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Machine Interference Problem: A Taxonomy and Critical Review

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Abstract

Machine interference problem has received attention in the literature because of its diverse industrial applications and articles on the subject are scattered in disparate journals. Hence in this paper, a critical review of the current trend in the research on machine interference problem is presented. An extensive search on academic data bases is the source of the articles considered in this review. Articles considered for this review are restricted to works published since 2005 but few articles published in 2004 are also included. A taxonomy of articles on the machine interference problem is provided based on modifications of the simple machine interference problem. Research issues and challenges on the machine interference problems are identified. Majority of the papers reviewed concentrate on the determination of steady state measures of performance for the machine interference problem. Cost analysis is included in many papers and direct search method is the main approach for finding optimal solution to the cost optimization problem.

Keywords: machine interference, machine interference problem, machine repair, machine repairman, server vacation, transient analysis, vacation model, standby, additional repairman, repairable system, multiple vacations

1.0 Introduction

In the basic machine interference problem, a set of $M<\infty$, similar machines which are subject to fail during use are under the care of a group of R identical operatives who attend to the machines when they are out of order. The operatives are always available to attend to failed machines and failed machines always wait for service. The operatives are called servers or repairers. There are no spare machines but when a machine fails and it is repaired, it is assume that the performance of the machine is not affected by the repair work, i.e. the machine is restored and it is as good as new after a complete repair. A detail description of the basic machine interference problem is given by Cox and Smith [1]. Since the early work on the problem, various versions and modification of the basic machine interference problem have been addressed in the literature because of the diverse industrial applications of prototypes of the machine interference models. Hence the bourgeoning literature on the subject are scattered in numerous journals. Although recent articles on the subject contain some useful review sections, such reviews are focused on the objectives of the article in question, and therefore ignore research issues and challenges in the broad subject area of machine interference problem. There have also been a number of review articles, vide Haque and Armstrong [2]. The review by Haque and Amstrong [2] was available online in June 2006 but the work was submitted in September 2004. Since then a number of articles have been published and our interest is to look at the extent the open problems then have been addressed. Therefore, articles considered for this review are restricted to works published since 2005 but few articles published in 2004 are also included. We also restrict attention to articles on machine interference problem only. Papers combining machine interference to other areas such as maintenance [3] are ignored. In the general context of queueing theory, machine interference problems come under queueing systems with finite source.

The following modifications of the basic machine interference problem have been studied in the literature:

1. Servers or operatives are not always available to attend to failed machines i.e. servers can go on vacations, e.g. Ke and Wang [4].

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2. There are spare machines available in the system. There may be different types of spare machines: cold, warm or hot spares, e.g. Jain et al [5], Sharma [6].
3. A server can also brake down (unreliable server), e.g. Wang et al [7].
4. Additional server or servers are provided for long queues of failed machines, e.g. Yue et. al. [8].
5. There may be different classes of machines, e.g., Iravani et al [9].
6. Broken down machines can balk or renege, e.g. Jain et al [5] and Shawky [10].
7. The repair can be outsourced, i.e. apart from using in-house repair facility, repair facility can be provided by another organisation e.g. Hong and Sarkar [11].
8. Repair process may consist of different stages or phases e.g. Jain et al [12].
9. A repaired machine may not be as good as new.

of interest in the study of machine interference problems are the measures of performance. These are the decision making variables. The commonly evaluated measures of performance are related to the following variables (see Ke [13]; Wang et al, **[**14**]**; Jain and Upadhyaya, [15]):

- number of failed machines in the system
- number of operating machines in the system
- number of spare machines in the system
- number of busy servers in the system
- idle servers in the system
- balking rate
- reneging rate
- operative utilization
- number of vacationing servers
- fraction of time machines are working (machine availability)
- waiting time

The steady state expected values of these variables are normally obtained due to the difficulties associated with obtaining the distribution or other statistics associated with the variables.

In this paper, a taxonomy and a critical review of articles on machine interference problem is presented. The rest part of this paper is organized as follows: In section 2, we present a taxonomy of the machine interference problem. We do this by considering the attributes of servers and machines. In Section 3, we review articles on machine interference problems. Finally, conclusions are in section 4.

