Simultaneous Optimisation of Control Factors in Automated Storage and Retrieval Systems and FMS Using Stochastic Coloured Petri Nets and the Taguchi Method

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Automated storage and retrieval systems (AS/RS) are playing an important role in modern manufacturing systems such as flexible manufacturing systems (FMS). The integration of AS/RS systems and FMS is very complex owing to the complexity of the individual elements. Stochastic coloured petri nets (SCPN) can be used to model, simulate and analyse such a system efficiently and realistically. In this paper, SCPN based simulation, aided by the Taguchi method of design of experiments, has been used for analysing the influence of important factors on makespan, unproductive travel time, and the mean flow time, and is supported by an example.

Keywords: Automated storage and retrieval systems; Flexible manufacturing systems; Optimisation; Stochastic coloured Petri nets; Taguchi method

1. Introduction

Automated storage and retrieval systems (AS/RS) are being used in modern manufacturing systems, such as flexible manufacturing systems (FMS), at an increasing rate [1]. AS/RS have been traditionally used as storage systems in warehouses and distribution centres. Available publications concerned with AS/RS are relatively few, and are limited to applications in warehousing. Storage methods, dwell-point selection strategies, order sequencing, and control are the main research issues in this field. Researchers have mainly used analytical tools, simulation, and more recently, stochastic Petri nets to address these issues.

Scheduling in AS/RS is a complex task comprising pallet assignment, storage assignment, and interleaving. Optimal scheduling, considering storage assignment policies, with and without interleaving, has received considerable attention [2–4]. In this connection, many restrictive assumptions, such as continuous rack, negligible loading/unloading times of pallets, first come first served (FCFS) rule for storage request handling, and fixed input/output location, have been made. Alternative dwell-point strategies and variable input/output locations are important to fully utilise the benefits of these systems. Bozer and White [5] considered these issues in developing analytical expressions for the travel time of a stacker crane with the assumption that the rack is continuous and storage is random. Methods using linear programming, to dynamically select the dwell-point of a crane when idle, have also been used to minimise the service response time of the crane [6].

The FCFS rule is widely accepted for servicing storage requests since, in most of the systems, the sequence of these requests cannot be altered owing to the conveyor loop. However, in the case of retrieval requests, this rule is not justified because these requests are nothing but entries in the computer’s memory, and these entries can be altered for a better performance. As a better alternative to FCFS, researchers have suggested a ‘nearest-neighbour’ retrieval sequencing policy when the crane is operating in a dual address mode [7].

On-board storage can be a valuable addition to the stacker crane of an AS/RS for multiple-part handling in a single cycle. The influence of on-board storage, in the context of a direct-access-handler serving a manufacturing assembly line and for in-process systems, has been analysed by Chow [8–10]. Elsayed and Stern [11] studied the effect of on-board storage in an order picking warehouse when the stacker crane is operating in single address mode.

Once an AS/RS is installed and becomes operational, the planned benefits can be realised through effective methods of control. Expert system based controller development [12] and an information systems based approach for the study of operational controls of AS/RS [13] are the notable contributions in this area.

A flexible manufacturing system (FMS), because of its flexibility, is a complex system [14–17]. AS/RS can support work-handling activities in a FMS. In such an integrated system the stacker crane of an AS/RS can also transfer parts...
system the stacker crane of an AS/RS can also transfer parts between machines besides performing the storage and retrieval tasks. Researchers have studied AS/RS and FMS individually but not as an integrated system (hereinafter referred to as a combined system wherever convenient), mainly owing to its high complexity.

Petri nets (PN) are well-established graphical and mathematical modelling tools, appropriate for systems exhibiting concurrency, asynchronism, conflict, deadlock and randomness [18,19]. PN and their several extensions have been widely used in a variety of applications including computer systems, local area networks, FMS [15–17], JIT [20] and more recently, AS/RS [21]. PN facilitate rapid model development, flexible and detailed modelling capabilities and fast execution.

In this paper, stochastic coloured Petri nets (SCPN), an extension of timed PN, have been used as modelling and simulation tools. Basic details of stochastic Petri nets are available in [20–22]. A large number of factors influence the performance of the combined system, and since in practice, multiple performance measures need to be optimised simultaneously, an effective strategy is required in this context. This paper presents an SCPN based simulation, combined with the established Taguchi method of design of experiments to address this problem. The influence of important factors on makespan, unproductive travel time of crane and mean flow-time of parts, has been analysed.

