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A Review of Methods for the Extraction of Accurate Formulas, the Calculation of Exact Solutions and the Optimal Buffer Allocation in Serial Production Lines

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Abstract: A major problem encountered in production systems is the design problem. This is frequently found in practice, because of the fact that a small change in the setup of system parameters can lead to significant gains or losses to the production cost, or to other measurements of performance. That is why it is of concern to the academics and practitioners since the idea of optimization of systems appeared in industry. This paper surveys concepts and methods related to the estimationof throughput of a serial production system aiming mainly in obtaining general formulas for this purpose. These formulas may be used for the design of manufacturing lines. The presentation of methods initiates from the earliest attempts with Markovian analysis and ends up with the use of genetic algorithms in order to extract accurate formulas. The complexity of the problem of the overall design of a production line attracts methods from computational intelligence which can be used to produce some general formulas. In the paper, there is also reference to optimal buffer allocation problems regarding serial production lines.

Keywords: Serial production lines, throughput, computational intelligence, design problems, combinatorial optimization

1. INTRODUCTION

In literature two types of models, for the design of manufacturing systems, can be found, (a) evaluative models that assume a particular configuration of the examined manufacturing system and performance measures are obtained, and (b) Generative models for the determination of an optimal solution to the system parameters considering the overall manufacturing system structure and an objective function to be optimized. It isan issue of crucial importance the existence of a synergistic relationship between these two types of models in order to design an optimal manufacturing system.An overview of the existing research in the area of evaluative and generative models of manufacturing systems can be found in two review papers,Dallery and Gershwin (1992) and Papadopoulos and Heavy (1996) and also in a number of books likeBuzacott and Shanthikumar (1993) and Papadopoulos *et al.* (2009), among others.

First the work on Evaluative models is considered. A variety of methods exist in order to evaluate the performance of a manufacturing system. There are two distinct approaches to the analysis of models of manufacturing systems, (a) simulation methods and (b) analytical methods. Analytical methods involve formal mathematical solutions to the problems. Due to the complexity of the mathematical models, two approaches are involved for obtaining a solution, exact and approximate methods.

An exact solution is obtained by an efficient computational procedure due essentially to the large number of associated states of the underlying Markov chain of such systems. Such an approach was that of Hillier and Boling (1967) where there was developed a numerical approach for solving reliable exponential and Erlang production lines. Papadopoulos and O'Kelly (1989), Papadopoulos, Heavey and O'Kelly (1989, 1990) and Heavey, Papadopoulos and Browne (1993), further developed this work by producing efficient numerical algorithms for generating the transition matrices for reliable and unreliable production lines with exponential and Erlang processing and repair time distributions and efficient solution methods.

In the domain of approximate methods belongs also the decomposition method which has been proposed by Gershwin (1987)and it is used for many types of systems, Dallery and Frein (1993), Di Mascolo, David and Dallery (1991). The decomposition approach as applied to a K-station line consists of decomposing the original line into a set of K-1 sub-lines. Each sub-line normally consists of two stations and an intermediate buffer which corresponds to a buffer of the original line.

The expansion method is an approximation technique developed by Kerbache (1984), published also in Kerbache and MacGregor Smith (1987) and extended by Jain and MacGregor Smith (1994). This method is characterized as a combination of repeated trials and node-by-node decomposition solution procedures.

An approximate technique was introduced by De Coster (1987) and Terracol and David (1987). Lim, Meerkov and Top (1990) published an approximation approach used in the analysis of transfer lines, which has come to be known as the aggregation method. This method works in a reverse way than the decomposition method.

The simulation method involves the representation of the real manufacturing system in a computer based model via the use of an appropriate simulation package such as Arena or eM-plant. There are many papers with reported results on simulation studies. Some books about this method are Altiok and Melamed (2001), Kouikoglou and Phillis (2001), Guide to Arena Standard Edition by Systems Modeling Corporation (1999), Papadopoulos *et al.* (1993), among others.

2. SERIAL PRODUCTION LINES

Buzacott (1967) describes the first theoretical projects which –as it seems-havefirst appeared in Russia around 1946. The most important work of those times was done by Vladzievskii (1952), when for first time the probability theory was introduced in an attempt to explain the behavior of automated transfer lines. The problem is of concern to researchers till today, because of the high competition rate and the dynamically evolving business environments. Yu,Retsker and Bunin (1964) gave curves based on Vladzievskii's work which enabled the economic optimum number of sections into which a line should be divided to be found. Buxey *et al.* (1973) presented a survey with a wide variety of phenomena such as line balancing, human factors, parallel stations, flexibility, allocation of part types to production lines and the effects of buffer stock.