2.0 Taxonomy of Articles on Machine Interference Problems

The usual method of classifying machine interference problem is to consider the arrival process, the service process and the number of servers. The current work on machine repair problem has gone beyond such classification scheme. Today we have machine interference problem where the inter arrival times cannot be described by a simple probability distribution, the number of servers is not fixed, the servers are not identical and so the service time distribution cannot also be described by a single probability density function for all servers. In this section, we attempt a taxonomy of the current work on machine interference problem under the headings: Server and Machines.

2.1 Server: Number, Availability, Reliability and Service Times

In the simplest machine interference system it is assumed that there are a fixed number of servers which are always available to attend to failed machines and that there is no change in their performance. This assumption has been modified in several directions. In this section, we shall consider the directions in which this assumption has been modified in the literature.

Table 1: classification of machine interference problem with respect to server.

AUTHORS		REGULAR SERVERS					RESERVED SERVERS		
	R	Homogeneous	Service Rate	Reliable	Vacation	R	homogeneous	Reliable	vacation
Jain et al [16]	1	yes		yes	None	1			yes
Jain et al [17]	1	yes		Yes	none	1			yes
Jain [18]	R	No	same	yes	yes	0	-	-	-
Wang et al [7]	1	yes	same	No	no	0	-	-	-
Chen [19]	1	yes	same	no	no	0	-	-	-
Yang et al [21]	1	yes	same	no	no	0	-	-	-
Ke et al [22]	R	yes	same	no	no	W	yes	no	no
Jain et al [5]	R	no	multiple	yes	none	R	no	yes	none
Ke and Wang [4]	R	no	multiple	yes	two	0	-	-	-
Ke and Lin [23]	R	yes	same	no	no	S	-	no	no
Jain and Kumar [24]	2	no	Not the same	no	no	R	no	yes	no
Wang et al [25]	1	yes	Two levels	yes	Working vacation	0	-	-	-
Yuan and Xu [26]	1	yes	phase	yes	Multiple	0	-	-	-
Ke and Wu [27]	R	yes	same	yes	synchronous	0	-	-	-
Hadad et al [28]	R	no	multiple	yes	no	0	-	-	-

2.1.1 Number of Servers

The assumption of a fixed number of servers has been modified to accommodate situations where we have regular servers and additional servers for long queues. Under this modification, the number of servers will vary from time to time depending on the queue length of failed machines. Articles that considered additional servers for long queues include Jain et al ([16] [17]), Jain [18], Jain et al [5], Yue et al [29]; Wang et al [25], Yue et al [8], and Sharma [21]. Articles that considered fixed number of servers include: Jain [18], Wang et al [7], Yang et al [21], Wang et al [25], Ke and Lin [23], Ke and Wu [27] and Hadad et al [28].

2.1.2 Availability of Servers

The assumption that the servers are always available has been modified to include cases where the servers can go on vacations. It is argued that the vacation period can be used to do ancillary work. Several vacation models have been considered in the literature and vacation policies can also affect the number of servers available in a system. Under vacation policy a server can take a single vacation or multiple vacations. In some cases all servers can go on holiday at the same time, or a group of servers can go on holiday at the same time. This is called synchronous vacation. Further, there are cases where some servers can go on holiday and others cannot go on holidays in the same system. In an N- Policy, a server takes vacations repeatedly until he or she finds that the repair facility has at least N waiting failed machines in the queue. Another type of vacation is working vacation. This is the case where the servers reduce the rate at which customers are attended to during vacation. In other words, under working vacation policy, the serve operates two level of service, one lower than the other. The lower service level is operated when the server is on working vacation. Articles that address vacation for the servers include: Ke [13], Ke et. al. [30], Ke and Wang [4], Yue et. al. [29], Jain and Kumar [24], Wang et. al. [31], Hu et. al. [32], Maheshwari et. al. [33], Yu et. al. [8], Yuan and Xu([26] [34]), Yue et. al. [8], Sharma [6], Ke and Wu [27].

2.1.3 Reliability

The assumption that the server is always available to serve a failed machine can be modified by taking into consideration the reality that the server can fail. In such situations, the servers are termed unreliable servers. Papers that have considered unreliable servers include: Wang et al. [7], Ke [13], Ke et. al. [22], Sharma [6], and Ke et. al. [35].

