

Optimising the maintenance strategy for a multi-AGV system using genetic algorithms

R.D. Yan, S.J. Dunnett & L.M. Jackson

Loughborough University, Loughborough, Leicestershire, UK

ABSTRACT: Automated Guided Vehicles (AGVs) are playing increasingly vital roles in a variety of applications in modern society, such as intelligent transportation in warehouses and material distribution in automated production lines. They improve production efficiency, save labour cost, and bring significant economic benefit to end users. However, to utilise these potential benefits is highly dependent on the reliability and availability of the AGVs. In other words, an effective maintenance strategy is critical in the application of AGVs. The research activity reported in this paper is to realise an effective maintenance strategy for a multi-AGV system by the approach of Genetic Algorithms (GA). To facilitate the research, an automated material distribution system consisting of three AGVs is considered in this paper for methodology development. The movement of every AGV in the multi-AGV system, and the corrective and periodic preventive maintenances of failed AGVs are modelled using the approach of Coloured Petri Nets (CPNs). Then, a GA is adopted for optimising the maintenance and associated design and operation of the multi-AGV system. From this research, it is disclosed that both the location selection of the maintenance site and the maintenance strategies that are adopted for AGV maintenance have significant influences on the efficiency, cost, and productivity of a multi-AGV system.

1 INTRODUCTION

AGVs are increasingly used in modern society attributed to their high efficiency, accuracy, low cost and therefore significant economic benefit (Tuan, 2006).

However, with the emerging trend in modern society for AGVs designed for more complex tasks they have become larger and larger in size, where the reliability and maintenance issues in recent years are receiving increasing concern. However, to the author's best knowledge, so far there has not been sufficient research being conducted in this area except a few preliminary researches (Vis, 2006). For example, three major hazards, i.e. collision, tilting over and falling, have been identified during the operation of AGVs (Trenkle, 2013); as well as a combined Markovian model and a neural network were applied to maximise the reliability of AGVs and minimise their repair cost at the same time (Fazlollahab, 2013). Little research has been conducted to deal with the maintenance issue of failed AGVs except using a control method for enhancing the failure control management of both loaded and unloaded AGVs in an underground transportation system (Ebben, 2001). For this reason, the purpose of this research is to fill this technology gap through developing an optimal maintenance strategy for a typical multi-

AGV system. At present, preventive and corrective maintenance are two basic strategies that are popularly adopted in engineering practice (Smith et al., 1973). In the past decades, there have been a number of research studies conducted to optimise the maintenance strategies dedicated to various kinds of industrial applications. For example, a simulation was carried out to evaluate the performance of manufacturing production lines with different maintenance policies (Lei, 2010); The maintenance cost and availability of an aircraft system was optimized using a mathematical replacement model (Fornlöf, 2016) and so on.

In this paper, both preventive and corrective maintenance strategies dedicated to a multi-AGV system are studied by the combined use of a Coloured Petri nets (CPN) simulation model and a specifically designed Genetic Algorithm (GA) model.

The remaining part of the paper is organised as follows. A brief description of the multi-AGV system considered in the paper is given first in [Section 2](#); the potential of the CPN in describing the paths, routing and maintenance issues of the AGVs is explored in [Section 3](#); the maintenance strategy of the multi-AGV system is optimised with the aid of GA in [Section 4](#); and the paper is finally ended with a few key research conclusions in [Section 5](#).

Table 1. Presumed time duration of every phase.

Phase	Phase length (hours)
1	0.02
2	0.2
3	0.02
4	0.2
5	0.02
6	0.2

2 CONFIGURATION OF THE MULTI-AGV SYSTEM

The AGV transport system described in (Yan, 2017) is also considered in this research. However, instead of considering a single AGV, a more complicated transport system consisting of three AGVs will be investigated in this paper. This will allow the investigation of the interactions between different AGVs and the impact of the failure of either one or more AGVs on the operation of the others in the same transport system. In addition, it is worth noting that in this research the subsystems of the individual AGVs are assumed to fail 12 times every year, as cited in (Yan, 2017). The mission of the AGVs is divided into six phases, namely (1) mission allocation and route optimization, (2) dispatch to station, (3) loading of item, (4) travelling to storage, (5) unloading and (6) travelling back to base. In order to facilitate the research, the time duration of every phase is presumed and listed in Table 1 for demonstration purpose. They would be different when the AGV is requested to deliver different types of missions.