In this paper the main focus is given on the serial production lines, with intermediate storage spaces. A K-station production line with K-l intermediate buffers is a system in which, each part enters the system from the first station, passes in order from all the stations and the intermediate buffer locations, and exits the line from the last station. If a station has completed processing and the next buffer has space available, the processed part is passed on and the station starts processing a new part that is taken from its input buffer. If the buffer has no parts, the station remains empty, until a new part is placed in the buffer. This process causes the well-known phenomenon of blocking and starving in manufacturing.

The whole system operates under the assumption that the first station is never starved and the last station is never blocked. This means that is concerned the saturated model which has the maximum throughput undependable from factors out of the system. All used random variables are independent random variables.The processing (service) times at each station are assumed to be independent random variables following a common distribution, with mean service rates, μ_i.,$i=1,2,\ldots,K$. In addition a station may stop working (breakdown) or not. If the system has failures then the time which the station operates normally is a random variable also. Figure 1 represents a K-station line having *K-1* intermediate locations for buffers, whose capacity is denoted as C_2, C_3,.... ,C_K. Transition times are equal to zero.

The failures are single machine failures and when a failure occurs, the work resumes exactly at the point it stops without scrapping of parts. The basic performance measures in the analysis of production lines are the mean production rate or "throughput" and the average work-in-progress *(WIP)* or equivalently the

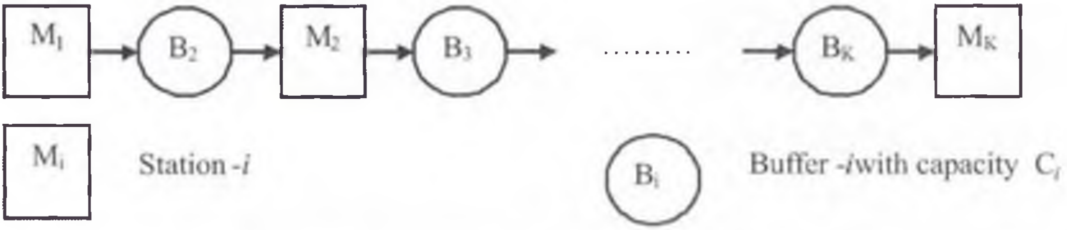

Figure 1: A serial production line (K-stations and K-l buffers)

average production time. Note that the number of feasible allocations of *N* buffer slots among the *K-1* intermediate buffer locations increases dramatically with *N* and *K*.According to the majority of related literature, the previous system is treated with some assumptions:

*Blocking issues:*Usually appears the situation "Blocking-After-Service" (BAS). This happens when for the machine M_i, the downstream buffer is full at the time of task completion, see Gun and Makowski (1989), Onrural and Perros (1986), Perros (1989). On the other hand "Blocking-Before-Service" (BBS) happens when the machine can start processing a part only if there is a space available in the downstream buffer. Otherwise it has to wait until a space becomes available.

*Processing time:*Processing time is the time what a machine needs to complete a task. This time could be constant or variable and then it supposed that is a random variable which follows a common distribution for each machine. Each processing time is independent of one another. Usuallyis used deterministic (constant) elaboration time or exponential distributions, geometric distributions, Erlang distributions,Coxian distributions and phase-type distributions, see Kleinrock (1975) and Neuts (1981). It is significant for the use of prior distribution the "memoryless" property of exponential distribution though we know from empirical studies, e.g. see Dudley (1963), Dudley (1968), Murrel (1962), Slack (1982) among others, that it is not suitable for representing real repetitive task time distributions.

Failures and repairs: The test system can consist of reliable machines (without damages) or it can have damages and then the machine should be repaired and it is not able to elaborate parts. Then the machine is treated as unreliable machine which corresponds to more complicated systems. Two types of damages are discussed by Buzacott and Hanifin (1978), the "Operation Dependent Failure" (ODF) and the "Time Dependent Failure" (TDF).

Some researchers extended the basic model to approximate more closely the actual systems. Mintenburg (1987) and Lavenberg (1975) for example, deal with the calculation of the variance of a transfer line's behavior over a limited time period. The issue of scrap i.e. the rejection of bad parts is considered in Shanthikunar and Tien (1983), Jafari and Shanthikunar (1987). Ignall and Silver (1977) based on Buzacott's observation (1967) where was developed an approximation method for two state systems with multiple identical machines in each stage. Forestier (1980) replaced the single machines before and after the buffer with banks of machines operating in parallel. The same system studied by Mitra (1988) Iyama and Ito (1987), where they analyzed a line with parallel machines and exponential processing times by solving the underlying Markov chain. Dudick (1979) studied some restrictions due to limited repair personnel and Buzacott (1982) extended some Dudick's results. Finally, Commault and Semeny (1990) and Lin (1990) considered the possible effect of non-zero transfer time in buffers.