2.1.4 Service Times

In the basic machine interference problem, it is assumed that the service times of failed machines are independent and identically distributed. This assumption has been modified in different directions. The machines may be different and so, they may require different repair process, such as a specialist attention. In some cases, the repair process may be similar, but the rates may be different. For example, we have stated earlier that a working vacation can affect the serve rate of an operative. The queue length of failed machines is another factor that can affect the service times. Authors that have taken this into consideration include: Ke and Lin [23], Wang et. al. [31], Hong and Sarkar [11], Jain et. al. [12], Ke et. al. [35], and Wang et. al. ([36] [37]).

There are cases in which severs are not identical. When the servers are not identical, we say they are heterogeneous (not homogeneous). Jain and Upadhyaya [15] considered the machine interference system with heterogeneous operatives. When the servers behave alike, we say they are homogeneous. In majority of the articles reviewed, the servers are homogeneous. In some systems, there are spare servers or reserve servers. The attributes of the spare servers may be similar to those of the regular servers.

Table 1 shows the features of the servers in some of the articles considered in this review and the corresponding authors. The table shows the varieties in the ongoing work on machine interference problem with respect to the server. A new dimension in the machine interference literature is that in some cases a fixed number of servers are required for repair to take place in a broken down machine. Another innovation is the outsourcing of repair. In this case, a server is invited from outside when the in-house server is unable to complete the repair work in a specified time, Hong and Sarkar [11].

2.2 Machine Types

Various variations have been introduced in the literature on the types of machines attended to in the machine interference problem. In the simplest case, the machines are identical and have the same failure rate. In this case, we say the machines are homogeneous. The machines can also be heterogeneous in which case the failure rates differ from one machine to another, Iravani et. al. [9], Sharma [6]. Another complication is that some machines are regarded as spare machines and even here, the spare machines may be different. They may be cold, warm or hot, see Jain et. al. [16], Wang et. al. [7], Wang et. al. [14], Ke et. al. [30], Ke et. al. [22], Ke and Wang [4], Ke and Lin [23], Shen et. al. [38], Yue et. al. [29], Jain and Kumar [24], Hong and Sarkar [11], Sharma [6], Yuan and Meng [39], Yuan and Xu [26], Jain et. al. [12], Yue et. al. [8], Ke et. al. [35], Ke and Wu [27], Wang et. al. ([36] [37]) and Maheshwari and Ali [40].

Table 2 shows the attributes of the machines examined in some of the articles reviewed in this paper. Under spare machine in Table 2, if $S=0$, there are no spare machine in the system. If we have $S\neq 0$, it means the number of spare machines is $S \geq 1$. In some machine interference problems, a fixed number of machines are required for production to take place, Jain et al [5]. We refer to such system as systems requiring combined operations. In other cases, the machines operate independently.

2.3 Arrival Patterns

The arrival patterns are not different from those reported by Haque and Amstrong[2]

2.4 Nature of Results Obtained

Majority of the authors obtained steady state expected values of the measures of performance for the system. In some cases these steady state measures of performance are used to develop cost function for the system with the aim of obtaining prescription for the conditions for the system to operate optimally in terms of the number of servers to employ, the number of spare machines, the number of reserved servers, and the best vacation policy as the case might be. There are very few papers that address transient results.

Table 2: classification of machine interference problem with respect to machines.