In the model, it is assumed that the AGV will be taken away from the system immediately to prevent deadlock and conflicts as long as it fails, so that the downtime of the system due to AGV failures can be minimised. To meet such a need, it is essential to optimise the location of the maintenance site in the system to enable the recycle vehicle (the vehicle collecting the failed AGV) to reach and recycle the failed AGV in the shortest time.

3 SIMULATION MODELLING

3.1 Coloured Petri Nets (CPNs)

Attributed to the unique efficiency and cost-effectiveness features, modelling has been identified as one of the most important approaches to improve the design and operation of a system. In particular, a Petri net (PN) is regarded as one of the most economic and effective tools to model AGV systems (Wu, 1999; Nishi, 2010). The concept of a PN was developed by Petri (1962), which is a direct bipartite

graph. It consists of four types of symbols, i.e. circles, rectangles, arrows and tokens, as shown in Figure 1. Where, circles represent the places, which may be conditions or states (e.g. mission failure, phase failure, or component failure); rectangles represent the transitions, more abstractly actions, or events which cause the change of condition or state; Arrows connect places and transitions; Tokens are small marks that gives dynamic properties of the PN. They move via transitions if the enabling condition is satisfied. It provides an intuitive graphical representation of a system and allows flexible description of events.

What Figure 1 shows is an example explaining how the tokens move through a net. From Figure 1a, it is seen that there are two inputs and one output place connected to a timed transition with a time delay t . The input places have arcs with weights 2 and 1, respectively. Once the transition is enabled after the time delay, t , the arc weight number of tokens will be taken out from the corresponding input place to fulfil the transition after the time delay t associated with the transition. For the example, as Figure 1b shows, one more token will appear in the output place.

However, conventional PN methods are found inefficient in describing complex systems or describing a system that is designed to carry out complex tasks or missions (Jensen, 2015). To address this issue, a more advanced PN method, namely Coloured Petri nets (CPN), was proposed by Rene (1994). In comparison with the conventional PN, each individual token in the CPN is designed with a specific colour, which either has different identities or carries different information. Therefore, they are more informative than those present in the conventional PN.

3.2 System modelling

In a multi-AGV system, every AGV need to be distinguishable as they may be located at different positions in the transport system and may fail at different times. In view of the powerful capability of CPNs in describing the kind of complex situations (Wu, 2002; Aized, 2009), CPN is employed in the following research.

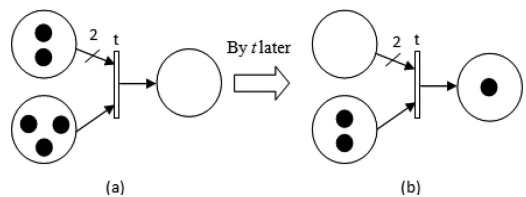


Figure 1. Enabling and switching of transition, (a) before enabling transition, (b) after enabling transition.

To correctly describe the operation and maintenance activities in a multi-AGV system, three types of CPN models are purposely developed and detailed below:

1. Path Petri nets (PPN) – for describing the layout configuration of the system;
2. Corrective maintenance Petri nets (CMPN) – for defining the corrective maintenance of failed AGVs in the system;
3. Periodic maintenance Petri nets (PMPN) – for defining the periodic maintenance of all AGVs in the system.

Herein, the CMPN and PMPN share the AGV failure information and feed their responses into PPN.

