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Modelling and performance maximization of an integrated automated guided vehicle system using coloured Petri net and response surface methods ☆

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ABSTRACT

The objective of this study is to model and maximize performance of an integrated Automated Guided Vehicle System (AGVS), which is embedded in a pull type multi-product, multi-stage and multi-line flexible manufacturing system (FMS). This study examines the impact of guide-path flexibility on system performance through the development of three different guide-path configurations which range from dedicated to flexible relationships between automated guided vehicles (AGVs) and machine/assembly station resources. The system is modelled using coloured Petri net method (CPN) and the simulation results lead to identify the resource redundancy which can be rectified to achieve lower overall cost of the system through the development of flexible guide-path configurations. The study is extended to seek global near-optimal conditions for each guide-path configuration using response surface method, which yields improvements in system throughput and cycle time along with a decrease in the numbers of AGVs.

1. Introduction

In modern manufacturing environments, automated guided vehicle systems have become an integral part of overall manufacturing systems. An AGVS contains one or more automated guided vehicles which are driverless vehicles used for horizontal movement of materials. AGVs are commonly used in facilities such as manufacturing plants, distribution centres, warehouses and transhipments. The AGVS studied in this paper is a discrete event dynamical system (DEDS), i.e. a dynamic system with state changes driven by occurrences of individual events. This DEDS is event driven, asynchronous and non-deterministic in nature. Also, the considered AGVS is integrated with FMS and is interacting with flexible manufacturing/assembly system. Petri net are powerful techniques to model such systems in that they can handle complex system modelling concepts and constraints. Moreover, coloured Petri net (CPN) provides compact models of large systems with a higher level of abstraction (Desrochers & Al-Jaar, 1995). Hence, this study uses CPN method for modelling the system and the data generated by the CPN model are used to develop the response surface models to explore near-optimal conditions of the system.

2. Related work and originality

Most machine scheduling research studies assume either that there are an infinite number of transporters for delivering jobs or that jobs are delivered instantaneously from one location to another without transportation time involved(Lee & Chen, 2001). The majority of the research work available in FMS modelling literature considers only the modelling of materials processing through work centres and assumes uninterrupted availability of material handling equipment. This could be valid for conveyorized production system but it is not reasonable for AGV-based systems (Tamer, Abdelmaguid, Ashraf, Kamal, & Hassan, 2004). Several researchers have stressed that efficient scheduling of material handling system is critical to the overall efficiency of FMS (Ulusoy & Bilge, 1993). The integration of material handling system (MHS) with manufacturing activities can result in manufacturing systems characterized by flexibility, high productivity and low cost per unit produced (Jawahar, Aravindan, Ponnambalam, & Suresh, 1998). Problems that address the optimal co-ordination of machine scheduling and job transporting are certainly more practical than those scheduling problems that do not take these factors into consideration. Also, to achieve global optimization between material processing and material handling activities, manufacturing planning should consider these two functions simultaneously (Seo & Egbelu, 1999). Nevertheless, the integration of MHS with FMS inevitably increases the complexity of a problem as it comprises inseparable decisions for both material processing and material handling activities (Lee & Chen, 2001). The earliest scheduling paper that explicitly considers the transportation factor is probably the one by Maggu and Das (1980). They considered a two-machine flow shop make-span problem with unlimited buffer spaces on both machines in which there are sufficient number of transporters so that whenever a job is completed on the first machine, it could be trans-

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ported with a job-dependent transportation time, to the second machine immediately. Maggu, Das, and Kumar (1981) considered the same problem with the additional constraint that some jobs must be scheduled consecutively. Kise (1991) studied a similar problem but with only one transporter with a capacity of one and showed that the problem was NP-hard, even with job independent transportation times. Stern and Vitner (1990) considered a two-machine flow shop make-span problem where there is only one transporter with a capacity of one. They assumed that transportation times are job-dependent and that there is no intermediate buffer space at either machine. They formulated the problem as an asymmetric travelling salesman problem and gave a polynomial-time heuristic. Panwalker (1991) considered the same problem except that the buffer space at the second machine is infinite. He provided an optimal polynomial-time algorithm. The design and control processes of an AGVS involve many issues like (Vis, 2006):

- guide-path layout,
- traffic management: prediction and avoidance of collisions and deadlocks,
- number and location of pick-up and delivery points,
- vehicle requirements,
- vehicle-dispatching, routing and scheduling,
- positioning of idle vehicles,
- battery management and
- failure management.

Among these factors, guide-path or flow-path configuration design can be seen as a problem at strategic level (Le-Anh & De Koster, 2006). The guide-path layout influences the performance of a system as it impacts the travel time to transport a load from its origin to its destination, the number of vehicles required and the degree of congestion (Seo & Egbelu, 1999). The most common performance criterion in guide-path design is minimizing the total vehicle travel distance corresponding to given layout and flows (Gaskins & Tanchoco, 1987; Kaspi & Tanchoco, 1990). The direction of AGVs' travel along guide-path may be unidirectional, bidirectional or a mix of unidirectional and bidirectional paths. Other developments in flow path design are single loops, tandem configurations and segmented flow configurations. The configuration of mixed unidirectional and bidirectional flow paths was studied in (Rajotia, Shankar, & Batra, 1998) with the purpose to reduce travel distance. It indicated that benefits could be obtained in throughput rates and in the size of vehicle fleet whereas the rate of vehicle congestion was increased and traffic control became more important. Gaskins and Tanchoco (1987) were one of the first to discuss the AGV guide-path layout problem with unidirectional arcs. The problem was presented as a network and formulated as a 0–1 integer linear programming model. The objective was to minimize the total transportation distance of AGVs. Kaspi and Tanchoco (1990) described a model with extra constraints and gave a computationally efficient procedure, namely branch and bound approach which was extended by Kim and Tanchoco (1993) by considering the fixed costs for construction, control and space of the system. Ko and Egbelu (2003) stated that in today's dynamic production environment, changing product mixes and machine routes were realistic. They proposed and tested a heuristic for the design of AGV networks that could respond to changes in production volume and flow patterns. Asef-Vaziri, Laporte, and Sriskandarajah (2000) formulated the shortest loop design problem as an integer linear programming model. Bilge and Ulusoy (1995) considered an integrated production and material handling scheduling problem with the objective of minimizing the make-span in an FMS. Lee and DiCesare (1994) studied the integrated production and material handling scheduling in a job-shop context. A Petri net was presented and a heuristic method was proposed. The objective was to minimize the make-span. They considered a shop of three machines and one robot for transformation activities and five AGVs for material handling activities. Two cases were presented. In the first case, the AGV was dedicated to a job, accompanying it till the end of processing. In the second case, the AGV was dedicated to a machine to move the jobs after being processed by the machine. Two AGVs were dedicated to the load/unload station. (Sabuncuoglu & Hommertzheim, 1992a, 1992b) studied integrated scheduling of production and material handling for an FMS with a job-shop production environment. Simulation was used to evaluate the performance of scheduling rules. The objective considered was to minimize average flow time. The simulation methodology was used to model traditional, tandem and tandem/loop configurations in (Farling, Mosier, & Mahmood, 2001) and the benefits and limitations of each configuration was discussed. Aized, Takahashi, and Hagiwara (2007a) presented coloured Petri net based modelling and analysis of multiple products FMS with resource breakdown and automated inspection. This study did not address the issues related to material transportation and assumed an uninterrupted availability of dedicated automated guided vehicles. Aized, Takahashi, and Hagiwara (2007b) modelled and analysed an integrated automated guided vehicle system using coloured Petri net but this paper did not discuss any scheme for performance maximization considering multiple input factors simultaneously.