In practice a production system might be different. Each station might consist of some parallel machines, we also might have main production lines and some parallel lines or sub-lines, feeder lines, feed-forward lines, rework lines or loops, merge or split machines and scrap split machines. All these can exist simultaneously in one system. There are research reports like the paper by Dallery and Gershwin (1992) and Papadopoulos *et al.* (2009) and Li *et al.* (2009) and Demir and Tunaliand Eliiyi (2014) among others, who survey and present the complete literature with the different types of production systems.

3. ESTIMATIONS OF THROUGHPUT AND RELATIVE DESIGN PROBLEM WITH INTELLIGENT TECHNIQUES

The domain of serial production lines lacks the existence of general formulas for acquiring useful measurements and line characteristics, such as throughput. It is of great assistance to designers to have these general formulas to determine the throughput of production lines among other measurements of performance. For this reason in the past several attempts have been made in order to find a kind of such formulas. A number of formulas of this kind have been developed, based on insights from queuing theory, considerations and sometimes curve-fitting. The earliest paper proposing such formulas is that of Hunt (1956). In his work he analyzes a three-station line with exponential and no identical servers using a Markov process. He obtains a generalized formula for the maximum utilization. The expression is the ratio of a numerator polynomial that has degree eight and 22 terns. The denominator polynomial has degree seven and 24 terns. After this work Markov modelswere evolved as a tool for analyzing such systemsnevertheless there were difficulties in the number of system states, which increases dramatically in any extension of the examined system i.e. number of stations or use of an Erlang rather than an exponential distribution. This work has showed the difficulties associated with the huge number of states, i.e. for a production line with 20 workstations, whereeach one has 2 states in work or under repairand 19 intermediate buffers with each one has a capacity of 10 parts, the number of possiblestates of such system exceeds 10^{25}.

Many subsequent researchers extended his result. For exampleHilier and Boiling (1967), developed an exact analytical procedure for solving very short lines without intermediate buffers, as well as an approximating procedure for longer systems with exponential servers. Basu (1977) extended in his approximation other cases than the exponential case. Freeman (1968) and Anderson and Moodie (1989) obtained empirical formulas for utilization of the production line, based on regression analysis of various sets of simulation data. Knott (1970) offered a formula based on theoretical and intuitive reasoning. Rao (1975) worked on the integral equation approach introduced by Muth (1973) which was then used in Rao (1976) for the analysis of production lines with three stations and derivation of several closed form expressions for the throughput rate. In the approach three different models are treated. In the first model, two stations have exponential service times and one has fixed service time. In the second model, two stations have fixed service times and one has exponential service time. In the third model, the two outside stations have exponential service times and the middle station has uniform service time.

Mishra *et al.* (1985) derived two closed form expressions for the throughput rate of threestation lines in which the service time of the two outside stations was exponentially distributed and the service time of the middle station was either a gamma distribution or a hyperexponential distribution.

Muth (1977) and Muth (1987) developed an expression using both theoretical analysis and curve fitting procedures. Makino (1964), Muth (1984) and Muth (1987) offered formulas for the exponential and two-phase Erlang and distribution-free cases with no intermediate buffers between successive stations. In Muth (1984), a new approach is adopted and the holding model is introduced. Blumenfeld (1990) extended Muth's formula for throughput of a production line with variable processing times and buffers of finite capacities.

Martin (1993) later developed a model and he gave a predictive formula for utilization of an unpaced production line for any number of workstations any interstation buffer capacities and for realistic workstation processing time distributions,considering trainee and experienced workers. Papadopoulos (1996) using Muth's holding time model developed an analytical formula for the throughput of a K-station production line with no intermediate buffers and exponential processing times which may be different at the various stations of the line. A particular simpler formula was developed for the balanced line. In Blumenfeld and Li (2005) a simple formula for the throughput of a serial production line with workstations that are subject to random failures was obtained. The formula applies in the special case of a line with identical workstations and buffers of equal size. The limitations of seeking exact solutions to production line problems are related to problems arising from the number of states of such systems and the difficulties associated with a numerical approach.