3.2.1 PPN

A three-AGV dispatching system is considered in this paper. It consists of 1 AGV base, 1 pickup station, 1 storage site, 1 maintenance site, and a number of transport paths. The base is for storing and recharging the AGVs; the pickup station is the place where items are collected; and storage is the destination for unloading the items. All these places are assumed to have sufficient space for parking multiple AGVs. To demonstrate the significant influence of layout configuration on the efficiency of recycling failed AGVs from a multi-AGV system, three different layout configurations are considered, as shown in Figure 2. Where, MS indicates the location of the maintenance site.

From Figure 2, it is seen that different layout configurations are distinguished by the different locations of maintenance site and the extra paths for recycling failed AGVs. For example, in Figure 2a the maintenance site shares the same space with the base; in Figure 2b the maintenance site is located between the base and the storage. In addition, an extra path between the pickup station and the maintenance site is designed to prevent deadlock caused by the breakdown of AGVs; in Figure 2c the maintenance site situates at the centre of the system. Accordingly, three extra paths are designed to assure its accessibility to the AGVs that could fail at anywhere of the system. Based on the aforementioned designs, the PPN models for these three different layout configurations can be readily constructed by defining the movement directions of the AGVs. For example, the PPN for the configuration in Figure 2b is shown in Figure 3, where only one direction of movement is enabled, and the dotted arrows represent the information flows coming from other CPNs. The tokens in the figure represent AGVs. Once the required action is completed a token from other CPN enables the corresponding transitions.

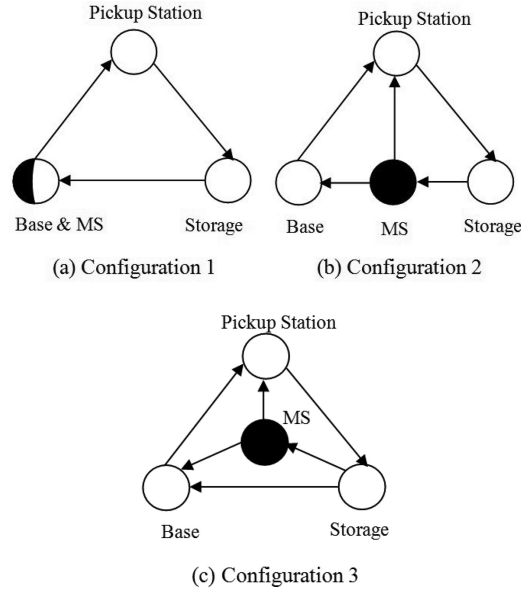


Figure 2. Three layout configurations.

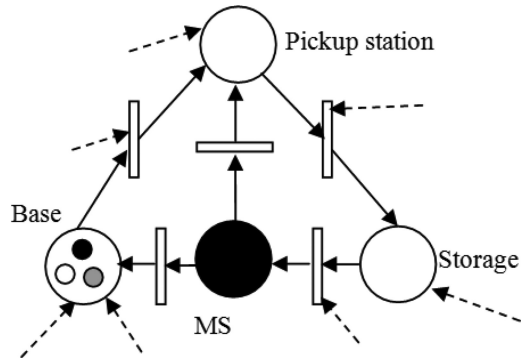


Figure 3. PPN for the configuration in Figure 2b.

Then, the AGV token with the same colour can move to the place of the next station.

3.2.2 Corrective Maintenance Petri Nets (CMPN)

Once the failed AGVs are recycled and towed back to maintenance site, the corrective maintenance will be implemented immediately if the maintenance engineers are available to work on the failed AGV. However, once the maintenance engineers are unavailable, the failed AGVs will have to queue. On completing the corrective maintenance, the recovered AGV will be assumed having a perfect condition as a brand new one does. In the meantime, the maintenance engineer who undertakes

the repair of this AGV will be released. They will become available to undertake the repair of other failed AGVs. In the model, a normal distribution function is employed to describe the repair time of the failed AGVs. The developed CMPN model is shown in Figure 4. Once a token exists in both 'Failed AGVs recycled' and 'Available engineering' places, the token will be produced in 'under repair' place. Following the repair process, the AGV will be back to the healthy state. This will be indicated by a token produced in the 'Up' place.

