Integrated automated guided vehicle design problem and preventive maintenance planning

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Providing an integrated mathematical model for automated guided vehicle design problem and preventive maintenance planning

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Abstract

Nowadays, automated guided vehicles (AGVs) play a key role in manufacturing systems because of improving system efficiency and lowering the cost of production. To increase the efficiency and stability of AGVs, it is crucial to consider maintenance planning for them. To the best of our knowledge, it is rarely found studies related to maintenance planning and AGVs' design and control. Accordingly, in this paper, a new integrated nonlinear mathematical model is developed for optimizing the AGV design (including AGV fleet sizing and AGV assignment to workshops) and preventive maintenance policy. The proposed model aims to determine the preventive maintenance cycles, an optimal number of employed AGVs in manufacturing, and the optimal assignment of AGVs to manufacturing workshops so that the total cost is minimized. To solve this model, a genetic algorithm (GA) is developed, and their performance is compared with the global solver of LINGO software on 15 test problems, some of which are large dimensions. In order to tune the GA parameters, a Taguchi method is used. Moreover, a sensitivity analysis is performed to represent the validity of the model and solution approach. The results have demonstrated the effectiveness of GA in terms of computational time and solution quality.

Abstract: Automated Guided Vehicle, Preventive Maintenance, Genetic Algorithm, Sensitivity Analysis

1. Introduction

The AGVs have been used as an important part of material handling in inside and outside environments such as manufacturing systems, warehouses, cross-docking centers, and container terminals since their introduction [1]. They can realize intelligent manufacturing for the industrial 4.0 era ([2],[3]). They can bring many benefits to any environment in which they are used, including reduced costs, improved safety as well as productivity, routing flexibility, and reduced material damage [4]. The issues which are addressed for the AGV system can be divided into two categories: (1) AGV design and (2) AGV control. The design concerns the flow path layout, the number of employed AGV, the traffic flow pattern, buffer capacity for vehicles, location of pickup and delivery stations, and AGV assignment to workshops. On the other hand, the control issues cover dispatching, scheduling, and routing problems of AGVs. Two of the most important design issues are to determine the optimal number of employed AGV and the optimal AGV assignment to workshops. In the first issue, the minimum number of AGVs required in the system has to be determined because the underestimated number of them does not guarantee that all jobs are performed within desirable time while overestimated number leads to more congestion [5]. The goal of the second issue is to assign the AGVs to manufacturing workshops so that only the AGV allocated to one workshop is responsible for transferring of tasks from the same workshop to other workshops and even the warehouse.

Each AGV consists of several subsystems such as a laser navigation system, safety system, battery, brake system, and steering system. Each of these subsystems can be encountered with random failure and make AGVs unavailable. Therefore, AGVs cannot perform their duties properly in such circumstance and this influence on the efficiency of the system. An appropriate maintenance policy can ensure the availability of AGVs and increase system efficiency and performance [6]. Corrective maintenance and preventive maintenance are two basic categories of maintenance. Maintenance that is regularly performed on each equipment to decrease the probability of its failure and keep them up to date and functional is named preventive maintenance (PM). On the other hand, corrective maintenance (CM) involves any task that resolves the occurred failures with equipment and returns it to a proper operating state. In practice, some actions such as cleaning, oil changes, lubrication, repairs, adjustments, inspecting and replacing parts, and partial or complete overhauls that are periodically scheduled are included in a PM schedule. In an AGV consisting of different subsystems, reliability and availability as two main factors for increasing the system efficiency can be achieved by replacing and repairing critical subsystems [7]. An unplanned stop resulting from the random failure of any subsystem can reduce the performance of AGVs and therefore the system cannot meet the consumer demand and face higher costs. Thus, a PM schedule can reduce costs by increasing reliability and availability. There are many papers about AGV design problems that integrate the types of issues above-mentioned. But, most of them assume that AGVs can act at their maximum capacity (nominal capacity) while this assumption is not real because in a real environment an unexpected failures can influence the system efficiency and capacity. In this state, AGVs work with a real capacity that is usually less than nominal capacity. Although when a random failure takes places for AGVs, both cost and time for PM plan are needed to maintain them and return to a suitable status and this follows fewer completed missions through the horizon planning, but in another hand, a PM plan will generally reduce the total cost by increasing the availability and reliability of AGVs in manufacturing system. The purpose of this paper is to provide an integrated mathematical model of AGV design and PM scheduling. Also, the research questions are:

1. What kind of AGV is assigned to each workshop?
2. How many AGVs are placed in each workshop?
3. What is the size of the maintenance cycle for each selected AGVs in the manufacturing system?
4. What is the effect of AGVs speed, AGV capacity, and workshop distance on the objective function value (overall cost)?

In this model, the optimal maintenance policy for each kind of AGV as well as the optimal AGV fleet size and assignment of them to workshops is determined. Generally, the main considered innovations in this paper are as follows:

1. A new mathematical model that considers the AGV design problem and maintenance planning simultaneously is developed.
2. A multiple AGV-based job shop with various AGVs in capacity and speed is considered in the proposed model.
3. There is both a regular periodic inspection and a repair/replace action after random failure in developed PM.
4. A genetic algorithm is used to solve problems, especially for large-sized ones.
5. A sensitivity analysis is applied to investigate the effect of several important parameters on the objective function value.

The remainder of the paper is organized as follows. A review of the literature on the AGV design problem and AGV and maintenance planning problem is included in Section 2. In Section 3, the problem is introduced and in Section 4, the mathematical representation of the problem is developed. In Sections 5, a genetic algorithm is described in detail. In Section 6, several examples are generated to illustrate the efficiency of the model and algorithm. Section 7 is associated with sensitivity analysis and finally, the conclusions and future researches are stated in Section 8.