In this study, an AGVS is integrated with an FMS and the interactions between FMS and AGVS are modelled and global system optimization is carried out using response surface method. The contribution of this study is that it analyses the impact of flexibility on the performance of an integrated AGVS through the development of different guide-path configurations. The configurations are developed in such a way that flexibility, defined in terms of guide-path configurations design to accommodate varying number of AGVs, is gradually enhanced and its impact on system performance is examined in order to propose the best configuration. The details of the configurations are discussed in Section 4. The problem of AGV congestion as discussed earlier (Rajotia et al., 1998) is solved through a suitable control policy for the FMS. Also, this study is extended to seek global near-optimal performance in each configuration and the configurations are compared to propose the best performance of the manufacturing system. The system is modelled through CPN method and response surface method (RSM) is implemented in order to achieve the best performance of the system. The joint use of CPN and RSM can be taken as a general methodology for modelling, analysis and optimization of a discrete event dynamical system. Moreover, this study presents the application of advanced tools like CPN Tools and Design Expert and shows how these powerful tools can be used to model, analyse and optimize a manufacturing system.

3. Coloured Petri net (CPN)

A flexible manufacturing system is a discrete event dynamical (DEDS) system, which is asynchronous, parallel, and event driven in its nature. A DEDS can be characterized by events and conditions, which can be described by Petri net method easily. In an FMS, events are occurring in a parallel way that can be modelled compactly by coloured Petri net method. A Petri net consists of places, transitions and directed arcs represented by circles, rectangular bars and arrows, respectively. Arcs run between places and transitions. Places may contain any number of tokens. A distribution of tokens over the places of a net is called a marking. Transitions act on input tokens by a process known as firing. A transition can fire if it is enabled, i.e., there are tokens in every input place. When a transition fires, it consumes the tokens from its input places, perform some processing task and places a specified

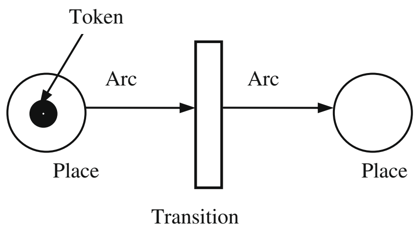

Fig. 1. A Petri net representation.

number of tokens into each of its output places. A simple Petri net structure is shown in Fig. 1.

The conditions of a DEDS are described by places, events are described by transitions, relations between events and conditions are described by arcs and holding of conditions are described by tokens in places. The occurrences of events are described by firing of transitions which remove tokens from input places and add tokens to output places and the behaviour of a system is described by firing of transitions and movements of tokens. Places, transitions and tokens must be assigned a meaning for proper interpretation of a model. In manufacturing systems, normally places represent resources like machines, materials etc. and the existence of one or more tokens in a place represents the availability of a particular resource, while no token indicates that the resource is unavailable. A transition firing represents an activity or process execution, for instance, a machining process. Places and transitions together represent conditions and precedence relationships in a system's operation. Fig. 2 shows a Petri net example from manufacturing system point of view.

In case, there are more than one "Material" tokens in a place, these become indistinguishable. To make these tokens distinguishable, a higher class of Petri net called coloured Petri net can be used. The following two reasons given in Desrochers and Al-Jaar (1995) justify the use of CPN for manufacturing system modelling:

(1) A detailed model of even simple systems might result in a very large net. A CPN reduces the size of net.

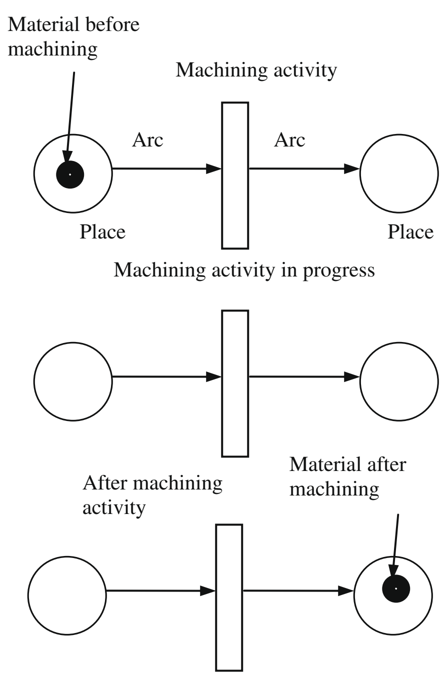

Fig. 2. A simple Petri net for a manufacturing process.

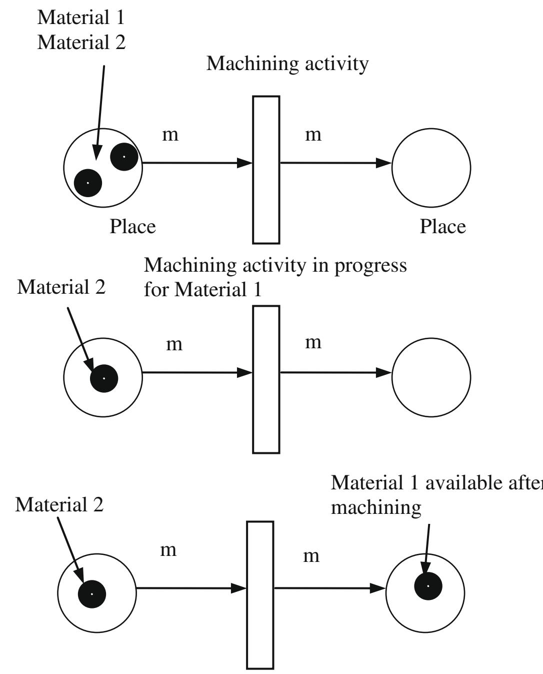

Fig. 3. A coloured Petri net example.