3.2.3 Periodic Maintenance Petri Nets (PMPN)

A PMPN model that considers periodic maintenance has been developed and is shown in Figure 5. Likewise, in this model the recovered AGVs are assumed having perfect health condition as a new one does.

It is worth noting that in the model shown in Figure 5 the three transitions with different colours indicate the failure time of the three AGVs in the system. For the simplification, a simple corrective maintenance policy is taken in this research, i.e. all AGVs in the system will receive periodic maintenance in spite of their actual health condi-

tion. Moreover, the corrective maintenance will last only for 2 days regardless of the actual condition of the AGVs. For example, in Figure 5 it is assumed there are m AGVs in healthy condition and n AGVs in faulty condition. The healthy AGVs are in 'Up' place and faulty AGVs are in 'Failed AGVs recycled' place. Regardless the actual health status, all AGVs will receive periodic maintenance. Therefore, there will be $m+n$ tokens in 'Periodic Maintenance' place. Accordingly, all AGVs in the system will not start to work until the 2-day period of corrective maintenance expires. On the expiry of the period of corrective maintenance, all AGVs in the system are assumed to have perfect health condition as a brand new one does.

3.3 Simulation results

By integrating the above CPN models, a more comprehensive model can be readily obtained, which not only considers the specialities of the layout configuration but also considers the maintenance processes of the AGVs. In order to verify the model and investigate the influences of different maintenance strategies on the operational performance of a multi-AGV system, an algorithm has been developed to simulate the comprehensive model, the input variables of which include the failure rate and repair rate of all AGVs, the time taken to perform periodic maintenance, and phase lengths that are required by the AGVs to deliver assigned tasks.

Firstly, the influence of different layout configurations on the recycle time of failed AGVs is investigated. In the layout configurations described in Figure 2b and c, separate maintenance sites are designed. Such a design significantly reduces the risk of conflict and deadlock and therefore improves the efficiency of the recycle process, although with the cost of extra space and extra routes to enable the operation of such a design. The simulations considering all three types of layout configurations are performed and the corresponding recycle time calculation results are listed in Table 2. From the table, it is found that when the maintenance site is placed in the centre (see Figure 2c), the recycle time will be the minimum.

Subsequently, the influence of different maintenance strategies on the performance of the multi-AGV system is investigated. Assume the operation time of the system is 10 hours per day, the corresponding simulation results obtained for the layout configuration illustrated in Figure 2b are listed in Table 3. In the table, the number of missions completed is employed as a criterion for performance assessment.

From Table 3, it is found that if without applying any maintenance strategy within the period of

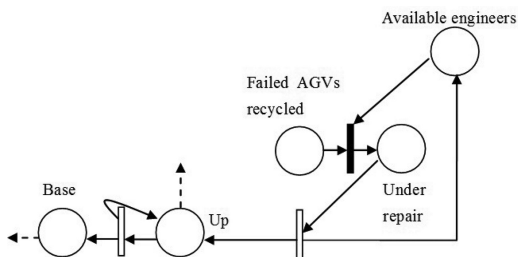


Figure 4. CMPN model.

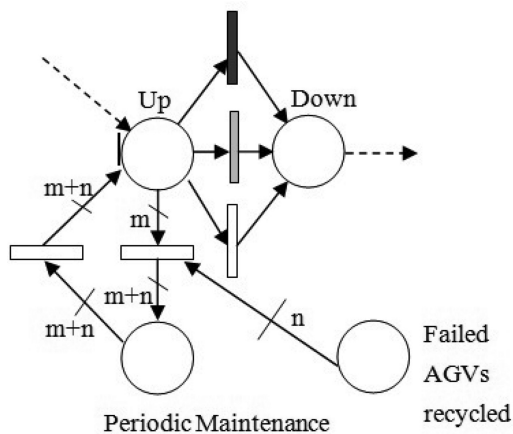


Figure 5. PMPN model.

Table 2. Recycle time.