2. Literature review

Various papers have been published about AGV design and control after introducing them in 1955 [8]. Several studies are in the design fields, for example, Nishi et al. [9] discussed the guide path of AGV systems. Also, Ryck et al. [10] designed a charging station into an AGV-based manufacturing system. Fransen et al. [11] developed a path planning for AGVs. Dehnavi-Arani et al. [12] determined the optimal dwell location for AGVs in a cellular manufacturing system. Other papers such as [13], [14], [15], [16],

[17], [18], [19], [20], [3] focused on a design problem. Some other studies considered the control issue of AGVs. For instance, Vale et al. [21] evaluated the navigation of AGVs in nuclear fusion facilities. Mahaleh and Mirroshandel [22] addressed path detection for an AGV-based system. Wang et al. [23] investigated a novel scheduling problem for AGV in workshop environments. Bae and Chung [24] presented an AGV routing problem. Other papers can be mentioned in control field such as [25], [26], [27], [28], [29], [30], [31], [32]. Also, there are several comprehensive review studies in the literature that the readers can refer to for a better understanding like [33], [34], [1], [35]. In this section, initially, several studies on AGV fleet sizing and assignment are reviewed, then studies on integration of maintenance and AGV issues are reviewed.

2.1. AGV fleet sizing and assignment

The goal of the fleet sizing model is to determine the number of employed AGVs in a manufacturing system. In literature, both analytical model and simulation methods are mostly utilized to determine the optimum number of AGVs. For example, Valmiki et al. [36] determined the estimation of fleet size of AGVs in a flexible manufacturing system by simulation. The objective of their method was to minimize the travel time or overall cost. Yifei et al. [37] developed analytical and simulation methods simultaneously to find the optimum number of AGVs in a flexible manufacturing system. Pjevcevic et al. [38] designed a decision-making approach based on data envelopment analysis to determine the fleet size of AGVs at a port container terminal. They used simulation to solution approach in their paper. Chawla et al. [39] developed a mathematical model to determine the number of AGV in a flexible manufacturing system. The solution approach was the gray wolf optimization algorithm in their article. Choobineh et al. [40] also used an analytical model based on queuing network to find the optimal AGV requirement. Koo et al. [41] used a queuing model for fleet sizing procedure. Liu and Ioannou [42] minimized the number of AGVs for achieving zero idle time in AGV-based job shops. They used heuristic and Petri net theory to solve this analytical model. In Chang et al. [43] also a simulation-based framework was represented for AGV fleet size. Some papers are associated with AGV assignments such as Angeloudis and Michael [44] that they studied the AGV assignment problem in a container terminal under uncertainty. They also used a simulation method for earning the desirable factors. In another paper, Huang et al. [45] optimized the AGV assignment for dynamic demand of transportation in a shop floor in an uncertain environment. Mohamad et al. [46] focused on a multi-load AGV assignment in a flexible manufacturing system. In this paper, each operation of the job should be allocated to AGV. Weyns et al. [47] studied task assignment for AGVs transportation systems by a field-based approach. Recently, the requirement of the use of autonomous mobile robots in in-patient care has been developed in Kriegle et al. [48]. Fu et al. [49] determined the vehicle requirement of the AGV system based on discrete event simulation and response surface methodology. Other papers related to AGV assignment can be found in [50], [51], [52] and [53].

2.2. Integrated preventive maintenance and AGV issues model

Maintenance has been an essential sector in the context of industry 4.0 [54]. Many papers show this importance such as [55], [56], [57]. In this way, the maintenance of AGVs as widely used vehicles in smart manufacturing considered in industry 4.0 is a crucial problem. The issues of combining PM and AGV design/control are extremely rare in literature. As an example, Yan et al [58] investigated the reliability of AGVs in their paper. They analyzed the reliability by fault tree analysis and evaluated the vehicle mission reliability via Petri net method. Fazlollahtabar and Naini [7] proposed a Markovian model for flexible manufacturing systems. They considered the reliability of machines and AGVs simultaneously. Yan et al. [59] modeled the corrective and preventive maintenance of failed AGVs using the colored Petri nets. To optimize the model, a genetic algorithm has been proposed for the results of Petri nets. They modeled the problem to achieve both the location selection of the maintenance site and the maintenance strategies. Fazlollahtabar and Saidi-Mehrabad [60] developed a multi-objective mathematical model so that the objectives are to maximize the total reliability of machines and AGVs, and minimize the total repair cost. They used fuzzy goal programming to change the multi-objective model to single-objective ones. Tavana et al. [61] developed a bi-objective stochastic programming model with AGV reliability considerations. In that paper, the first and second objectives were to minimize the total cost of production and the total production time, respectively. The authors considered a job shop environment equipped with an AGV. In order to transform the bi-objective model to single-objective, they apply a perceptron neural network. Yu et al. [62] considered a reliability-based AGV online scheduling and conflict-free routing in warehouse system where AGVs quickly sort a large number of packages. The main difference between our proposed model and other approaches in other paper is that the proposed model considers PM as an AGV capacity reducer and also the probability of AGV failure reducer in a multiple AGV system. Moreover, our model integrates the AGV fleet sizing and AGV assignment to shops as two important issues in the AGV design, and maintenance model simultaneously.

3. Problem statement

Here, a manufacturing system, including several workshops, parts, and AGVs is considered. It is assumed that the process route for each job has been known. AGVs are employed to transfer the parts among different workshops. Each AGV can be assigned to one or more workshops to pick up parts from these workshops and deliver them to destination workshops while each workshop can select only one AGV type to transfer their processed parts.

