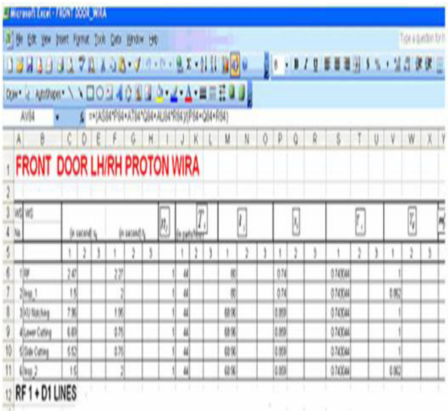

Fig.4 The spreadsheet for Input Block

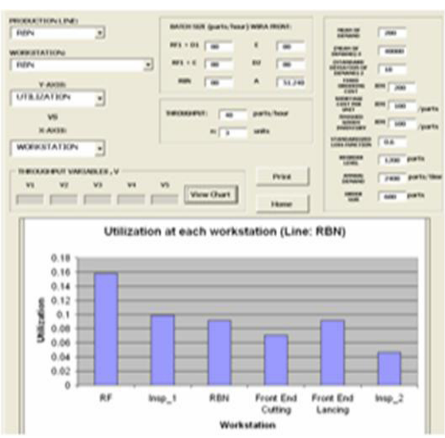

Fig.5 The spreadsheet for Output Block – Graph section

5. MODEL VALIDATION

A validation was performed by comparing the outputs of the spreadsheet model with those obtained through an existing simulation model i.e. Arena software©. In this case, the quantity and type of data to be entered to the spreadsheet model are the same with the quantity and type of data to be entered to Arena© model. The outputs to be compared are parameters of utilization and manufacturing cycle time. For this purpose we experienced with an assembling production line of local company manufacturing automotive car parts. The production line consists of many workstations as shown in Figure 6, and the type of product to be processed in this line is front door-sash as shown in Figure 7.There are twelve workstations, each of which is responsible for saw cutting, oil press cutting, plasma welding (surface), knocking, plasma welding (back), welding CO_2, manual welding, die matching, finishing (single), finishing (double), checking, and anti-rust oil spray.

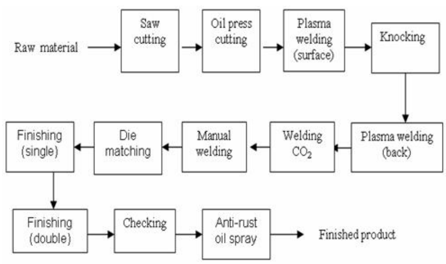

Fig.6 A schematic of workstations in an assembling production line

The experiments were carried out for two different cases. The first case is for 80 units/batch (batch size) and 31 units/hours (throughput), and the second case is for 80 units/batch and 35 units/hours. For the first and the second case, a comparison of the utilization and manufacturing cycle time parameters between two models i.e. spreadsheet model and simulation model is described in Table 1 and Table 2, respectively.

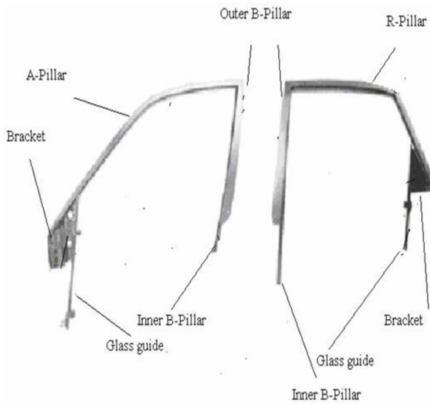

Fig.7 Front door-sash for car

Workstations	Assembling Production Line					
	Utilization			Manufacturing cycle time		
	Spreadsheet model	Simulation model	Relative error	Spreadsheet model	Simulation model	Relative error
Saw cutting	0.7254	0.7657	-0.05	1922.5	1876.0	0.02
Oil press cutting	0.0905	0.1027	-0.12	232.1	248	-0.06
Plasma welding (surface)	0.7768	0.8200	-0.05	2058.8	2009.0	0.02
Knocking	0.0771	0.0814	-0.05	204.5	199.5	0.03
Plasma welding (back)	0.6411	0.6767	-0.05	1699.1	1658.0	0.02
Welding CO_2	0.7264	0.7667	-0.05	1925.1	1878.5	0.02
Manual welding	0.2805	0.2562	0.09	719.4	638.8	0.13
Die matching	0.1972	0.2082	-0.05	522.7	510.0	0.02
Finishing (single)	0.7014	0.7404	-0.05	1859.0	1814.0	0.02
Finishing (double)	0.5423	0.5724	-0.05	1437.3	1402.5	0.02
Checking	0.0637	0.0479	0.33	145.5	125.0	0.16
Anti-rust oil spray	0.7388	0.7712	-0.04	1687.8	1889.4	-0.11
Average Relative Error			0.01			0.03

Table 1 Utilization and manufacturing cycle time at each workstation for input 80 units/ batch and 31 units/hours

Workstations	Assembling Production Line					
	Utilization			Manufacturing cycle time		
	Spreadsheet model	Simulation model	Relative error	Spreadsheet model	Simulation model	Relative error
Saw cutting	0.7922	0.9000	-0.12	2031.7	2157.0	-0.06
Oil press cutting	0.0905	0.1027	-0.12	232.1	246.4	-0.06
Plasma welding (surface)	0.7777	0.8789	-0.12	1994.8	2102.2	-0.05
Knocking	0.0741	0.0835	-0.11	190.1	200.3	-0.05
Plasma welding (back)	0.5396	0.6059	-0.11	1384.5	1448.3	-0.04
Welding CO_2	0.9797	0.9092	0.08	2512.8	2148.0	0.17
Manual welding	0.2805	0.2562	0.09	719.4	615.0	0.17
Die matching	0.1848	0.1688	0.09	474.0	405.2	0.17
Finishing (single)	0.6835	0.6146	0.11	1752.9	1464.2	0.20
Finishing (double)	0.6611	0.5866	0.13	1695.5	1389.8	0.22
Checking	0.0658	0.0438	0.50	145.4	105.0	0.38
Anti-rust oil spray	0.7908	0.6252	0.26	1748.3	1471.1	0.19
Average Relative Error			0.06			0.10

Table 2 Utilization and manufacturing cycle time at each workstation for input 80 units/ batch and 35 units/hours

Table 1 show that the average relative errors of spreadsheet results are 1% and 3% for utilization and manufacturing cycle time parameters respectively. This relative error value is far below 32% which is the limit value determined by Koo et. al [2]. In Table 2 the average relative errors is 6% and 10% for utilization and manufacturing cycle time, respectively. Based on this data, the spreadsheet model developed in this study has shown its validity for being applied.

6. CONCLUSION

Spreadsheet model discussed in this paper try to integrate deterministic-static features and stochastic feature. So far, not so much spreadsheet model that discusses such integration features. By using this developed spreadsheet model, there are many advantages can be achieved especially during product design stage of new product. This spreadsheet model enables the designer to make various changes in decision parameters (i.e. s_{ij} and t_{ij} are affected by design parameters) and examine the effects of the changes on performance measures very easily and quickly. In other word, the time needed for design phase can be reduced for a new product because redesign activities have been done in the earlier stage of design phase. In other word, design changes initiated as a result of analysis using the model are possible to be performed in the earlier stage of design phase of a product. So the time for launching that new product also can be reduced. In the earlier stage of product design, a broad range of decision variables has been examined. The study also showed that the validity of spreadsheet model is good enough to apply because the maximum value of relative error is 10%, far below the limit value suggested by Koo et al. [2].

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