(2) In manufacturing environments, a system could have numerous similar components. Hence, instead of having a separate net representing each component, one CPN can model all such similar components.

Fig. 3 shows an example of CPN for two materials, Materials 1 and 2, *m* is an arc function, a mapping from place to transition (input arc function) and from transition to place (output arc function). It is an illustration of mapping the value of '*m*' to 'Material 1'.

4. Flexible manufacturing system configuration

The overall system configuration is illustrated in Fig. 4. The system is composed of two major activities; that is, manufacturing and assembly and is a multi-product, multi-stage and multi-line manufacturing/assembly system. Each manufacturing cell produces four numbers of parts which are taken to the assembly cell where these are assembled in a specific pattern to produce four final products and hence is a multi-item assembly facility. Both manufacturing cells have the same configuration as shown in Fig. 5. There are two production lines in each manufacturing cell whereas each line is composed of three machines to show multi-line, multi-stage manufacturing. The second and the third machine in each production line can also perform the operation of its corresponding machine of the other line in the same manufacturing cell in case of breakdowns of corresponding machines, thus forming alternative routing of materials as a measure of routing flexibility. Each manufacturing cell is provided with three material handling robots to serve the corresponding machines in both lines and the relevant automated guided vehicles (AGVs).

The assembly cell configuration is shown in Fig. 6. This specific configuration for the assembly cell has been chosen to emphasize the multi-item production, as there are two assembly stations available. The parts from both manufacturing cells are brought here by AGVs and the condition of breakdowns of assembly robots is also applied here. The robots R 7 and R 8 are performing assembly operations at assembly stations. Both assembly robots can perform in place of each other under breakdown conditions.

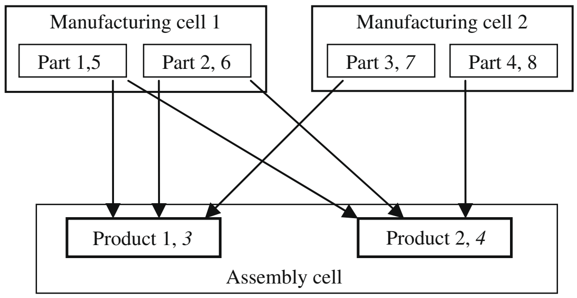

Fig. 4. Overall manufacturing system.

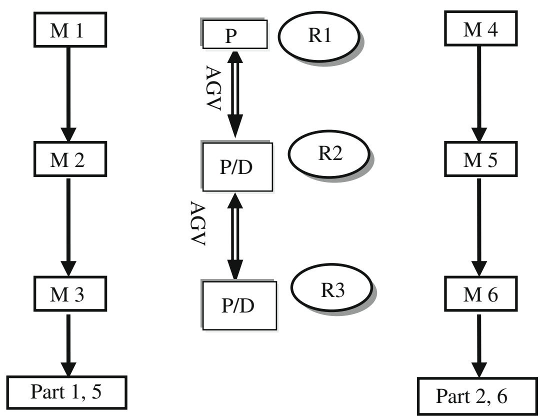

Fig. 5. Manufacturing cell configuration. Legend: M (i) – Machine (i), R (i) – Robot (i), P – Pick-up point, P/D – Pick/Delivery point, AGV – Automated guided vehicle.

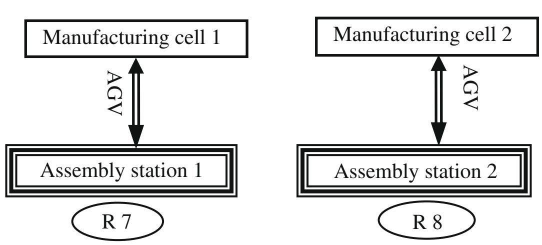

Fig. 6. Assembly cell configuration.

4.1. AGVS configurations

The integrated AGVS is analysed by developing three guide-path configurations. These configurations range from dedicated to flexible relationships between AGVs and machines/assembly stations. In Configuration 1 (C1), AGVS is modelled in such a way that an AGV is provided between two adjacent machines or a machine and the assembly station. Each AGV is serving corresponding machines in both production lines of the manufacturing cell and this holds true for both manufacturing cells. This configuration, shown in Fig. 7, has dedicated relationships between the AGVs and the machines/assembly stations.

The dedicated AGV-machine/assembly station relationship of C1 is relaxed in configuration 2 (C2) in which a dock is developed for the parking of the AGVs in each manufacturing cell. All the AGVs are allowed to serve any pick, pick/delivery or delivery point within a manufacturing cell and the corresponding assembly station but the AGVs can not serve the other manufacturing cell or assembly station. In this configuration, a limited flexibility is added in the AGVS. This is shown in Fig. 8 in which intersection point (I) is the point of intersection of two guide-path segments. At I, an AGV has to stop only if there is some other AGV in the guide-path segment just beyond this point in order to avoid any collision. The control point (C) is the point at which the direction of further travel is decided keeping in view the control policy, which is explained in Section 5.

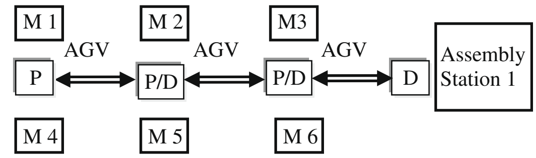

Fig. 7. AGVS configuration 1.

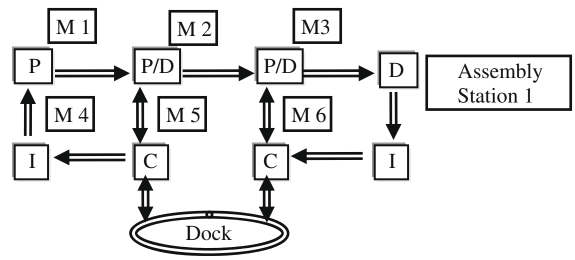

Fig. 8. AGVS configuration 2. Legend: P – Pick point, D – Delivery point, P/D – Pick/Delivery point, I – Intersection, C – Control point.