There are various kinds of AGV in terms of capacity, speed of movement, purchase price, fixed cost, operational cost, and failure rate. In reality, AGVs may be failed subject to uncertain fluctuation which causes the downtime of the production system. In such a situation, AGVs cannot work with maximum capacity through horizon planning therefore failure of AGVs impacts on the number of completed emissions by them. A PM must be performed to restore AGVs into “as good as new” status and increase the AGV capacity and decrease the failure rate, and corrective maintenance is used to restore AGVs into “as good as old” status and restart the AGVs again. Of course, it should be noted that maintenance is costly. The purpose of the model is to determine the PM cycle so that the needed completed emission for horizon planning is met and the average total cost is minimized. Notably, the maintenance plan and cost for each kind of AGV in the manufacturing system are assumed the same.

An example of the above-mentioned manufacturing system has been represented in Fig 1. In this figure, there are 5 workshops and 4 AGV types. As can be seen, four AGVs type 3, three AGVs type 1, two AGVs type 1, two AGVs type 2, and one AGV type 4 have been assigned to workshops 1-5 respectively. The routes of AGVs assigned to workshops 1-5 have been represented with red, green, orange, blue, and yellow colures. Moreover, one of AGVs type 1 in workshop 3 and AGV type 4 in workshop 5 are not available because they are under PM and CM, respectively.

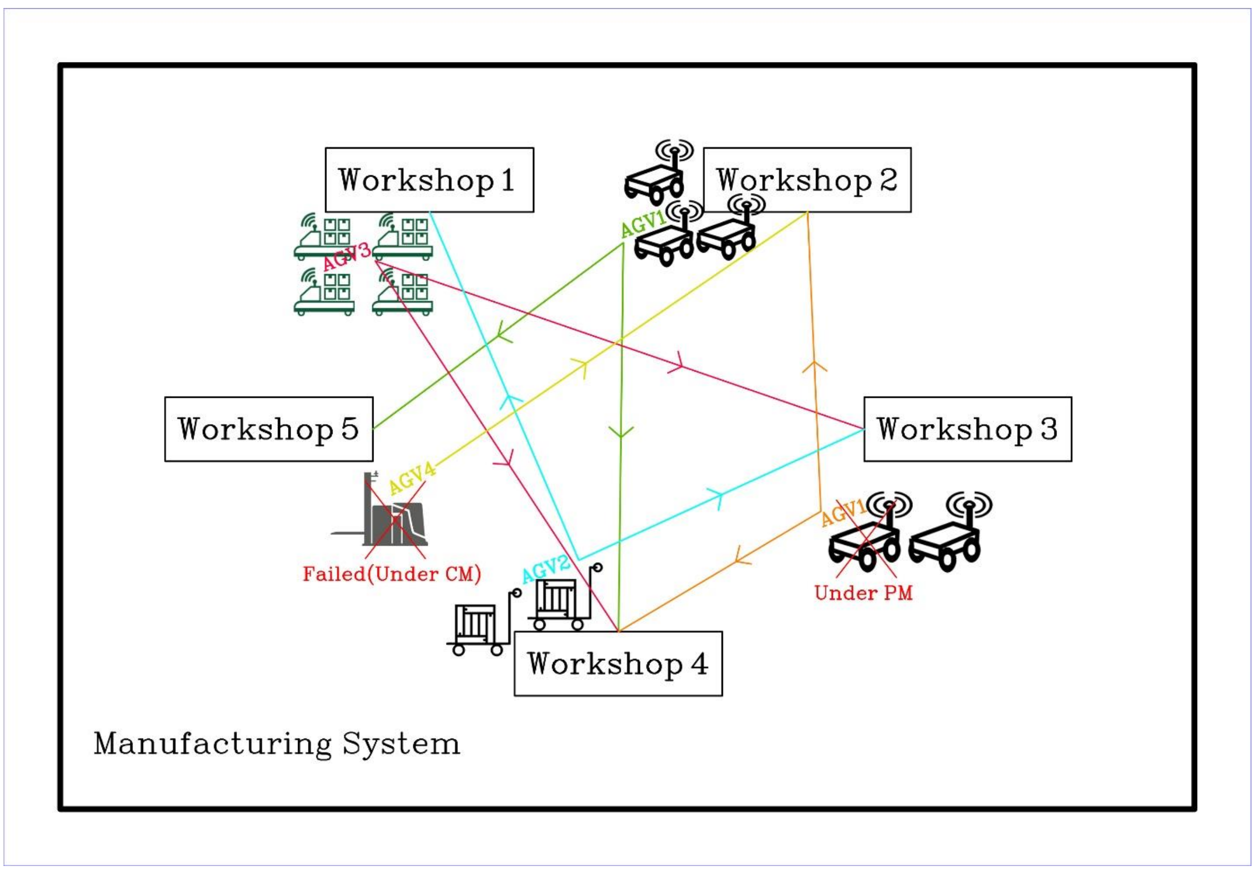


Fig. 1. A schematic view from manufacturing understudy

4. The mathematical model

The integrated model of the problem under study is described in this section. The considered sets, parameters, and decision variables are as follows:

- **Sets**

j: Index for AGV types ($j = 1. \dots . J$)

$(n. m. k. m')$: Index for workshops ($n. m. k. m' = 1. . N$)

t: Index for periods ($t = 1. \dots . H$)

- **Parameters**

fc_j: The constant cost of AGV type j (e.g. purchase cost, installation cost, etc.)

vc_j: The variable cost of AGV type j

nc_{nm}: The cost of missions that they don't complete between workshops n and m in horizon planning.

d_{nm}: The distance workshops n and m

s_j: The speed of AGV type j

cap_j: The capacity of AGV type j

Rm_{nm}: The required volume of the parts to be transferred between workshops n and m

lt_{jn}: The loading time for AGV type j in workshop n

ut_{jm}: The unloading time for AGV type j in workshop m

pr_{nm}: If there is a processing route between workshops n and m equal to 1; otherwise 0

C_{jt}: The maintenance cost of AGV type j when they have the size of maintenance cycle t

$AV_{jtt'}$: The available time for each AGV type j in the length of period t if maintenance cycle t' is selected.