Authors	REGULAR MACHINES			SPARE MACHINES		Methodology	Nature of Measures of Performance
	M	Homogeneous	Combined Operation	S	homogeneous		
Jain et. al [16]	M	Yes. Reneging allowed	no	S	Yes. Reneging allowed	Laplace transform	Steady state
Jain et al [17]	M	Yes. Reneging allowed	no	S	Yes. Reneging allowed	Recursive	Steady state
Wang et al [7]	M	Yes	No	S	Yes	MAPLE	Steady state
Jain [18]	M	No	No	0		Recursive	Steady state
Chen [19]	M	yes	no	0		Mathematical programming	Steady state
Yang et al [21]	M	yes	no	0		Recursive	Steady state
Ke et al [22]	M	yes	no	W	yes	Laplace transform	Steady state
Jain et al [5]	M	no	no	S	no	Matrix geometric and optimization	Steady state
Ke and Wang [4]	M	yes	no	Two types	no	Matrix geometric	E[F], E[Fq], E[O], [S1], E[S2], E[B], E[V], E[I]
Jain and Kumar [24]	M	yes	no	Mixed spare	heterogeneous	Recursive	Steady state
Wang et al [31]	M	yes	no	0	-	Maple software and optimization	Steady state
Ke and Lin [23]	M	yes	yes	S	no	Optimization	Steady state
Wang et al [25]	M	yes	no	0	-	Recussive and optimization	E[F], E[Fq], E[O], [S1], E[S2], E[B], E[V], E[I]
Yuan and Xu [26]	M	no	no	S	yes	and optimization	Steady state
Ke and Wu [27]	M	yes	no	S	yes	Matrix geometric and optimization	Steady state
Hadad et al [28]	M	No	no	0	-	optimization	Steady state

3.0 Overview of Current Research on Machine Interference Problem

In this section we provide a historical overview of articles on machine interference problems since 2004. The articles highlight the numerous modifications to the simplest machine interference problem. These articles were used to attempt a modern taxonomy of the research on machine interference problems as shown in Tables 1 and 2.

Jain et. al. [16] studied the reliability characteristics of a machine interference system with M identical machines and S warm standby machines with one removable server. The removable server operates an N-policy. Failed machines are allowed to renege (a failed machine may be removed from the queue without being serviced) when the servers are busy. Laplace transform technique was used to derive the explicit expressions for both the reliability function and the mean time to system failure. Jain et. al. [17] studied a similar system but used a recursive method to obtain steady state measures of performance. Jain [18] used a recursive method to study the multi-server machine interference problem. In the system examined, the number of servers changes depending on the queue length. Cost functions were derived based on the average number of customers in the system. Jain et. al. [5] extended the study to include mixed standbys (either cold or warm standbys) balking and reneging. Two modes of failure of the machines were considered.

Wang et. al. [7] studied a machine interference problem with M machines, S standby machines and a single unreliable server that is subject to unpredictable breakdowns. They obtained expression for the reliability of the system and the mean time to system failure with the aid of MAPLE software.

Chen [19] extended the machine interference models to fuzzy environments by regarding the machine breakdown rate and the service rate as fuzzy numbers. Using the concept of fuzzy number, two mathematical models were developed to give lower and upper bounds of the measures of performance. Extensive sensitivity analysis was carried. Pardo and de la Fuente

[41] also proposed the use of fuzzy concept for the analysis of machine interference problems. Simulation experiments were carried out. Robert and Ritha [42] studied machine interference problem using fuzzy sets. They show that when machine breakdown or service rates are fuzzy, the system performance measures of the machine interference problem will be fuzzy as well. By using function principle as a fuzzy arithmetical operator of fuzzy trapezoidal numbers they derived the performance measures of the system.

Wang et. al. [14] studied the machine interference problem with M identical machines, R identical operatives and S standby machines. In the system, a machine can be in a standby state, operating state, failure state, repair state and failed machines can balk (do not enter a queue), or renege (leave the queue after entering). Further, there is a switching device that changes the state of a machine automatically when the condition of a machine changes. The switching device can also fail. Furthermore, the repair of a failed machine that balked or reneged is outsourced and the state of such machines is changed immediately from failed to repair. Steady state measures of performance were proposed and an optimization procedure for obtaining the optimal values of the number of spare machines and the number of operatives simultaneously was developed.

Yang et. al. [21] used a queueing network model to solve machine interference problem with a single operator. The model was applied to an integrated circuit (IC) ink-marking machines in Taiwan.

Mishra [43] developed a cost model for the machine interference problem with homogeneous machines and multi-servers. The cost model was based on the expected number of customers in the system.

Shawky [10] considered a machine interference problem with a single server. The service has r stage with rate rμ. Failed machines can balk or renege. Steady state measures of performance were obtained for the system.

Cascaval and Cascaval [44] studied machine interference problem with M identical looms, served by one weaver. Using the superposition principle and a reduced semi-Markov chain they evaluated the efficiency of the weaving machines and the work load of the weaver: They obtained steady state result using the analytical and simulation techniques to demonstrate the effectiveness of the simplified analytical approach.