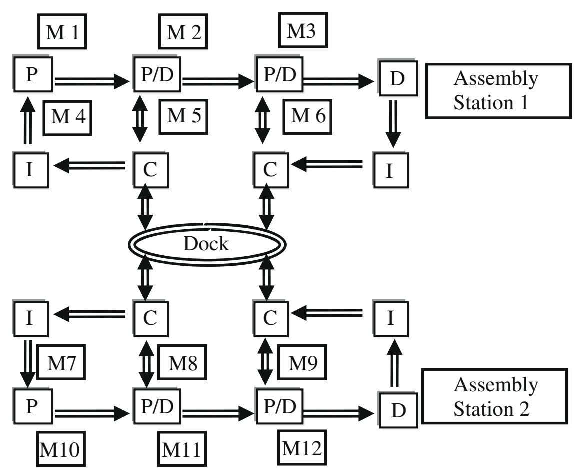

Fig. 9. AGVS configuration 3.

The limited flexibility of the AGVS of C2 is enhanced in configuration 3 (C3) where all AGVs are parked at one dock and every AGV can serve any pick, pick/delivery or delivery point throughout the FMS. This is shown in Fig. 9. C1 has bidirectional whereas C2 and C3 have a mix of uni/bidirectional guide-path layouts. The control point, shown as "C" in Figs. 8 and 9, are the points where an AGV has to wait due to traffic jams.

5. Control policy

The main objective of the control policy is to satisfy demands for transportation as fast as possible and without occurrences of conflicts among AGVs. The control of AGVS is developed in such a way that it is hierarchical in nature and has two layers of hierarchy (see Fig. 10).

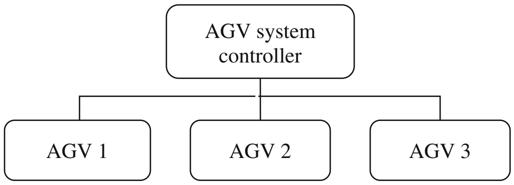

Fig. 10. The AGVS hierarchical control format.

The first layer represents the overall control of the AGVS whereas the second layer which contains AGVs 1, 2 and 3 act to control first, second and third machines' pick and/ or delivery points on each production line respectively. Due to non-deterministic nature of the system, on-line scheduling methodology is used. Vehicle-dispatching rules can be classified as single-attribute, multi-attribute, etc. (Le-Anh & De Koster, 2006). Single-attribute dispatching rules dispatch vehicles based on one parameter/ criterion only. Parameters can be travel distance (distance-based), queue length (workload-based), load waiting time (time-based), etc. Multi-attribute rules dispatch vehicles using more than one parameter. In general, they outperform single-attribute dispatching rules. This study uses multi-attribute workstation initiated dispatching rule which consists of two rules, that is, Shortest Travel Distance First (STDF) rule and Look ahead dispatching rule, as all AGVs are scheduled depending upon the shortest distance and look ahead policy. According to shortest travel distance rule, a vehicle is dispatched to the work centre closest by. The objective of this rule is to minimize empty travel times of vehicles (Vis, 2006). For example, referring to Fig. 8, an AGV picks up some material from point 'P' near M1/M4 and delivers this material at point 'P/D' near M2/M5. After material delivery, this AGV will travel to the 'Dock' through point 'C' near M5. At the moment when this AGV is at 'C' near M5, if M2 or M5 calls up some AGV for picking up some material, then there are two options available. Either the AGV which is at point 'C' is to be routed towards point 'P/D' near M2/ M5 or some AGV from the 'Dock' is to be despatched. As the 'Dock' is farther in distance from the 'P/D' compared with the 'C', hence the first option is adopted. The look ahead rule uses advanced information about the loads to be available shortly to dispatch vehicles (Le-Anh & De Koster, 2006). In this study, for example, if a batch of '*p*' number of materials/parts is to be transported from one point to another, then at the moment when *p*th material/ part is started to process at each work station, an AGV is called up for transportation activity. This requires less time for an AGV to be available at a certain point compared with the situation if it is called up after finishing all processing activities. The joint use of shortest travel distance first and look ahead rules makes vehicles available too quickly and hence improves overall system performance. The deadlock and collision is avoided by specifying the capacity of each guide-path segment in this system.

6. Model development

The model development consists of two phases, coloured Petri net (CPN) modelling and response surface modelling (RSM) for analysis of the simulation results of the CPN model to explore the global near-optimal conditions of the manufacturing system. The models are scalable and can be modified according to the requirements.

6.1. CPN modelling

The CPN modelling is carried out using CPN Tools which is a CPN-based program developed on the basis of CPN ML language which is derived from Standard ML, a general purpose functional language. The model consists of different modules which are hierarchical in nature and are developed for specific functions. These are System coordinating module, Robot module, Machining module, Assembly module and AGV module. The modular structure of the model is shown in Fig. 11.

The system coordinating module is coordinating all activities of the system and hence is interacting with all other modules. Robot module is developed to carry out all material loading/unloading operations on/from machines, assembly stations and AGVs and hence is interacting with all other modules of the model. Machining module is responsible for all machining operations and consists of two sub modules, Machining 1 and Machining 2. Machining 1 is carrying out all machining operations and machining 2 is developed to implement routing flexibility regarding material flow. Assembly module is accomplishing all assembly operations and has two sub modules called Assembly 1 and Assembly 2. Both assembly sub modules are developed to carry out assembly operations and also contain the provisions to use alternate assembly stations in case of breakdown of an assembly station. The AGV module is responsible for all material transportation activities and consists of four sub modules which are AGV system controller, AGV 1, AGV 2 and AGV 3. AGV module is developed to implement the control policy and the guide-path configuration design of the AGVS and can be modified in order to implement any of the stated guide-path configurations. All transportation operations are modelled using exponential distribution function.