Z: A big number

- **Decision variables**

N_{jn}: The fleet size of AGV type j assigned to workshop n

N_j: The fleet size of AGV type j

Tm_j: The total movement time for AGV type j

Dc_{nm}: The desirable level of missions between workshops n and m by AGV

Cm_{jnm}: The number of completed missions between workshops n and m by AGV type j

Cm_{jnmt}: The number of completed missions between workshops n and m by AGV type j in the length of period t

A_{jnm}: If AGV type j has been assigned to route between workshops n and m 1; otherwise 0

T_{jnm}: The time lasting for AGV type j from workshops n to m

Tt_{jnm}: The total time that AGV type j needs from workshops n to m to complete its mission

x_{jt}: If AGV type j select the size of maintenance cycle t equal to 1; otherwise 0

- **Objective function**

The objective function of the proposed model is as Eq. (1):

$$min \quad \sum_{j=1}^{J} fc_j N_j + \sum_{j=1}^{J} vc_j Tm_j + \sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{m=1}^{N} nc_{nm} \max(0. Dc_{nm} - Cm_{jnm})$$

$$+ \sum_{j=1}^{J}\sum_{t=1}^{H} C_{jt} x_{jt} \qquad (1)$$

The first term of the objective function is a constant cost for all of the AGVs used in the production system. This cost is obtained by the sum of the product of the fleet size of AGV type j and their associated costs such as purchase cost, installation cost, etc. The second term shows the variable cost of employed AGVs. This cost is the sum of the product of the total time of movement for AGV type j (i.e. the AGV workload) and their associated cost. The third term calculates the total cost for uncompleted missions through horizon planning. It is the sum of the product of maximum between zero and deviation of completed mission and desirable level of completed mission from workshops n to m, and their associated cost. The final term is related to the total maintenance cost which is the sum of the product of maintenance cost if AGV type j select the size of maintenance cycle t. The maintenance cost C_{jt} is obtained as follows:

- **Maintenance cost**

In this paper, the developed maintenance model by Yalaoui et al. [63] is used. It is assumed that the failure rate has a probabilistic function as the Eq. (2):

$$r_j(t) = \frac{f_j(t)}{1-F_j(t)} \quad \forall j \epsilon j, t \epsilon H \qquad (2)$$

Where $f_j(t)$ is the probability function and $F_j(t)$ is the cumulative distribution function of time's failure of each component (i.e. component means AGV in this paper). The horizon planning is divided into H periods with a length of τ. It is assumed that the PM of each AGV is performed in the first period of each maintenance cycle. Also, each maintenance cycle for each AGV is MC_j which consists of g_j periods ($MC_j = g_j \tau$). Then, the PM is done at the beginning of the 1, $(g_j + 1).(2g_j + 1)$, ….,H. The maintenance cost for any AGV has a nonlinear function of both PM and CM. For each AGV type j in each cycle period of MC_j, the cost of PM is fixed and is equal to pc_j and cost of CM is estimated based on the average number of failures ($\int_0^{MC_j} r_j(t)dt$) and unit cost CM that is equal to cc_j. The PM and CM plan and costs have been depicted in Fig.2.

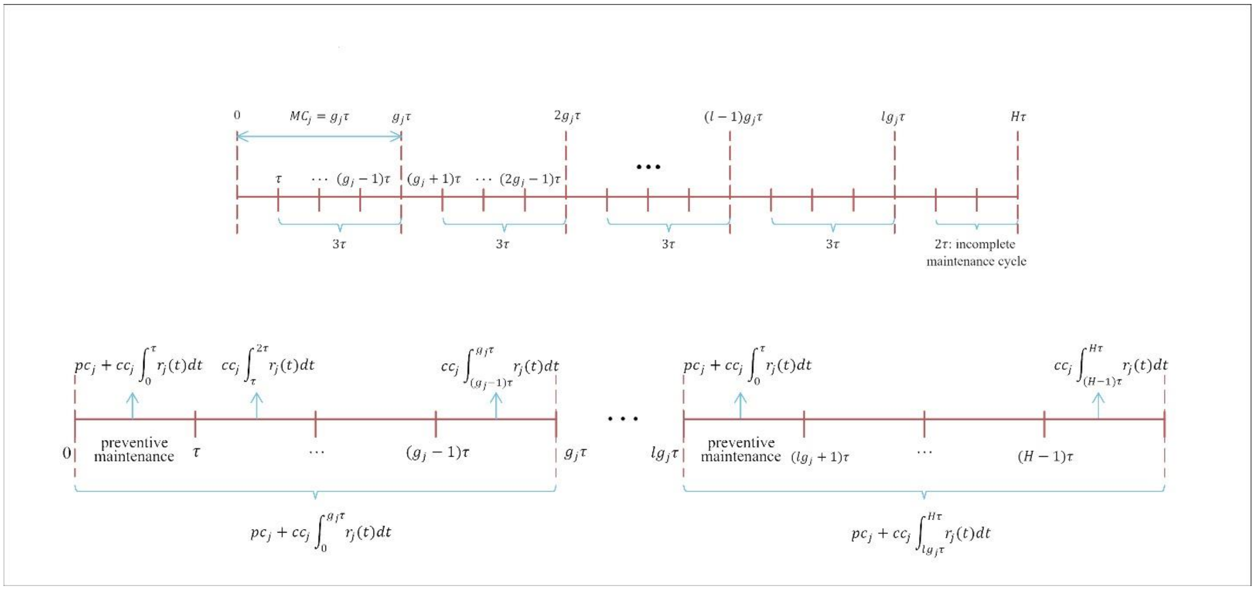


Fig. 2. The considered PM plan and cost in this study

According to [63], the maintenance cost of AGV type j when they have the size of maintenance cycle t can be computed as Eq. (3):

