Reliability Optimisation of Flexible Manufacturing Systems with Spare Tooling

A. A. Altumi, A. M. Philipose and S. M. Taboun

Industrial and Manufacturing Systems Engineering, University of Windsor, Ontario, Canada

Tool reliability plays an important role in the performance and justification of flexible manufacturing systems (FMSs). Failure of a single tool can cause downtimes over the entire system. This would cause due dates to be missed and can result in inferior products. Therefore, in order to justify the large capital investment associated with FMSs, the system must perform in a reliable manner to give an acceptable or required rate of return on the investment. In order to arrive at this objective, FMS reliability must be studied at the planning and design stages, tool failures pose a major obstacle to achieving this objective. In this paper, a mathematical model has been developed to determine the spare tooling requirement for the tooling system in an FMS, so that a desired system reliability is achieved and the cost is minimised. The influence of tool sharing on cost, reliability, spares requirement, and tool magazine capacity of the FMS are analysed. The tools and tool transporter are subject to general failure distributions.

Keywords: Flexible manufacturing systems; Nonlinear integer programming; Reliability optimisation; Spare requirements; Tool sharing

1. Introduction

Flexible manufacturing systems (FMSs) are designed to produce a trade-off between the efficiency of transfer lines and the flexibility of job shops. FMSs are able to accomplish this trade-off because of their reduced level of human interaction and their ability to eliminate the set-up times between consecutive operations.

Changing market demands and intense competition have contributed to the need for flexibility and automation in manufacturing systems. Although such systems promise flexibility, they also generate new problems. Misconceptions in the design or mistakes in implementation can lead to unreliable systems with low levels of availability, inadequate production efficiency,

Correspondence and offprint requests to: Professor S. M. Taboun, Industrial and Manufacturing Systems Engineering, University of Windsor, Ontario N9B 3P4, Canada. E-mail: taboun@uwindsor.ca

low reliability and high operational cost. A high degree of reliability is essential to justify the investments. When FMSs are employed for machining, assembly, or fabrication, they use sets of tools to perform different operations. Such tools wear out, break, or require resetting and maintenance to ensure successful operation. Industrial data indicates that tooling accounts for 25–30% of the fixed and variable cost of production in an automated machining environment [1]. A certain level of reliability is required of the tooling system to ensure uninterrupted production runs. Sufficient redundancies must be foreseen at the production planning stage in order to allow for the random failure of tools. Whereas the cost of redundancy is a negative factor, the additional reliability gained is a positive one. Therefore, redundancy is an issue requiring economic justification.

2. Review of Literature

Reliability is defined as "the probability that an item (system) will perform its function adequately for the desired period of time when operated according to the specified conditions" [2]. The relationship between average tool life and cutting velocity was developed earlier [3]. To provide the relationships between the feed, speed, and depth of cut for a given tool life, the extended tool life relationship was proposed [4]. These deterministic equations provide the expected values based on a slow-death mechanism of tool failure. Tool life, however, depends also on the stochastic arrival of single-injury events. In general, a failure rate function is best developed from tool-failure data. Machining economics based on a deterministic tool life concept yields inaccurate results. Therefore, the stochastic nature of tool life is represented by treating tool life as a random variable whose distribution is parameterised by the cutting conditions.

A heuristic solution methodology, which addresses the relationship between tooling issues and machining conditions, was developed [5]. Optimum machining conditions in conjunction with tool allocation was studied with the cost minimisation as an objective. A tool life constraint was added to the single machining operation problem (SMOP). This allowed for the inclusion of tooling issues such as tool wear and tool avail-

ability. In addition, a new cost measure was proposed to allow for possible trade offs among the conflicting decisions of tooling, machining conditions selection, and to link operational level decisions to the system level.

The production rate decided by feedrate, and spindle speed is used to optimise the system. It was shown that the cutting speed that minimises unit cost is less than the speed that maximises profit [6]. The model assumes that tool replacement can be made within the setup time of a workpiece. It was shown in a study that tool wear and maximum permissible feed and speed for a multipass turning operation can be more economical than single-pass operations [7].