6.2. Response surface modelling

Response surface method (RSM) is a planned approach for determining cause and effect relationships and can be used for studying more than one input factor in a single experiment (Anderson & Whitcomb, 2005). Derringer and Suich (1980) described a multiple response method which makes use of an objective function, called desirability function. The general approach is to first convert each response into an individual desirability function d_i that varies over the range, $0 \leqslant d_i \leqslant 1$, where if

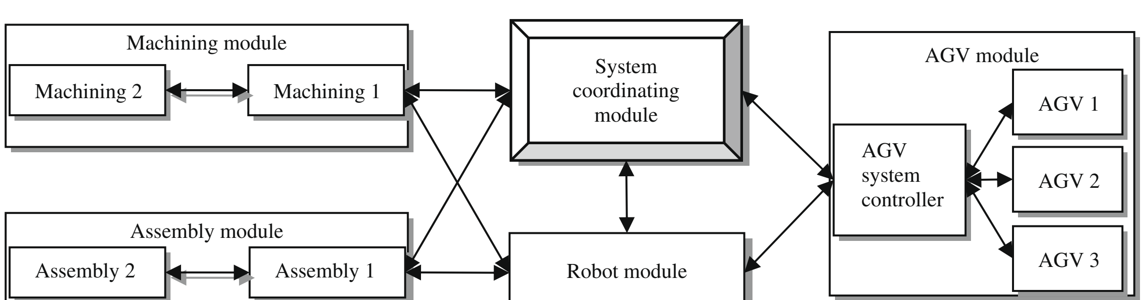

Fig. 11. The modular structure of the model.

the response is at the goal or target, then $d_i = 1$ and if the response is outside an acceptable region, then $d_i = 0$. If any of the responses fall outside its desirability range, the overall function becomes zero. For simultaneous optimization each response must have a low value (l_v) and a high value (h_v) assigned to each goal, such that for maximum goal:

$$d_i = 0 \quad \text{if } y_i < l_v, \quad 0 \le d_i \le 1 \quad \text{if } l_v \le y_i \le h_v, \quad d_i = 1 \quad \text{if } y_i > h_v$$

and for minimum goal:

$$d_i = 1 \quad \text{if } y_i < l_v, \quad 1 \le d_i \le 0 \quad \text{if } l_v \le y_i \le h_v, \quad d_i = 0 \quad \text{if } y_i > h_v$$

The simultaneous objective function is a geometric mean of all transformed responses. In desirability function, each response can also be assigned an importance relative to the other responses. Importance (r_i) varies from the least important to the most important. By assigning different importance to different responses, the objective function is given by:

$$D = (d_1^{r_1} \times d_2^{r_2} \times \ldots \times d_n^{r_n})^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{\frac{1}{\sum r_i}}$$

where n is the number of responses. The shape of desirability function also changes with the addition of weights function which is used to emphasize upper or lower bounds. RSM modelling and analysis have been carried out using Design Expert 7.0.2 tool.

7. Simulation results and discussion

The following are the simulation assumptions:

- The lengths of all guide-path segments are the same.
- When an AGV enters into any guide-path segment, it will continue travelling till the end of the segment.
- The AGV speed for all segments of the guide-path is the same.

Before collecting the resulting data, it is important to detect warm-up period to access steady state behaviour of the system. This study uses four stage SPC approach (Robinson, 2002) to find out steady state results. The SPC approach has the following four stages.

Stage 1: Perform replications and collect output data.
Stage 2: Test the output data to meet the assumptions of SPC.
Stage 3: Construct a control chart for the batch means data.
Stage 4: Identify the initial transient.

As the input factors vary for individual simulation runs in this study, hence the warm-up period is also varying depending on the particular input factor settings. In general, we have carried out ten independent replications for each input factor settings and have determined the warm-up period. This period has been excluded while collecting the data from the simulation runs and the length of the steady state period has been determined according to the recommendations given in Robinson (2002). Hence, the simulation results are repeatable. There are many input factors in this system which are either related to material processing (called FMS input factors) or material transportation (called AGV input factors). The FMS input factors may include mean material loading/unloading time, mean machining/assembly time, mean time to breakdown, etc. The values of all these FMS input factors is fixed in this section and is taken as one time unit or minute. The only input factor that is varied in this section is the number of AGVs as this factor is directly related to guide-path configuration design. In Section 8, multiple input factors are varied to maximize performance of multiple responses of the system. All AGV transportation operations are modelled through exponential distribution function which requires a single parameter, the mean time to cover a segment of the guide-path. Since the lengths of the guide-path segments are taken equal and the speed of the AGV is also fixed, the mean time to cover a guide-path segment (exponential distribution parameter) is taken as one time unit or minute.

7.1. Performance measures

The overall performance of the system is measured through material processing system and material handling system measures. The material processing or FMS measures include mean throughput (number of products/day) and mean cycle Time (number of minutes) whereas material handling or the AGVS measures include mean AGV utilization (percentage of total time), mean AGV response time (number of minutes) and mean AGV congestion (percentage of total time). Mean AGV utilization is defined as the percentage of total time for which an AGV is used to transport a load from one location to another. In cases of C2 and C3, the AGV move time associated in moving to claim a load is included in utilization calculations. Mean AGV response time is defined as the mean time from the moment when an AGV is called up by a workstation to the moment when the AGV is available at the nearest pick-up point of that workstation for carrying the load. AGV congestion is defined as the percentage of total time that an AGV waits at a control point due to traffic jams.

The numbers of AGVs in C1 are six which is a fixed number as C1 has a rigidly dedicated AGVS format. C2 has two fleet of AGVs, each fleet is serving a specific manufacturing and relevant assembly station and an addition of one AGV in each fleet results two more AGVs in the AGVS. Hence, the numbers of AGVs begin from two and can increase with a multiple of two in the AGVS. For the simulation experiments, the numbers of AGVs are ranging from 2 to 8. C3 has the most flexible guide-path design and the number

Table 1
The simulation results (St.Dv.: standard deviation).

	Configuration Level (CL)	Number of AGVs	Throughput (products/day)		Cycle time (min)		AGV utilization (percentage of total time)		AGV response (min)		AGV congestion (percentage of total time)	
			Mean	St. Dv.	Mean	St. Dv.	Mean	St. Dv.	Mean	St. Dv.	Mean	St. Dv.
C1	3	6	2.33	0.09	4825.44	207.57	15.85	0.60	0.00	0.00	0.0000	0.0000
C2	1	2	2.30	0.15	4770.27	291.01	55.68	3.56	59.54	4.55	0.0000	0.0000
	2	4	2.44	0.08	4653.45	119.88	33.42	1.21	15.31	1.62	0.0100	0.0030
	3	6	2.39	0.07	4693.68	107.62	23.2	0.74	7.07	0.75	0.0200	0.0050
	4	8	2.36	0.08	4731.09	163.85	17.86	0.57	4.59	0.56	0.0200	0.0060
C3	1	1	1.97	0.09	5482.08	234.07	91.74	1.50	179.69	10.13	0.0000	0.0000
	2	2	2.34	0.09	4735.03	142.17	59.28	2.23	37.42	2.61	0.0080	0.0015
	3	3	2.36	0.04	4776.50	116.78	43.42	1.67	15.98	1.59	0.0096	0.0020
	4	4	2.27	0.14	4763.56	241.36	32.75	1.72	9.05	1.12	0.0160	0.0040

of AGVs can range from one to any multiple of one; for the simulation experiments, the number varies from one to four. A configuration level (CL) is defined as a measure of numbers of AGVs and is used to compare different numbers of AGVs in all three configurations. For instance, the value of CL equals to one means two AGVs for C2 and one AGV for C3. The CL for C1 is taken three which makes the comparison of the configurations easy. The simulation results are shown in Table 1.