$$C_{jg_j} = \sum_{l=1}^{\left\lceil \frac{H}{g_j} \right\rceil} (pc_j + \sum_{t=(l-1)g_j+1.t\leq H}^{lg_j} cc_j \int_0^{\tau} r_j(u + (t - (l-1)\,g_j - 1)\tau)du) \quad (3)$$

Eq. (3) can be simplified as Eq. (4):

$$C_{jg_j} = \left\lceil \frac{H}{g_j} \right\rceil pc_j - log\left[\left(1 - F_j(g_j\tau)\right)^{\left\lfloor \frac{H}{g_j} \right\rfloor} \left(1 - F_j\left(H - \left\lfloor \frac{H}{g_j} \right\rfloor g_j\right)\right)\tau \right] cc_j \quad (4)$$

Now, based on all of the candidate cycles, all of the expected maintenance costs are calculated.

- **Constraints**

$$\sum_{j=1}^{J} A_{jnm} = pr_{nm} \qquad \forall\, n \in N.m \in N \qquad (5)$$

$$\sum_{\substack{m\prime=1 \\ m\prime \neq m}}^{N} A_{jnm\prime} \leq \left(\sum_{k}^{N} pr_{nk} - 1\right) A_{jnm} \qquad \forall j \in J.n \in N.m \in N \qquad (6)$$

$$N_{jn} \leq \sum_{m=1}^{N} pr_{nm} \qquad \forall j \in J.n \in N \qquad (7)$$

$$N_{jn} \geq A_{jnm} \qquad \forall j \in J.n \in N \qquad (8)$$

$$N_j = \sum_{n=1}^{N} N_{jn} \qquad \forall j \in J \qquad (9)$$

$$Tm_j = \sum_{n=1}^{N} \sum_{m=1}^{N} Cm_{jnm} * \frac{d_{nm}}{s_j} \qquad \forall j \in J \qquad (10)$$

$$Cm_{jnm} \leq ZA_{jnm} \qquad \forall j \in J.n \in N.m \in N \qquad (11)$$

$$Cm_{jnm} = \sum_{t=1}^{H} Cm_{jnmt} \qquad \forall j \in J.n \in N.m \in N \qquad (12)$$

$$Dc_{nm} = \sum_{j=1}^{J} \frac{Rm_{nm}}{cap_j} A_{jnm} \qquad \forall n \in N.m \in N \qquad (13)$$

$$T_{jnm} = \frac{2d_{nm}}{s_j} \qquad \forall j \in J.n \in N.m \in N \qquad (14)$$

$$Tt_{jnm} = \left(T_{jnm} + tl_{jn} + tu_{jm}\right)A_{jnm} \qquad \forall j \in J.n \in N.m \in N \qquad (15)$$

$$Tt_{jnm}Cm_{jnmt} \leq \sum_{t'=1}^{H} AV_{jtt'}\, x_{jt'}N_{jn} \qquad \forall j \in J.n \in N.m \in N.t \in H \qquad (16)$$

$$\sum_{t=1}^{H} x_{jt} = 1 \qquad \forall j \in j \qquad (17)$$

$$N_{jn}.N_j.Cm_{jnm}.Cm_{jnmt} \geq 0 \; and \; integer \; ; \quad Tm_j.T_{jnm}.Tt_{jnm}.Dc_{nm} \geq 0 \; ; \; A_{jnm}.x_{jt} \in \{0.1\} \qquad (17)$$

Constraint (5) says that if there is a processing route between two workshops so an AGV type is assigned to that route otherwise no AGV is allocated. Constraint (6) states that all AGV types that transfer parts from one particular workshop to other workshops are the same. In other words, only one AGV type can be assigned to each workshop, and this AGV transfer output of that workshop towards another. Constraint (7) determines the number of AGVs assigned to each workshop. This number should be equal or lesser than the number of AGVs assigned to routes that went out from the workshop. Constraint (8) assures that if an AGV is assigned to a route from workshop n toward any destination, the number of that AGV in that workshop should be Constraint (8) calculates the total employed AGV type j in the manufacturing system. Constraint (9) computes the total movement time for AGV type j. This movement time is considered as AGV workload. Constraint (10) ensures that if no AGV is assigned to the route between workshops n and m, the completed missions on that route will be zero. Constraint (11) ensures that the total completed missions on each route are equal to the sum of completed missions on that route in the thorough horizon planning. Constraint (12) calculates the desirable completed mission between workshops n and m. This level is obtained by dividing the required volume of the parts to be transferred between workshops n and m to the capacity of assigned AGV to workshop n. Constraints (13) and (14) compute the total time required for the movement of each AGV from workshop n into workshop m.

Constraint (15) is related to available time capacity for each AGV between workshops n and m. A detailed explanation of this constraint is given as follows. Constraint (16) indicates that each AGV type can select only one maintenance cycle time. Eventually, constraint (17) shows the kind of decision variable in the model.