Ke [13] considered machine interference problem with M identical machines and an unreliable server who is responsible for maintaining the machines. The machine interference model developed is characterized by two vacation policies and state dependent service rate. Furthermore, he developed a profit model to determine the optimum number of machine to be assigned to the server at maximum expected profit per machine per the unit time. The work was extended by Ke et. al. [30] to a system with S spare machines, and R servers. The spare machines are used to replace any failed machine immediately. The servers take vacation of random length whenever all the operating machines are functioning. Thereafter, the servers operate two vacation policies when they return from the initial vacation. In the first policy, the servers operate an N policy with N=1. In the second policy, the servers do not go on holiday again. Under both policies steady state measures of performance were obtained and a cost model was developed.

Wang and Chiu [45] proposed a cost benefit analysis for a machine repair system with active and warm standby units. Three repair time distributions are compared.

Ke et. al. [22] studied the machine interference problem consisting of M operating machines with W warm standby and R unreliable servers. The spare machines are used to replace any failed machine immediately there is failure but the switching process between warm standbys a regular machine can fail. Ke et. al. [22] proposed expressions for the system reliability and the mean time to system failure.

Alazemi et. al. [46] used a variant of the machine interference model to propose a stochastic analysis of distributed coordination function.

Morales et. al. [47] studied the Machine interference model using Bayesian criteria and applied their model to a real problem in the aeronautical maintenance.

Shashiashvili [48] studied machine interference problem with n identical machines. He developed and solves a cost minimization problem related to the machine interference model.

Ke and Wang [4] studied the machine interference problem consisting of M machines with two types of spare machines and a finite number of multi- servers (repairmen). The server can leave for a vacation of random length when there are no failed machines awaiting repai At the end of the initial vacation, two vacation policies were operated. The first policy was an N=1 policy, and in the second policy, the servers do not take a vacation again and remain idle until the first failed machine arrives for service. The matrix geometric approach was used to find the steady-state probabilities of the number of failed machines in the system. The steady state probabilities were then used to derive usual steady state measures of performance and an optimization problem was solved to determine the optimal values of the number of two types of spares and the number of servers subject to a minimum specified level of system availability.

Ke and Lin [23] examined a manufacturing system consisting of M operating machines and S spare machines under the control of group operatives who repair the machines when they fail. The repair process may require several phases. Two models were developed. In model 1, the service process required two phases and in model two the service process required k>2 phases. In each model, the operatives may also breakdown during the service process. A profit model involving the allocation of operating machines, spare machines and the number of operatives was developed.

Jain et. al. [5] studied the machine repair problem with regular and reserved servers. The system has both regular and standby machines so that failed machines are immediately replaced by standbys if available. The standby machines consist of both warm and cold standbys. The failed machines may balk or renege. The matrix geometric method was used to obtain steady state measures of performance and a procedure for determining the optimal number of warm and cold standbys machines required for the desired level of quality of service was proposed. Jain et. al. [5] obtained transient results for the machine repair problem with regular and reserved servers where failed machines can balk or renege. The system has provision for the use of cold and warm standby machines and the reserved servers are turned on following a threshold policy. Further, a fixed number of functioning machines are required for the system to function in normal model otherwise it will operate in short mode. Jain and Upadhyaya [15] obtained steady state measures of performance for a similar system.

Ke et. al. [49] used the Bayesian method and Monte Carlo simulation to study the characteristics of a machine interference problem with two machines and one unreliable server.

Shen et. al. [38] considered a machine interference problem with warm standby. The change from a working machine to a standby when there is failure is automatic but the standby machine can fail when in a standby mode and the switching machine can also fail. The authors obtained the steady state properties of the measures of performance of the system.

Yue et. al. [29] studied the machine repair vacation model with warm spares and two repairmen. The first repairman is always available for serving the failed units while the second repairman leaves for a vacation of random length when the number of failed units is less than N. The repairman return from vacation if there are N or more failed units accumulated in the system (N-policy), otherwise the repairman goes for another vacation. Some performance measures for the queueing and the reliability of the system were obtained by them. Furthermore, they developed a cost model to determine the optimum N while the system availability is maintained at a certain level.