7.2. The impact of guide-path configurations on throughput and cycle time

Figs. 12 and 13 show the relationships between configuration level (CL), which is a measure of number of AGVs, and throughput and configuration level and cycle time respectively. There are three data series shown; C1 is a series with only one datum point as it has fixed number of AGVs which is six and is represented by CL equals to three for comparison purposes. A careful examination of the mean values of throughput and cycle time along with their standard deviation values show that the throughput and cycle time are almost at the same level for C1, which has six number of AGVs, and for C2 at all configuration levels. The minimum number of AGVs for C2 are two, that is one AGV for each manufacturing cell. Hence, by using C2, numbers of AGVs can be decreased to two while keeping throughput and cycle time at the same level. If only one AGV is used in C3, the throughput is somewhat lower and the cycle time is higher compared with the respective values of C2. The higher cycle time value is due to delayed availability of the AGV as is shown by a high AGV response time value in Fig. 15 for this case (CL = 1 for C3). Also, Fig. 14 shows a high value of AGV utilization for the same case (CL = 1 for C3). When another AGV is added in C3 (CL = 2 in Figs. 12 and 13), the throughput is increased and

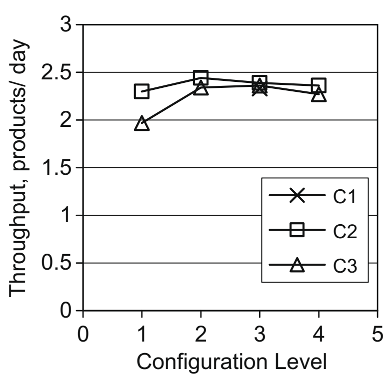

Fig. 12. Impact of the configurations on throughput.

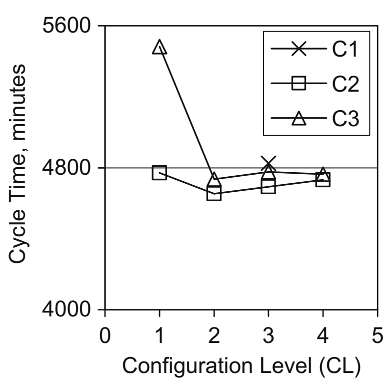

Fig. 13. Impact of the configurations on cycle time.

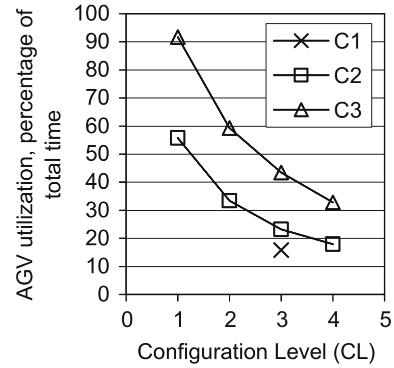

Fig. 14. Impact of the configurations on AGV utilization.

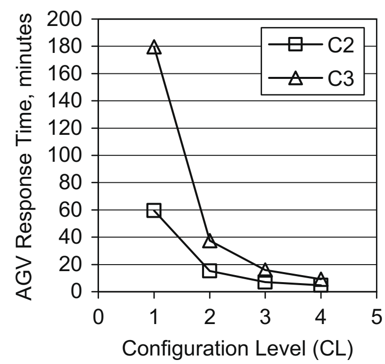

Fig. 15. Impact of the configurations on AGV response time.

the cycle time is decreased due to a quicker response of the AGVs (CL = 2 for C3 in Fig. 15) at the expense of lower utilization (CL = 2 for C3 in Fig. 14). In this case, the throughput and the cycle time have become almost same as in the cases of C1 and C2. This implies that the dedicated AGVS format of C1 is only a means of resource redundancy which requires unnecessary capital and operational expenditures. Also, the dedicated AGVS format of C1 lakes in fault tolerance as under the situations of AGVs break downs, the throughput of the system is bound to deteriorate. Hence, by using C2 or C3, not only the same throughput and cycle time can be achieved with fewer AGV resources but also it improves fault tolerance of the system. Again, if C2 is used with two numbers of AGVs, there will be a problem of lack of fault tolerance as only one AGV will be available for each manufacturing cell and the relevant assembly station. This situation can be improved either by using four number of AGVs in C2 which will again be a case of resource redundancy or by using C3 with two numbers of AGVs.

7.3. The impact of guide-path configurations on AGV utilization

Fig. 14 shows the impact of the configurations on AGV utilization which is at a lower level for C1 which means that the resources are not properly utilized as these are bound to specific pick or pick/delivery points and under the situations when work stations are executing the processes, these resources are just idle and are unutilized. C2 shows comparatively better utilization of AGVs especially when there is one AGV in each manufacturing cell but the utilization is decreasing as the numbers of AGVs are increasing. C3 utilizes AGVs more than C2, especially when there is only one AGV in the AGVS; the utilization reaches more than 90%. Nevertheless, by using C3 with only one AGV, there are associated disadvantages of comparatively lower throughput, higher cycle time and the lack of fault tolerance under the situations of break downs of the AGV. These shortcomings can be overcome by an addition of another AGV to the system but this will decrease the utilization of AGVs as is shown in Fig. 14; also a further increase in AGVs in C3 will again decrease the utilization factor without any improvement in throughput and cycle time.

7.4. The impact of guide-path configurations on AGV response time

As the AGVs are dedicated to specific pick or pick/delivery points in C1 and are almost immediately available when are needed, hence AGV response time is negligible for dedicated AGVS format. The response time of AGVs in case of C3 is higher than C2, especially when only one AGV is used because every transportation tasks is to be carried out by a single AGV resource. This situation can be improved with an addition of another AGV in the system but a further increase of AGVs in the AGVS will yield lower response times without gains in throughput and cycle time. C2 has a lower response time compared with C3 at each configuration level. In case of C2, there are two AGVs in the system when CL equals to one and the system lacks in fault tolerance if any of the AGVs faces a breakdown situation and hence the throughput will be decreased. The next configuration level of C2 solves the problem of lack of fault tolerance but creates the problem of resource redundancy because there will be four AGVs in the AGVS. This concludes that C3 with two numbers of AGVs is a preferred configuration as far as throughput, cycle time and AGV utilization are concerned; although it has a higher response time value compared with C2 at the same configuration level. Thus the addition of flexibility has helped to decrease the number of AGV resources which decreases the overall cost of the system. It is also worth mentioning here that the dedicated AGV configuration has the advantage of simple control structure and requires less floor space compared with C2 and C3.