- **Available capacity**

It is now time to discuss exactly how the time capacities of each route are calculated for each period of H. According to reference [63], If AGV type j is maintained with a cycle period g_j, the available capacity values are identically distributed over all maintenance cycles. So, it is sufficient that the calculations for periods of the first cycle are obtained and other cycles behavior similar to the first cycle. The capacities for periods of first cycle based on [63] is as following Eq. (18):

$$\begin{cases} AV_{j\tau} = NC_j - \theta_{jp} + \theta_{jr} \log\left(1 - F_j(\tau)\right) \quad \forall j \in J \\ AV_{j(l\tau)} = NC_j - \theta_{jr} \log\left(\dfrac{1 - F_j\left((l-1)\tau\right)}{1 - F_j(l\tau)}\right) \quad \forall j \in J.\, l = 2. \dots .\, g_j \end{cases} \tag{18}$$

Where NC_j is nominal capacity of the jth AGV in each period, θ_{jp} and θ_{jr} are amount of reduction of nominal value by PM and CM respectively and are $\theta_{jp} = \omega NC_j$ and $\theta_{jr} = \varphi NC_j$ in which $\omega, \varphi \in [0,1]$.

5. Solution approach

The nonlinear above-mentioned mathematical model has been coded in LINGO 18 software to solve the numerical examples, especially in small-sized dimensions. For medium and large-sized, a genetic algorithm (GA) is utilized to find optimal or near-optimal solutions for example. Generally, in the first stage, the cost of each AGV for each maintenance cycle and the capacity of each maintenance period are determined under candidate maintenance cycles. Also, in this stage, other parameters are entered into the model. In the second stage, the integrated model of AGV design and maintenance planning is formulated. Finally, Lingo and GA are used to determine the optimal/near-optimal obtained solutions. A schematic overview of the proposed integrated model is depicted in Fig. 3.

5.1. Genetic Algorithm

The genetic algorithm (GA) is a powerful method for combinatorial optimization problems which is proposed by Holland [52]. In GA, each problem is encoded by chromosomes in which each gene represents a feature of the considered problem. GA usually consists of five following steps:

Step 1: The population of chromosomes is initialized.

Step 2: The fitness of each chromosome is evaluated.

Step 3: New chromosomes by applying crossover and mutation to current chromosomes are created.

Step 4: The fitness of the new population of chromosomes is evaluated.

Step 5: Stop when the termination condition is satisfied and the best chromosome is returned otherwise go to Step 3.

In general, each GA method has several mechanisms that should be determined, including representation, initial population, selection, operators, fitness function, and the termination condition. These mechanisms, in the proposed GA, for the problem under this study are as follows:

5.1.1. Representation

To design a proper chromosome for the solution structure coding is the first and the important mechanism of GA. The chromosome was designed based on the model's variables and constraints. Here, each chromosome consists of the following genes:

1. The gene related to the number of AGVs assigned to each workshop and maintenance cycle which is a matrix $[X]^{n}_{1,k_n \times J}$ where $k_n = \sum_{m=1}^{N} pr_{nm}$ $\forall n \in N$, 1 is the number of row and $k_n \times J$ is the number of the column. The alleles of the matrix are limited to 0 and 1.
2. The gene associated with the number of completed missions between workshops which is matrix $[Y]^{H}_{1,k}$ where $k = \sum_{m=1}^{N} \sum_{n=1}^{N} pr_{nm}$, 1 is the number of rows and k is the number of columns. The alleles of the matrix are limited to integer numbers and follow Eq. (19) by considering Eq. (16):

$$0 \leq Cm_{jnmt} \leq \frac{AV_{jnmt}}{Tt_{jnm}} \qquad \forall j \in J, n \in N, m \in N, t \in H \tag{19}$$