Location indicated by	Recycle time (hours)	Extra space (unit)	Length of extra route required (unit)
Figure 2a	0.132	0	0
Figure 2b	0.128	1	$\sqrt{3}/2$
Figure 2c	0.101	1	$3\sqrt{3}/4$

Table 3. Number of completed missions.

T	P	N1	N2
7 days	0.03	11518	11840
1 month	3.93	12840	15264
3 months	36.32	9372	15972
6 months	77.34	6084	16142
12 months	98.06	3280	16234

Note: T—Time interval of periodic maintenance; P—Percentage of AGVs failed within the time interval if there is no maintenance (%); N1—Number of missions completed per year with periodic but without corrective maintenance; N2—Number of missions completed per year after taking both periodic and corrective maintenance.

12 months, 98% of AGVs will fail after completing 3280 missions. This fully highlights the added value and the necessities of conducting appropriate maintenance to the AGVs during their service life. Moreover, the larger values of N2 than the corresponding values of N1 prove that the corrective maintenance can actually enhance the performance of the multi-AGV system, i.e. the corrective maintenance can help to keep long-term high efficiency of the system, although it could cause extra financial and labour costs.

4 OPTIMISATION OF MAINTENANCE STRATEGY

4.1 Genetic algorithm

The results obtained from the CPN simulations can be used as factors for optimising the maintenance strategy of the AGV system. Since the resultant optimal maintenance strategy is desired to lead to a cost effective and time efficient operation of the multi-AGV system, the optimisation considered in this research becomes a typical multi-objective optimisation problem. In the paper, Genetic Algorithm (GA) is employed to carry out the optimisation. Nowadays, the GA has been regarded as one of the most popular tools to solve this kind of multi-objective optimisation problem attributed to its

powerful capability of conducting optimisation in a global range regardless of initial conditions and other derivative factors. Inspired by the biological evolution of living species, GA was first introduced by John Holland in 1970s (Holland, 1975). GA has been well applied for solving the scheduling and dispatching problems to AGV systems. For example, Reddy and Rao applied GA to minimise the make-span, mean flow time and mean tardiness at the same time (2006). A GA based simulation approach was proposed to find the optimal dispatching rules in complex environments (Chang et al., 2013).

To implement the GA optimisation, an initial population of individuals (also known as chromosomes consisting of genes) will be generated. The fitness of each chromosome is evaluated subject to the predefined objective functions. By selecting pairs of parents in the population, new chromosomes or children can be generated. This is known as crossover. The chromosomes with the higher fitness are more likely to be selected so that their genes can be passed on with higher probability. A mutation might also be involved to prevent early convergence of the solution. Through repeating such a process, the chromosomes with larger fitness values can be obtained until an optimal solution is reached.

4.2 Fitness functions

Following this idea, a GA program is developed in the research to optimise the multi-AGV system. The flowchart of the GA program is shown in Figure 6. The parameters used in the calculation are listed in Table 4. The following two objective functions are defined to optimise the system design:

Objective function 1: The maximum number of missions completed within a given time

$$Mission = \max(N_m \cdot N_p - T_{rc} \cdot N_f / T_m) \quad (1)$$

Objective function 2: The minimum cost for completing the missions

$$Cost = \min \left(\frac{N_a \cdot N_p \cdot C_p + N_f \cdot C_c + N_e \cdot C_e}{C_{ms} + N_m \cdot C_a + L_r \cdot C_r + C_{lm}} \right) \quad (2)$$

where $N_p = 365/T$ is based on the assumption that there are 365 days in a year.

Based on the aforementioned two objective functions, a fitness function is developed as

$$fitness = \frac{Mission}{Cost} \quad (3)$$

The maintenance strategy is optimised subject to:

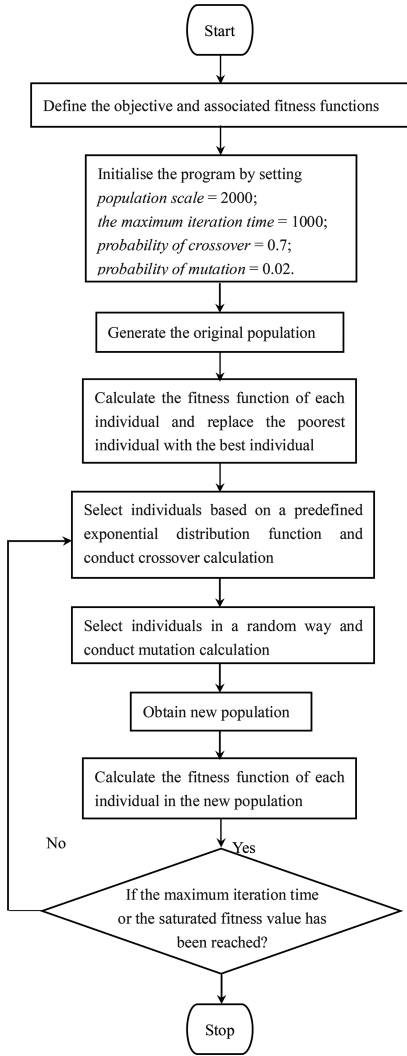


Figure 6. Flowchart of the GA based optimisation program.

$$\text{number of mission completed} \geq 10000 \quad (4)$$

$$\text{probability of all AGVs failed} \leq 0.1 \quad (5)$$

where, equation (4) means that the number of missions required to complete within one year is not less than 10,000; equation (5) means that the probability of all AGVs fail is not larger than 10%.

4.3 Selection

In the program, an exponential function is specifically defined for simulating the ‘survival of the

Table 4. Parameters used in GA program.

Parameters	Symbol	Value
Number of AGVs	N_a	3
Operation cost of an AGV to complete a single mission	C_a	8
Business costs of maintenance site per year	C_{ms}	10000 – with corrective maintenance 5000 – without corrective maintenance
Land cost for maintenance site per year	C_{lm}	1000 – Share site with AGV base 5000 – Separate site
Number of missions completed per year	N_m	See the values of N1 and N2 in Table 3
Time interval of periodic maintenance	T	See the values of T in Table 3
Periodic maintenance cost per AGV	C_p	400
Recycle time	T_{re}	See the values of recycle time in Table 2
Average time to complete a mission	T_m	0.66
No. of maintenance engineers on site	N_e	1
Cost of one Engineer in a year	C_e	25000
Total number of failures occurring in the system with corrective maintenance per year	N_f	14 (results obtained using PN)
Average cost for conducting corrective maintenance of an AGV failure	C_c	200
Extra route length	L_r	See the values of Length of extra route required in Table 2
Cost of per unit length extra route	C_r	1000

fittest’ principle in natural evolutionary process. For the i -th individual, its probability P_i being selected for participating in GA crossover calculation can be expressed as:

$$P_i = \frac{e^{w(f_i - f_{\min})}}{\sum_{j=1}^N e^{w(f_j - f_{\min})}} \times 100\% \quad (6)$$

where N denotes the size of population scale; f_i is the fitness of i -th individual; f_{min} is the fitness of the poorest individual; and w is a constant for controlling the efficiency of population evolution. It is worth noting that the larger the value of w , the more efficient the evolution tends to be. But it should be aware that too large a value of w would lead to risk of failure to obtain global optimisation results. In this research, w is taken to be 100.

4.4 Coding

It should be noted that there are three major factors, namely the period of periodic maintenance, the system configurations and the adoption of corrective maintenance. Their values are obtained from the CPN simulations. Hence the variation ranges of these factors need to be controlled by constraints. These three parameters are coded into binary numbers and then connected together to create a single ‘chromosome’.

4.5 Crossover operator and mutation operation

The crossover operation is applied to two randomly selected chromosomes with the crossover rate of 0.7. A one-point crossover is adopted with an illustrative example shown in [Figure 7](#).

The alternating position can be chosen at any point within the chromosomes. By combing two sets of genes from both parent generations, an offspring chromosome can be produced. The operation of mutation illustrated in [Figure 8](#), maintains genetic diversity of the population and prevents the solutions trapping to the local best. It is also implanted with a fixed mutation rate of 0.02.