Part- and tool-movement policies are among the basic approaches used for loading problems in an FMS. When the required tools to process a part are not mounted in the magazine, either the part may be sent to the machining centre where the required tools are available, or the required tools may be transported to the machining centre from another machining centre. The two strategies were compared; it was found that tool-movement policy was more advantageous [8]. Since parts do not move, there is no need to reposition the workpiece or recalibrate the position of the tool head, which results in higher cutting precision. In addition, a part is processed by only one machining centre. Since a part is delivered to the shop only when a machining centre is available, this policy results in lower work-in-process. A nonlinear programming model to load a set of tools on different machining centres, where each part visits only one of the machining centres for its entire processing, was proposed. The quadratic objective function is to minimise the amount of tool traffic among the machining centres with a reasonable workload balance. A heuristic was used to minimise the total number of tool exchanges, where the requisite, but unavailable, tools must be brought to the machine and the time needed to switch tools is significant, relative to the processing time [9].

Complex systems may contain some components, which fail frequently. It is sometimes not possible to reduce the failure rate of such components by improving quality. The system reliability is then improved by incorporating more redundancies at the locations where failures are expected. The reliability of an automated tool-changing system with carbide inserts and spares subject to Weibull failure distribution was analysed [10]. Using a recursive algorithm, an attempt was made to predict tooling-system reliability and determine the desired reliability and cost of spares combinations. A numerical approach was used to integrate the reliability function for each tool with different numbers of spares.

Two optimum redundancy algorithms, namely the Lawler–Bell algorithm and the new Lawler–Bell algorithm are presented [11]. These nonlinear integer-programming techniques are computationally precise but complex and often fail when applied to real-world situations. Dynamic programming, to allocate optimally the mean time between failures (MTBF), mean time to repair (MTTR) and the number of redundancies in a multistage system to achieve a given availability at minimum cost, was used [12]. A heuristic algorithm to solve the spares allocation problem for remote machines, in which machines were subsystems of a series system that would be used only for a specified period of time, is presented [13].

A methodology, which quantifies and includes reliability within the design frame of an FMS, was developed. This was done by using an efficient heuristic approach called "group method of data handling" or (GMDH). GMDH is a self-organisation technique, which was used successfully in environmental, ecological, social systems, and recently in manufacturing systems [14]. A review of different optimisation techniques was presented along with a genetic algorithm (GA) approach [15] to solve the general class of redundancy allocation problems. The GA was used on two different problems and compared with other techniques, it was concluded that the GA was very flexible and few restrictions were needed on the form of potential solutions. The GA results were consistently more favourable than results obtained with other compared techniques, however, owing to the stochastic nature of the GA search, convergence to the optimal solution could not be guaranteed

Although there are many papers on reliability optimisation, there is a lack of reliability-based modelling in the area of automated manufacturing systems. A greater emphasis should be placed on reliability considerations in the state-of-art of manufacturing systems optimisation.

2.1 System Configuration

The system under consideration consists of a number of machining centres (4 in this case). Parts enter the shop, if the local queue of the scheduled machine has the capacity to accommodate the batch to be reprocessed. Parts enter and leave the system by a common gangway. It is assumed that, in general, all the operations required to be performed on a part can be done by a single CNC machine in the flexible manufacturing system, as long as the required tools are available. The models, however, can accommodate the need to restrict a particular tool or operation to specific machine(s). Each machine has a tool magazine of a limited tool capacity. The tools are interchangeable between the machines, and the tool magazines are fixed to the machine.

2.2 Assumptions

When developing these models, the following assumptions were made, to simplify the modelling:

The demand for each part type is known in advance, and will not change during the production period.

All the spares of a particular tool type are assumed to be identical.

Tool failures are independent of one other. So, the failure of one tool does not affect the failure of another tool in the system.

A machining centre can perform all the required operations on the assigned parts, as long as the required tools are available in the tool magazine.

Machining parameters such as feed, spindle speed, depth of cut, etc. are determined before the production run, and do not change during it.