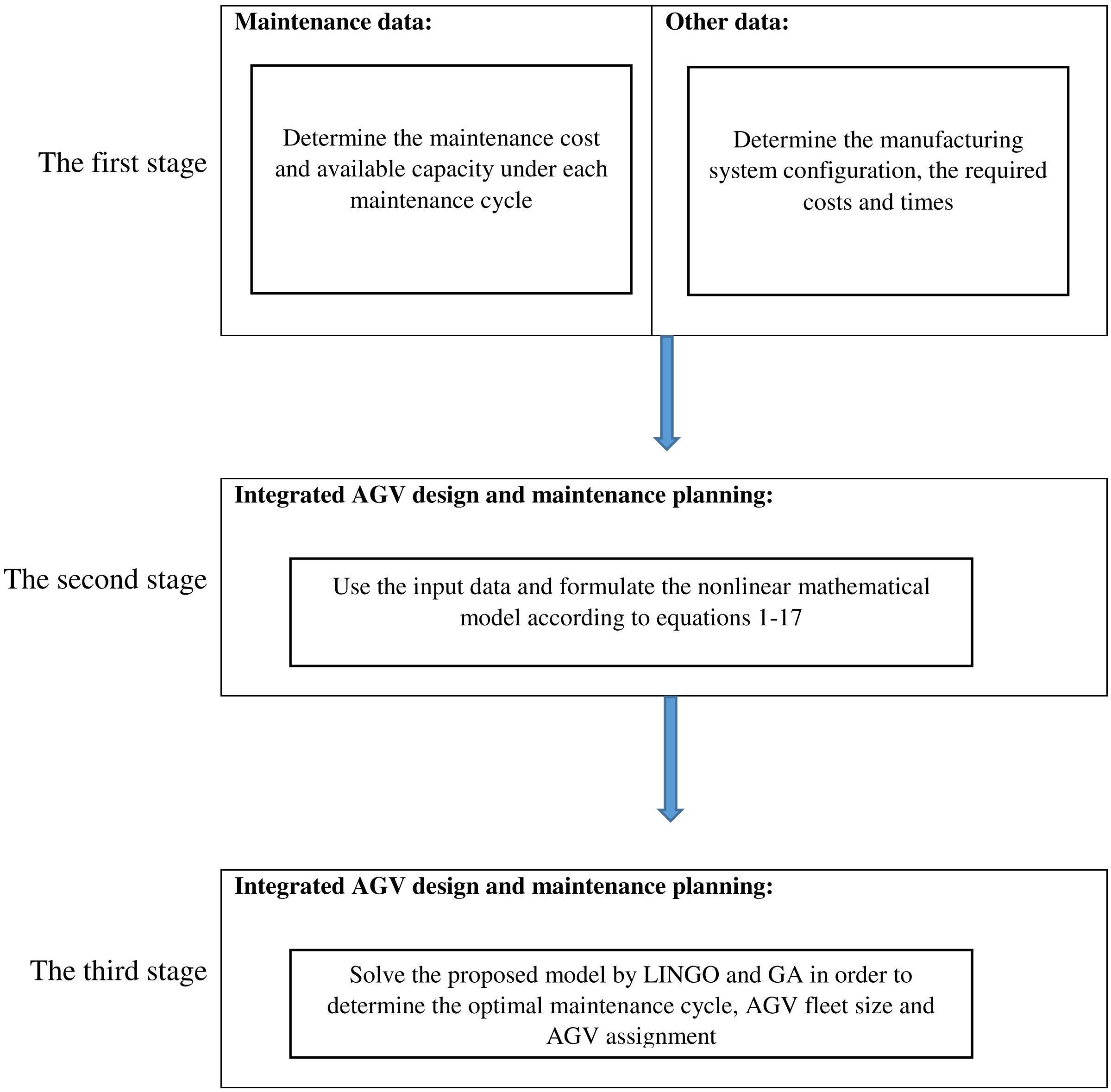


Fig. 3. An overview of the proposed model in this paper

There are other variables such as $A_{jnm}.N_{jn}.Tt_{jnm}$, etc. that they are obtained based on the defined chromosome and there is no need to define them in chromosomes separately. As an example, it is assumed that there are 5 workshops, 3 AGV types, and a horizon, including 2 periods as well as the jobs which should be transferred from a workshop toward all of the other workshops. Hence, the chromosome shown in Fig. 4 can be a solution for this example. This solution states that workshop 1 has 4 AGVs type 2 with a maintenance cycle 2, workshop 2 has 3 AGVs type 1 with a maintenance cycle 2, and workshop 3 has 2 AGVs type 3 with a maintenance cycle 1. Also, the number of completed missions between workshops 1 and 2 is 20 in period 1 and 18 in period 2; the number of completed missions between workshops 1 and 3 is 11 in period 1 and 9 in period 2, and so on.

$$[X]^1_{1.4\times 3} = [X]^1_{1.12} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 2 \quad 0 \quad 0 \quad 0 \quad 0]$$

$$[X]^2_{1.4\times 3} = [X]^2_{1.12} = [0 \quad 0 \quad 2 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

$$[X]^3_{1.4\times 3} = [X]^3_{1.12} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0]$$

$$[Y]^1_{1,20} = [20 \quad 11 \quad 10 \quad 5 \quad 23 \quad 20 \quad 12 \quad 8 \quad 12 \quad 10 \quad 20 \quad 14 \quad 6 \quad 14 \quad 20 \quad 10 \quad 13 \quad 13 \quad 5 \quad 9]$$

$$[Y]^2_{1,20} = [18 \quad 9 \quad 10 \quad 7 \quad 25 \quad 18 \quad 14 \quad 8 \quad 10 \quad 11 \quad 17 \quad 16 \quad 11 \quad 9 \quad 17 \quad 12 \quad 11 \quad 6 \quad 10 \quad 19]$$

Fig. 4. An example of considered chromosome in developed GA

5.1.2. Initial population

The initial population is a subset of chromosomes. In order to create an initial population, several feasible solutions as Fig. 4 are generated.

5.1.3. Selection

The selection is needed because it provides the opportunity to transfer the gene of a good solution to the next generation. The various selection methods are described in the literature. In this study, the roulette wheel selection is used.

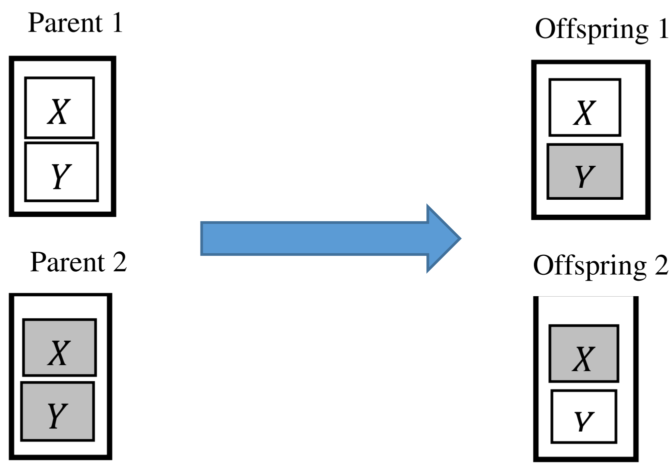
5.1.4. Genetic operators

Three kinds of crossover operators are considered in this paper: $[X|Y]$-level, $[X]$-level and $[Y]$-level. The $[X|Y]$-level crossover is to select randomly two genes $[X]$ or $[Y]$ from parents and swap corresponding matrixes. In $[X]$-level, one cut point is selected randomly on the only matrix $[X]$ in the vertical or horizontal direction, then the partial matrixes from two parents are swapped together. $[Y]$-level crossover is a two-child arithmetic crossover. In the two-child arithmetic crossover, two offspring by linear combining two selective parents are obtained. This crossover is based on Eq. (20) and Eq. (21). An example of kinds of crossover is drawn in Fig. 5 (a,b,c).