4.6 GA results and discussion

Using the developed GA program the location of maintenance site and the maintenance strategies of the multi-AGV system are optimised through integrating the two objective functions into one fitness function, i.e. the unit mission cost shown in equation (3). To illustrate the effectiveness of the GA optimisation, a numerical example has been taken. By applying the parameters defined in [Table 4](#) to the program, the population starts to evolve gradually. The resultant variation tendency of average fitness against the number of evolution times is shown in [Figure 9](#).

From [Figure 9](#), it is found that after the population is evolved for about 200 times, the average fitness reaches a saturated value. That means the optimal design of the multi-AGV system is achieved through 200 times of evolution calculations. The optimised results are listed in [Table 5](#).

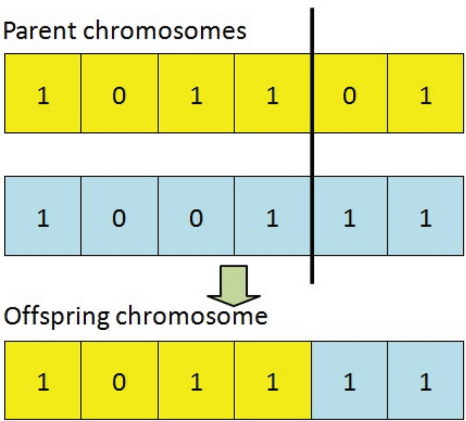


Figure 7. One-point crossover operator.

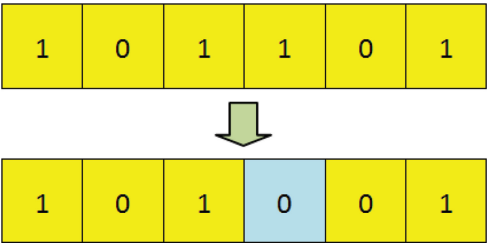


Figure 8. Mutation operator.

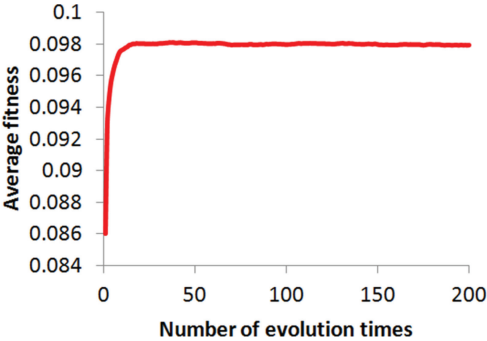


Figure 9. Evolution of GA population.

Table 5. Optimal results obtained from GA.

With corrective maintenance?	Yes
Location of maintenance site	In the AGV base
Time interval of periodic maintenance	12 months
Total cost (£)	164872
Mission completed per year	16231

From Table 5, it is found that

- The corrective maintenance is indeed essential for maintaining the long-term high efficiency of a multi-AGV system;
- Arrange the maintenance site to share the same place with the AGV base will save the cost on land, therefore result in the minimum unit mission cost;
- The positive influence of periodic maintenance on improving the performance of the system cannot be demonstrated if the ageing issue of the AGVs is not taken into account in the optimisation.

5 CONCLUSIONS

In order to develop a feasible and efficient approach to optimising the design, operation, and maintenance of a multi-AGV system, the CPN simulation models and the GA-based optimisation approach are developed in this research. From the research results described above, the following conclusions can be drawn:

1. The combined use of CPN and GA has been demonstrated an effective approach to assessing the performance of multi-AGV systems;
2. This hybrid approach enables the prediction to the optimal time interval of periodic maintenance and the assessment of the influence of correct maintenance on system efficiency;
3. The optimisation of the location of maintenance site and maintenance strategies can be skilfully converted to be a simple single objective optimisation problem with the fitness function of unit mission cost;
4. The corrective maintenance is an effective measure to maintain the long-term high efficiency of the system, although it may lead to extra maintenance costs.

Future work of this research will focus on dealing with more complex AGV systems.

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