Jain and Kumar [24] considered a machine repair problem consisting of two heterogeneous servers and mixed spares (warn and cold) in the system. The two repairmen can go on vacation using two different N policies. Further, the two repairmen are used under different conditions. Failed machines are immediately replaced by spare machines (either a cold spare or a warm spare). A bi-level control policy was used to introduce the servers into the system. Recursive method was applied to derive steady state measures of performances.

Wang and Chen [50] gave a comparative study of the availability of three machine interference systems with three configurations using supplementary variable technique to obtain the expression for the steady state availability of each repair system.

Wang et. al. [31] studied the machine repair problem with working vacation. In a working vacation, the server works with different repair rates rather than completely abandoning the repair facility during a vacation period. The working vacation starts when the system is empty so that the first failed machine to arrive at the repair point will be attended to but at a rate lower than the normal service rate. Matrix-geometric method was adopted in the development of the model for stationary probabilities and MAPLE software program was used to obtain the system performance measures. The direct search method and Newton's method were used in the optimization phase of the study.

Hu et. al. [32] examined "a series-parallel repairable system consisting of one master control unit, two slave units and a single repairman". The repairman is allowed to observe a single vacation. Supplementary variable method is used to obtain steady state measures of performance for the system.

Engin [51] studied the machine interference problem using simulation. The author gave the computational intractactability of results for machine interference problem based on queueing theory as the reason for using simulation.

Personè [52] considered a machine interference problem with *M* operating machines, *S* spare machines and p parallel servers. The servers can take single vacation or multiple vacation or hybrid (multiple/single) vacation. Personè [52] presented argument to show that the proposed method is computationally efficient. This work is one of the papers that include an analysis of the time complexity of the proposed algorithm. Maheshwari et. al. [33] investigated the machine repair problem comprising M operating machines with K type of warm spares, multi-repairmen and multiple vacations. The repairmen enjoyed multiple vacations subject to queue length and the repair rate depends on the queue length. The matrix recursive approach was used to obtain steady state queue size distribution and other performance measures were derived.

Yuan and Xu [26] studied the machine interference problem with one repairer and cold standby. The operative is allowed to take multiple vacations. The authors included cost model to determine when the regular machines are replaced by a cold standby. Yu et. al. [64] used the discrete time and supplementary variables to study the machine interference problem where the servers can enjoy multiple working vacations. Cost analysis was included to determine the optimal service rate.

Ke and Wu [27] studied a machine repair problem with M homogeneous machines and S standbys and R servers. The servers can go on synchronous vacation. Under this vacation policy when a group of servers, less than R are free, they proceed on vacation. The study included an optimization procedure to determine the optimal value of R, the number of servers that can go on vacation at a time and the number of groups of servers that can be on vacations at the same time. The authors were unable to establish that the cost function used in the optimization phase of the study was convex. Ke et. al. [20] also studied a similar system.

Yang et. al. [53] considered a machine repair problem with an unreliable server that can take multiple vacations. Time dependent (transient) machine availability was obtained for the system using MATLAB software. The time complexity of the algorithm was not analysed.

Mishra and Shukla [54] studied the machine interference problem by focusing on the optimality analysis of machine interference with spares less than the number of servers. They also develop a cost function to study the efficiency and economic level of the queueing system. They use the cost factor to show that a queueing system is of greater application if the associated cost is optimum and if the associated cost is high it seriously affects the applicability of the queueing model.

Gupta et. al. [55] studied the Non-Markovian queueing system $M^x/G/1$ with server breakdown and repair times. They assume that customers arrives the system in batches of various sizes, but are serve one by one. Further, they assume that the repair process does not start immediately after there is a breakdown. They fixed a delay time waiting for the repairs to start. Using probability generating function they obtain steady state results in explicit and closed form for the number of customers in the queue and the average waiting time in the queue.