2. The System and the Modelling Tool

An AS/RS is a complex system influenced by several factors such as storage/retrieval policies, crane operation modes and order sequencing. FMS is also a complex system because of a large number of interdependent and interconnected components, tooling constraints, pallet constraints, etc. In a combined system, an AS/RS serves as a central storage accessible to FMS, and also functions as an in-process buffer. The combined system calls for a proper coordination of the assignment policies and crane operation modes of an AS/RS, along with the job scheduling rules of the FMS, for the effective utilisation of these capital intensive systems. In a typical system, consisting of an AS/RS interfaced with an FMS, the stacker crane functions not only as a storage and retrieval machine but also as a transfer machine for moving semi-finished parts between machines. The FMS produces a number of part types on several machines. Alternative machines can be used to process parts. Palletised parts are stored in racks which also accommodate semi-finished and finished parts. A palletised part is moved on to various machines for processing, and on completion it is sent for inspection or for assembly. Machines can fail during the processing of a part. In such a system the stacker crane is required to attend to retrieval, storage and transfer requests which form separate queues. Conflicts, in the allocation of a request to the crane, can be resolved using a set of heuristics which take into consideration the status of queues, the availability of buffers in machines, the availability of bins in storage racks, and the on-board capacity of the stacker crane.

2.1 Stochastic Coloured Petri Nets

In order to take into account the complex and stochastic behaviour of both FMS and AS/RS, and to develop a compact model of the combined system, SCPN have been chosen for this work. An SCPN consists of the following elements:

\[ \text{SCPN} = \{ P, T, M, C(p), C(t), \text{IN}(P_i, T_j), \text{OUT}(P_i, T_j) \} \]

where

- \( P \) = a set of \( n \) places, \( n > 0 \)
- \( T \) = a set of \( m \) transitions, \( m > 0 \)
- \( M \) = a set of marking
- \( C(p) \) = colour set associated with each place \( p \in P \)
- \( C(p_i) = \{ a_{i1}, a_{i2}, \ldots, a_{in} \} \), \( i = 1, 2, \ldots, n \), and \( u = |C(p_i)| \)
- \( C(t) \) = colour set associated with each transition \( t \in T \)
- \( C(t_j) = \{ b_{j1}, b_{j2}, \ldots, b_{jm} \} \), \( j = 1, 2, \ldots, m \), and \( v = |C(t_j)| \)

If \( \text{IN}(P_i, T_j)(a_{ih}, b_{jk}) \neq 0 \) for some \( h \) and \( k \), then a directed arc exists from \( P_i \) to transition \( T_j \). This arc is labelled with linear input function \( \text{IN}(P_i, T_j) \). Similarly, if \( \text{OUT}(P_i, T_j)(a_{ih}, b_{jk}) \neq 0 \) for some \( h \) and \( k \), then a directed arc exists from \( T_j \) to place \( P_i \), and is labelled with \( \text{OUT}(P_i, T_j) \).

2.2 Enabling and Firing of Transitions in SCPN

A transition \( T_j \) is said to be enabled with respect to a colour \( b_{jk} \) in a marking \( M \) if and only if

\[ M(p_i)(a_{ih}) \geq \text{IN}(P_i, T_j)(a_{ih}, b_{jk}), \text{ for all } p_i \in P, a_{ih} \in C(p_i) \]

When a transition is enabled, it can fire. On completion of firing, a new marking \( M' \) is reached according to the following equation

\[ M'(P_w)(a_{ih}) = M(P_w)(a_{ih}) + \text{OUT}(P_i, T_j)(a_{ih}, b_{jk}) - \text{IN}(P_i, T_j)(a_{ih}, b_{jk}) \]

2.3 Modelling of the Integrated System

The modular and hierarchical approach of model development supported by SCPN has been exploited here to model the above described complex system. To this end, individual modules of processing activity of FMS, and of the retrieval, storage and transfer activities of AS/RS are obtained. These modules can be coalesced to obtain the complete model of the integrated system. Figures 1(a)–(d) depict the modules, and the interpretation of the places and transitions of these modules is presented in Tables 1(a) and 1(b), respectively. Two types of transitions can be seen. Those represented by thin bars are instantaneous transitions which fire immediately and have priority over the timed transitions represented by thick bars. The timed transitions can have either deterministic or stochastic firing time associated with them. For example, in this study, the travel time of the stacker crane from one location to the other is modelled by deterministic transitions whereas the processing time of a part on machines, and the failure and repair times of machines are modelled by stochastic