7.5. AGV congestion

The data for AGV congestion is also given in Table 1. There is no congestion in case of C1 as there is only one AGV in each guide-path segment. The congestion data values for C2 and C3 are relevant to the control points of these configurations. A higher value of congestion level is an indicator that the AGVs have to wait due to traffic jams as the capacity of each segment of guide-path configuration is specified to 1. All data values for C2 and C3 show a congestion level far less than just 1% of total time which indicates that the system is not facing the problem of congestion which shows the soundness of the control policy adopted.

8. Search for an optimal AGVS

Response surface method is used to explore global near-optimal conditions of the system by considering multiple input factors simultaneously as the results given in Section 7 are one-factor-at-a-time based because only one input factor, that is configuration design has been considered. At the second stage, multiple input factors are considered which are mean material handling robot loading/unloading time, MLT (min), mean machining time, MMT (min), mean assembly time, MAT (min), mean time to breakdown, MTB (min), automated inspection acceptance level, IAL (probability of each part/product to be good) and numbers of AGVs, AGVs (number). The impact of these factors on mean throughput, mean cycle time, mean AGV utilization and mean AGV response time is studied. The AGV resources are permitted to go under regular maintenance and repairs events after a specific numbers of transportation operations. For response surface study, every input factor must be assigned a lower and an upper value. The lower and upper values for each input factors may be varied according to specific cases, but each such variation may generate a different result regarding performance maximization of a system. In order to avoid the effects of different values of input factors, the same lower and upper values have been taken for MLT, MMT and MAT in this study.

Response surface study is conducted for all three configurations separately in order to know the global near-optimal conditions of each configuration. The particular design used is FCD (Face-centred central composite design) for the approximation of the quadratic polynomial models and their analyses of variance (ANOVA) are carried out. The design summary is shown in Table 2. The quadratic polynomial models are tested for different statistical tests which include normal probability plot which indicates whether the residuals follow a normal distribution, actual versus predicted plot which shows actual response values versus predicted response values of the model and box cox plot for power transformation. The box cox plot provides a guide line for selecting the correct power law transformation. The transformation of a response is recommended based on the best transformation power value found at the minimum point of the curve generated by the natural log of the sum of squares of residuals. Due to space limitation, the details of these tests are not shown here. The quadratic polynomial modelling for mean throughput, mean cycle time and mean AGV utilization for configuration 1 is given. The ANOVA tests have indicated that the developed models are significant. Similarly, the models have been developed for configurations 2 and 3 but are not shown here due to space limitation. The output responses can vary from

Table 2
Response surface design summary.

	Runs	Input factors												Output responses	Output response values						
		MLT		MMT		MAT		MTB		IAL		AGVs			Min	Max.	Mean	S.D.	Goal	Imp.	Tran
		Lv	hv	lv	hv	lv	hv	lv	hv	lv	hv	lv	hv								
C1	50	1	5	1	5	1	5	1	13	0.6	1	6	6	Throughput	0.3	9.8	2.8	2.2	Maximize	5.0	B.L
														Cycle time	869.3	17331.0	7076.7	4937.0	Minimize	4.0	B.L
														AGV utilization	2.1	55.2	31.0	17.3	Maximize	3.0	N
C2	86	1	5	1	5	1	5	1	13	0.6	1	2	10	Throughput	0.3	11.3	2.3	1.8	Maximize	5.0	B.L
														Cycle time	992.3	18896.6	7992.9	5339.9	Minimize	4.0	Sq.
														AGV utilization	2.8	74.2	48.6	23.9	Maximize	3.0	B.L
														AGV response	4.1	948.1	144.3	228.4	Minimize	3.0	B.L
C3	86	5	5	1	5	1	5	1	13	0.6	1	1	5	Throughput	0.31	12.1	2.2	1.8	Maximize	5.0	B.L
														Cycle time	929.0	17883.0	8141.4	5223.0	Minimize	4.0	Sq
														AGV utilization	3.4	99.3	68.7	32.8	Maximize	3.0	B.L
														AGV response	4.1	1841.0	257.0	454.0	Minimize	3.0	B.L

Lv, low value; hv, high value; Min, minimum; Max, maximum; S.D., standard deviation; Goal, optimization goal; Imp, importance; Tran, transformation; Sq, square root; B.L., Base 10 Log; N, none.

the most (taken as five) to the least (taken as one) important responses. For optimization, throughput and cycle time are considered more important responses whereas other responses are taken as less important. Table 2 also gives constraints for optimization. The following are the polynomial models for C1.

$$\begin{aligned}\log 10(\text{Mean Throughput}) &= +0.10485 - 0.025058*\text{MLT} - 0.16219*\text{MMT} \\ &- 0.15981*\text{MAT} + 0.11782*\text{MTB} + 10.11561*\text{IAL} \\ &+ 0.015762*\text{MLT}*\text{MMT} + 0.016294*\text{MLT}*\text{MAT} \\ &+ 2.83738\text{E}-004*\text{MLT}*\text{MTB} - 0.69827*\text{MLT}*\text{IAL} \\ &+ 0.016368*\text{MMT}*\text{MAT} - 5.31516\text{E}-004*\text{MMT}*\text{MTB} \\ &+ 0.24977*\text{MMT}*\text{IAL} + 3.35754\text{E}-003*\text{MAT}*\text{MTB} \\ &+ 0.30651*\text{MAT}*\text{IAL} - 0.046493*\text{MTB}*\text{IAL} \\ &- 0.011028*\text{MLT}^2 - 9.14639\text{E}-003*\text{MMT}^2 - 1.85258\text{E} \\ &- 003*\text{MAT}^2 - 5.55070\text{E}-003*\text{MTB}^2 - 32.13320*\text{IAL}^2\end{aligned}$$