Hong and Sarkar [11] examined a machine interference system with a single machine, one standby machine and a special repair procedure. In the system, as soon as the operating machine fails, it is replaced by the standby. An in-house regular repairer starts the repair of the failed machine immediately and is allowed a fixed patience time T to complete the repair of the failed machine. If the operating machine fails while the previous machine is still under repair, the system is said to have failed. Whenever the system fails or the patience time T has elapsed then an expert is called in. The expert on arrival, repairs all failed units. Two methods are employed in the analysis namely the Laplace transformation technique, and the extended semi-Markov process method. The authors demonstrated that the extended semi-Markov process method is easier to use. Only steady state results were considered.

Jayaraman and Matis [56] studied machine repairman model as a finite population model. They describe finite population queueing model as a finite number of customers handled by either single or multiple numbers of servers. They analyse the classical machine repairman model in steady state to discuss the related performance measures. The variation of the underlying characteristics and assumption of this model lead them to developing and analysing a broader class of queueing problem motivated by the application and extension for future reading.

Sharma [6] studied the machine interference problem consisting of M operating machines with S spare machines (cold standby or warm standby or hot standby machines) and R servers. The machines have two failure modes and the servers are unreliable, i.e. they are subjected to breakdown. Sharma [6] developed the Chapman-Kolmogorov steady state equations for obtaining the probability of failed machines in the system and proposed that a recursive method can be used to obtain the results when $R = 1$ and that the solution will require a computer program for $R > 1$. Sharma [6] gave no indication of the behaviour of the results or the organization of the computer program. Sharma [31] studied machine repairable system with spares and two repairmen. One repairman is always available for serving the failed machine while the other server is always on vacations when the queue length is less than N. This type of vacation is called 'the partial server vacation'. At the end of vacation period the second repairman comes back from vacation if there are N or more failed machines in the system- N policy vacation, otherwise he goes for another vacation. The steady state measures of performance were derived and used to propose a procedure for obtaining optimal N. The system studied by Sharma is similar to systems where additional servers are provided for long queues.

Sahba and Balcıog˜lu [57] compared the use of a multi-centre repair facility for a machine interference problem to a pooled repair facility. In the multi-centre repair facility case, the failed machines are repaired on-site whereas in the pooled facility case the failed machines are transported to a single location for repair. The authors concluded that "when transportation costs are reasonable, repair shop pooling is a better alternative".

Yuan and Meng [39] studied a machine interference problem with a warm standby and one repairman. Laplace transform is used to obtain reliability indexes and some steady state measures of performance. Wu and Wu (2011) and Yuan and Xu [26] also studied a similar system.

Jain et. al. [12] studied a machine interference problem with heterogeneous servers. In the system, cold and warm standby machines are provided and failed machines can balk or renege. The repair process consists of primary and secondary repairs. Steady state measures of performance are obtained and a cost model is derived. An extensive numerical experiment was performed by the authors.

Yuan [58] used the discrete transforms method to analyse the machine interference problem with R servers than can go on vacations. The vacations of the repairmen are independent and identically distributed. Yuan and Xu [59] examined a machine interference problem with one repairman who can go on vacation. When a machine fails and it is repaired, the machine is no longer as good as new. Reliability indices of the system are derived. A similar model was studied by Yuan and Xu [26] and Yuan and Cui [60]. These studies relaxed the assumption that repaired machines are returned to their original state before a failure occurs. They demonstrate that inter-arrival time distribution may not be stationary. In more restricted sense, Hadad et. al. [28] proposed a model for the machine interference problem (MIP), with N machines in which each machine randomly requests different service types and each repairman can provide only one service type. The model was used to determine the optimal numbers of operators that are needed for each service type subject to cost minimization or profit maximization.

Yue et. al. [8] considered the machine interference problem consisting of warm spares and two heterogeneous repairmen. One repair man is always available while the other repairman can proceed on vacation of random length when the failed units are less than N, a fixed number. Steady state measures of performance of the system were obtained and a cost model was used to determine the optimum value of N. A recursive method was used to obtain the steady state measures of performance while a heuristic method was adopted for the optimization problem to determine N.

Ke et. al. [35] examined the machine interference problem with standbys and unreliable multiple repairmen. The machines can also be in several states before it is finally broken down. When a repair man breaks down, it must be repaired before it can resume the repair of failed machines. The repair rate is a function of the number of broken down machines. Matrix recursive method was used to obtain steady state measure of performance. A cost model was included in the analysis.