Since the optimization of the pair evaluative and generative model is a combinatorial optimization problem, intelligent approaches seem to be appropriate methods for solving the large size of this problem in a reasonable computational time. Most of intelligent techniques deal mostly with the part of the generative model. In the general form models of this kind aim to maximize the throughput of a production line with parameters, the production rate of each station, the number of the parallel server at each station and the inter-station buffer size.

In the pure work-load allocation problem (WAP), the objective is to allocate a total capacity of K time units over K work-stations so as to maximize throughput given the machine specific buffers in the system. In the pure buffer allocation problem (BAP), the objective is to maximize throughput by allocating an overall buffer space of size N among the K−1 buffer locations, where each station has a fixed production rate. Finally, in the pure server allocation problem (SAP) the total number of servers in the system is fixed and the objective is to maximize throughput of the system by allocating an integer number of servers to each station given fixed station specific buffers.

In practice someone may meet combinations of the three previously mentioned problems. Towards this direction researchers worked and developed methods to deal with this problem. In Spinellis and Papadopoulos (1997, 1999) a description of simulated annealing in a BAP can be found. Spinellis, Papadopoulos and MacGregor Smith (2000) examined combinations of the above three types of allocation problems,using a robust generalized queuing network algorithm as an evaluative procedure and simulated annealing for optimizing production line configurations.

Shanthikumar and Yao (1988) dealt with the server allocation problem in multiple center manufacturing systems. They formulated the problem as a nonlinear integer program of allocating servers in a closed queuing network to maximize the throughput of the system. Ho *et al.* (1979) dealt with a gradient method for solving the BAP problem. Chow (1987) proposed a dynamic programming algorithm to solve the BAP. Jensen *et al.* (1991) also dealt with the buffer optimization problem in serial and diverging-branch (non-linear) configurations of production systems. They applied a classical dynamic programming algorithm for solving the problem by taking into account production system costs.

Yamashita and Altiok (1998) solved the buffer allocation problem by applying a dynamic programming algorithm associated with Altiok's (1989) decomposition method for analyzing the production line.Kubat and Sumita (1985) and Jafari and Shanthikumar (1989) also used dynamic programming approaches for solving the BAP in automatic transfer lines.In Papadopoulos and Vouros (1997) a model management system for the design and operation of production lines with the use of an artificial intelligence based technique among others is presented. In Vouros and Papadopoulos (1998) another knowledge based system that determines near optimal buffer allocation plans, with the objective of maximizing production lines throughput is introduced. Papadopoulos and Karagiannis (2001) and Spinellis and Papadopoulos (2000b) developed a genetic algorithm for solving the buffer allocation problem in unreliable and reliable production lines, respectively, with exponentially distributed service completion times. In Bulgak et al., the application of genetic algorithms on a BAP is described.Levantesi, Matta and Tolio (2001) presented a new search algorithm which in conjunction with a decomposition method for the performance evaluation of the production lines solved the buffer allocation problem very fast. In Spinellis and Papadopoulos (2000) a comparison between genetic algorithms and simulation annealing for solving the BAP in large reliable production lines is presented. In Tsakonas, Papadopoulos and Dounias (2001) and Papadopoulos, Tsakonas, and Dounias (2002) throughput is calculated for short exponential production lines by a formula through an application of genetic programming,and a near-optimal solution is provided.

4. CONCLUSIONS

In this paper a selection ofrepresentative methods used in the design of production systems was presented, mostly related to exact or approximate formulas throughput calculation and also to optimal buffer allocation problems. The work specifically dealt with the serial production systems with intermediate buffers and presented studies which aimat developing general formulas to calculate throughput. The problem concernsthe researchers for almost 70 years. The limitations due to large combinatorial complexity of the problem hamper the development of formulas that could be useful in both the design and operation of manufacturing systems.

In addition, a presentation of intelligent methods to optimize the design of the production line was given. Due to the growth of computing power and the development of architectures of parallel programming, the use of these methods could be extended further to the problem of calculation of throughput into larger systems approaching real lines. However research is required in this field in order to determine the way that the whole problem could be decomposed into sub-problems that can be reached more easily by these methods.

The next open problem to be tackled is the attempt to apply specific intelligent techniques,particularly capable in generalization, on sets of data concerning throughput evaluation from specific line characteristics using decomposition techniques, in order to obtain exact mathematical formulas. If the abovementioned formulas prove to be identical to those exact formulas that have been publishedin literature with the use of conventional methods for specific line settings, will establishthe use of intelligent techniques in future production line design.

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