$$\begin{aligned}\log 10(\text{Mean Cycle Time}) &= +3.83908 + 0.035853*\text{MLT} + 0.088559*\text{MMT} \\ &+ 0.17880*\text{MAT} - 0.099430*\text{MTB} - 8.47121*\text{IAL} \\ &- 0.012753*\text{MLT}*\text{MMT} - 0.017724*\text{MLT}*\text{MAT} \\ &+ 3.14536\text{E}-004*\text{MLT}*\text{MTB} + 0.64231*\text{MLT}*\text{IAL} \\ &- 0.018805*\text{MMT}*\text{MAT} + 3.13813\text{E}-003*\text{MMT}*\text{MTB} \\ &+ 0.074282*\text{MMT}*\text{IAL} - 2.56793\text{E}-003*\text{MAT}*\text{MTB} \\ &- 0.22779*\text{MAT}*\text{IAL} - 0.11596*\text{MTB}*\text{IAL} + 7.58189\text{E} \\ &- 003*\text{MLT}^2 + 8.16406\text{E}-003*\text{MMT}^2 - 5.68610\text{E} \\ &- 004*\text{MAT}^2 + 5.15153\text{E}-003*\text{MTB}^2 + 28.62070*\text{IAL}^2\end{aligned}$$

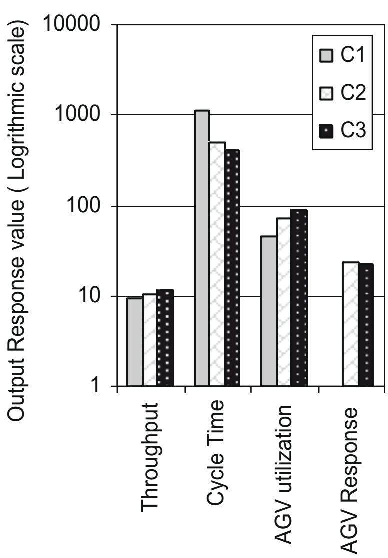

Fig. 16. Maximum performance comparison of all responses for three configurations.

$$\begin{aligned}\text{Mean AGV utilization} &= +9.24275 + 6.43176*\text{MLT} \\ &- 4.83632*\text{MMT} - 1.35765*\text{MAT} \\ &+ 0.40289*\text{MTB} + 181.98824*\text{IAL}\end{aligned}$$

8.1. The maximum performance solutions

The model design space is searched starting from random points and a number of solutions are found. For each configuration, the near-optimal output responses are achieved along with the near-optimal conditions of input factors. The solutions with the highest desirability value are chosen as the near-optimal solutions for this system which are shown in Table 3.

Fig. 16, generated on the basis of Table 3, gives a comparison of maximum performance for all three configurations.

From Fig. 16, it is concluded that:

(1) The throughput has been increased around 23% and the cycle time has been decreased around 64% gradually as we move from C1 towards C3.
(2) The AGV utilization has been increased approximately 86% from C1 to C3 where as AGV response has shown a small decrease from C2 to C3.
(3) MLT, MMT and MAT are found at either their minimum or close to minimum values as the higher these values are, the longer will be the cycle time and the lower will be the throughput values.
(4) The values of MTB are considerably higher than MLT, MMT and MAT in order to have a lower probability of resource breakdown during process execution and the values of IAL are higher to impose a very low probability of rejection of any part/material at automated inspection.

C1 has the lowest throughput and the highest cycle time because in this configuration, the AGVs are bound to specific machine resources and no AGV in the system can replace any other AGV under breakdown condition. In case of failure of an AGV in C1, it needs to repair before any further transportation activity takes place which lowers throughput and increases cycle time. C2 has a higher throughput value and a lower cycle time than C1 due to the availability of four AGVs in the system which means that two AGVs are available in each manufacturing and corresponding assembly cell. If one AGV is under repair and maintenance condition, the other is serving the machines. Nevertheless, only one AGV has to carry out all transportation operations in a manufacturing cell if the other is under maintenance event and this again is causing a higher cycle time and a lower throughput value if it is compared with configuration 3. C3, being the most flexible, offers the provision that if one AGV resource is under repair event, the other three can serve the entire system. Hence, C3 has the lowest cycle time and the highest throughput values. The AGV utilization is increasing from C1 to C3 because with the addition of flexibility in the guide-path design, the AGVs are not dedicated to specific pick and/or delivery points and can serve multiple machines and

Table 3
The near-optimum values for input factors and output responses.

	Input factors (near-optimal values)						Output responses (near-optimal values)											
	MLT	MMT	MAT	MTB	IAL	AGVs	Throughput			Cycle time			AGV utilization			AGV response		
							Pv	LV	Hv	Pv	LV	Hv	Pv	LV	Hv	Pv	LV	Hv
Configuration 1	1	1	1.01	10.95	92.9	6	9.5	7.1	12.8	1109.1	812.2	1514.4	46.0	40.1	52.2	0.0	0.0	0.0
Configuration 2	1.01	1	1	11.3	90.7	4	10.5	8.1	13.5	503.9	146.0	1076.5	71.1	52.4	92.4	23.0	17.6	30.1
Configuration 3	1	1	1	10.97	92.6	4	11.7	9.3	14.7	396.3	126.6	816.0	85.6	65.1	98.9	21.8	15.5	30.6

Pv: Predicted value, Lv: Low value, 95% Confidence interval, Hv: High value, 95% Confidence interval.

also the numbers of AGVs have decreased from six of C1 to four of C2 and C3 and hence fewer AGVs are carrying out the same numbers of transportation operations. There is no significant decrease in response time from C2 to C3 because the response time is considered less important in optimization criteria compared with throughput and cycle time. The response time can be decreased by increasing its importance with respect to other responses but that will also deteriorate the throughput and cycle time values.

9. Conclusion

This study has attempted to apply advanced tools of coloured Petri net and response surface methods to model and analyze the practical constraints of an integrated automated guided vehicle system. The flexibility addition in terms of guide-path design to accommodate varying number of AGVs has led to identify redundant AGV resources in dedicated AGVS format. These redundant AGVs can be removed and hence the overall cost of the system can be decreased while keeping the throughput and cycle time of the system at the same level. The fault tolerance of the system has also improved through the introduction of guide-path flexibility. Also, it has attempted to find global near-optimal solution of multiple responses simultaneously through desirability function approach. The mean throughput and mean cycle time has been considered more important output responses. The throughput, cycle time and AGV utilization have shown gradual improvements along with a decrease in the numbers of AGV resources due to the addition of guide-path flexibility. This modelling, analysis and optimization approach based on CPM and RSM can be used as a general methodology for achieving the best performance of a DEDS. The models developed through CPN and RSM are scalable and can handle changes in any FMS or AGVS.

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