Sabri-Laghaie et. al. [60] studied the machine interference problem with M identical machines and R repairmen. The distribution of waiting time for machines in a repair centre was derived and the associated cost function was also formulated. Steepest descent and direct search methods were used to obtain optimal production cycle and repairmen.

Ampatzidis et. al. [61] applied the machine interference model to improve a harvest process.

Wang et. al. [36] examined the reliability and sensitivity analysis of a repairable system with standbys. A failed unit may be replaced by a standby immediately if one is available. Under a long queue, the repairer can increase his repair rate. Expression for the reliability function and mean time to system failure were obtained. This work was extended by Wang et. al. [37] to include cost analysis using different methods.

Wang et. al. [25] considered a machine interference problem with M identical machines and variable number of servers. The minimum number of servers is one and the maximum number of servers that can be allowed in the system is a decision variable R. Failed machines can either join a queue or balk. They used a recursive method to obtain analytical steady-state measures of performance. A cost model was developed to obtain optimal number of servers. Maple was used to generate computer based solutions.

Maheshwari and Ali [40] studied a machine repair problem with warm and cold spares, balking and reneging. In the system, there are R permanent repairmen, r additional removable repairmen, M regular machines, S1 warm standby machines and S2 cold standby machines. The system works with at least m operating units where but for normal functioning M>m units are required. If a regular machine fails, it is replaced by a cold standby machine if available; otherwise it is replaced by a warm standby machine. The additional repair men are engaged when the number of failed machines is more than R. The recursive method was used to obtain steady state measures of performance. A cost minimization procedure was used to obtain the optimal number of spares and repairmen.

4.0 Research Issues and Challenges

A common trend in the study of machine interference problem is the use of computer software to aid analysis of mathematical models developed for machine repair systems. Examples include the use of MAPLE by Wang et al ([7] [31]) and Yang et al [53] who used MATLAB SOFTWARE. This trend was not reported by Amstrong and Haque [2]. It should be encouraged especially in the development of transient result. It is a direct application of Picard's iterative method for the proof of existence of solution of initial value problem in ODE. However, there are relatively few papers that include the analysis of the algorithm used in terms of time complexity. This is very important for algorithm or methodology used for obtaining transient results for MIP models.

Some authors have introduced purely queueing theoretic concepts such as balking or reneging into MIP. This is good. But they have failed to discuss the implications of such concepts in the machine interference context. For example Wang et al [25] stated that "a failed machine which on arrival finds *n* □□*s* failed machines in the system, either decides to enter the queue with probability b_n or balks (do not enter) with probability 1- b_n". The question is how are those machines which did not join the queue repaired? Are they still returned to the system? Since the number of machines in the system at the beginning of operation is finite, MIP cannot be treated in the same way we treat queueing systems with infinite source. If we allow a proportion of machines to drop out either through balking or reneging then at some stage, there will be no machines in the system since the initial number of machine is finite. Therefore, it is important to address this issue in future.

A number of computational procedures have been reported for the same system. It will be a good idea to compare these procedures. Ingolfsson et al [62] reported such numerical comparison for approximation methods for nonstationary M(t)/M/s(t).

Despite the wide variety of theoretical models, report of actual case studies is few and far between. It will be nice for case studies to be reported. The initial work on machine interference started from a practical background.

5.0 Conclusion

In this work we review machine interference problem with server vacation. One common feature in most of the article survey is that their model produces only steady state results-which does not give the description of the system at any given time t. Grassman [63] stated that'' in this world everything is in constant change, and steady state solutions are therefore nonexistent''. This is one area of future research.

Our review also shows that only expected values of measures of performance are available. The need to develop measures of variations for the measures of performance has been recognised as worthwhile. This problem was suggested by Haque and Armstrong [2] and our survey shows that no work has been done in this direction.

Our literature review also shows that there is room for further research on machine interference problems with reliable server vacation. Most articles studied machine interference problems with unreliable server vacation. In particular; we hope to obtain transient results for the machine interference problem with reliable server vacation. This is in contrast to the majority of the results available in the literature. Also some author studied their machine interference problem with server vacation while others did not. Finding a bridge between both models is another area of future research. Also very few authors considered machine interference problem with spare machine and reserve servers, this area need more work.

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