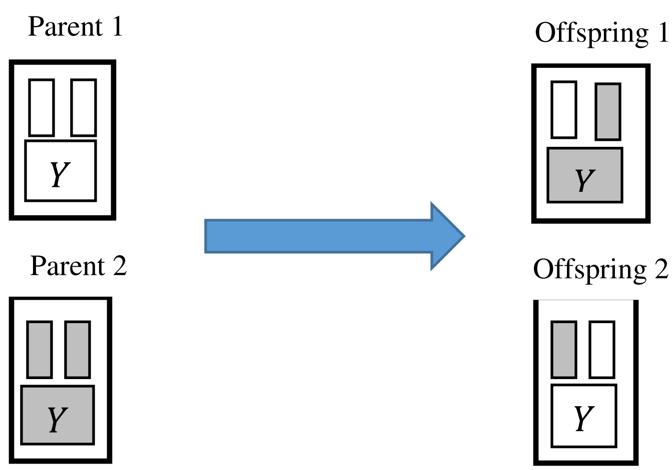
$$Y_{offspring1} = \lambda\left(Y_{parent1}\right) + (1-\lambda)\left(Y_{parent2}\right) \quad \forall\lambda \in [0.1] \qquad (20)$$

$$Y_{offspring2} = (1-\lambda)\left(Y_{parent1}\right) + \lambda\left(Y_{parent2}\right) \quad \forall\lambda \in [0.1] \qquad (21)$$

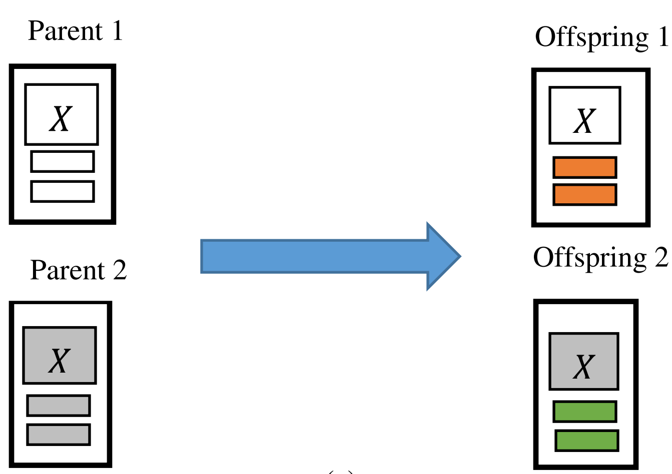
Mutation has two levels: $[X]$-level mutation and $[Y]$-level mutation. The mutation used in $[X]$-level is so that value of greater than 0 changes to 0 and other random selected genes except genes related to a value of greater than 0 change to a random number of greater than 0. On the other hand, the mutation used in $[Y]$-level is an arithmetic mutation where the value of a selected gene is reduced by the amount of Δ and then it is added to another selective gene. It should be noted that Δ should be selected so that value of the gene does not exceed its acceptable value. Fig. 6. (a) and (b) represent two kinds of mutation respectively.


Parent 1
X
Y
Parent 2
X
Y
Offspring 1
X
Y
Offspring 2
X
Y

(a)


Parent 1
Y
Parent 2
Y
Offspring 1
Y
Offspring 2
Y

(b)


Parent 1
X
Parent 2
X
Offspring 1
X
Offspring 2
X

(c)

Fig. 5. (a): $[X|Y]$-level crossover; (b): $[X]$-level crossover; (c): $[Y]$-level crossover

$$[X]_{before\ mutation} = [0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 2\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$[X]_{after\ mutation} = [0\ \ 0\ \ 4\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

(a)

$$[Y]_{before\ mutation} = [20\ \ 11\ \ 5\ \ 23\ \ 20\ \ 12\ \ 12\ \ 10\ \ 20\ \ 6\ \ 14\ \ 10\ \ 13\ \ 5]$$

$$[Y]_{after\ mutation} = [20\ \ 11\ \ 5\ \ 23-\Delta\ \ 20\ \ 12\ \ 12\ \ 10\ \ 20\ \ 6+\Delta\ \ 14\ \ 10\ \ 13\ \ 5]$$

(b)

Fig. 6. (a): $[X]$-level mutation; (b): $[Y]$-level mutation

5.1.5. Fitness function

The fitness function is the same as the objective function Eq. (1) in Section 3.

5.1.6. Stoppage condition

The stoppage condition is to reach an upper limit on the number of generations (i.e. a maximum iteration.

5.2. Genetic parameter setting

A Taguchi method is applied for tuning the parameters of GA and finding the optimum combination of effective parameters on the performance of GA. Taguchi method is based on a signal/noise (S/N) ratio that means a ratio of an average standard deviation. A higher ratio indicates better performance for parameters. The S/N ratio for the developed problem can be calculated as Eq. (22):

$$\text{S/N}= -10 \times log_{10}\left[\frac{1}{n} \times \sum_{i=1}^{n} of_i^{2}\right] \tag{22}$$

Where n is the number of observations in the experiment and of_i is the same as the objective function value. The important parameters which should be tuned for a GA usually consist of many chromosomes in a population (*NPop*), the number of iterations to reach the best result (*MaxIt*), crossover rate (*CrR*), and mutation rate (*MuR*).

In summary, the developed GA algorithm is shown in Fig. 7.

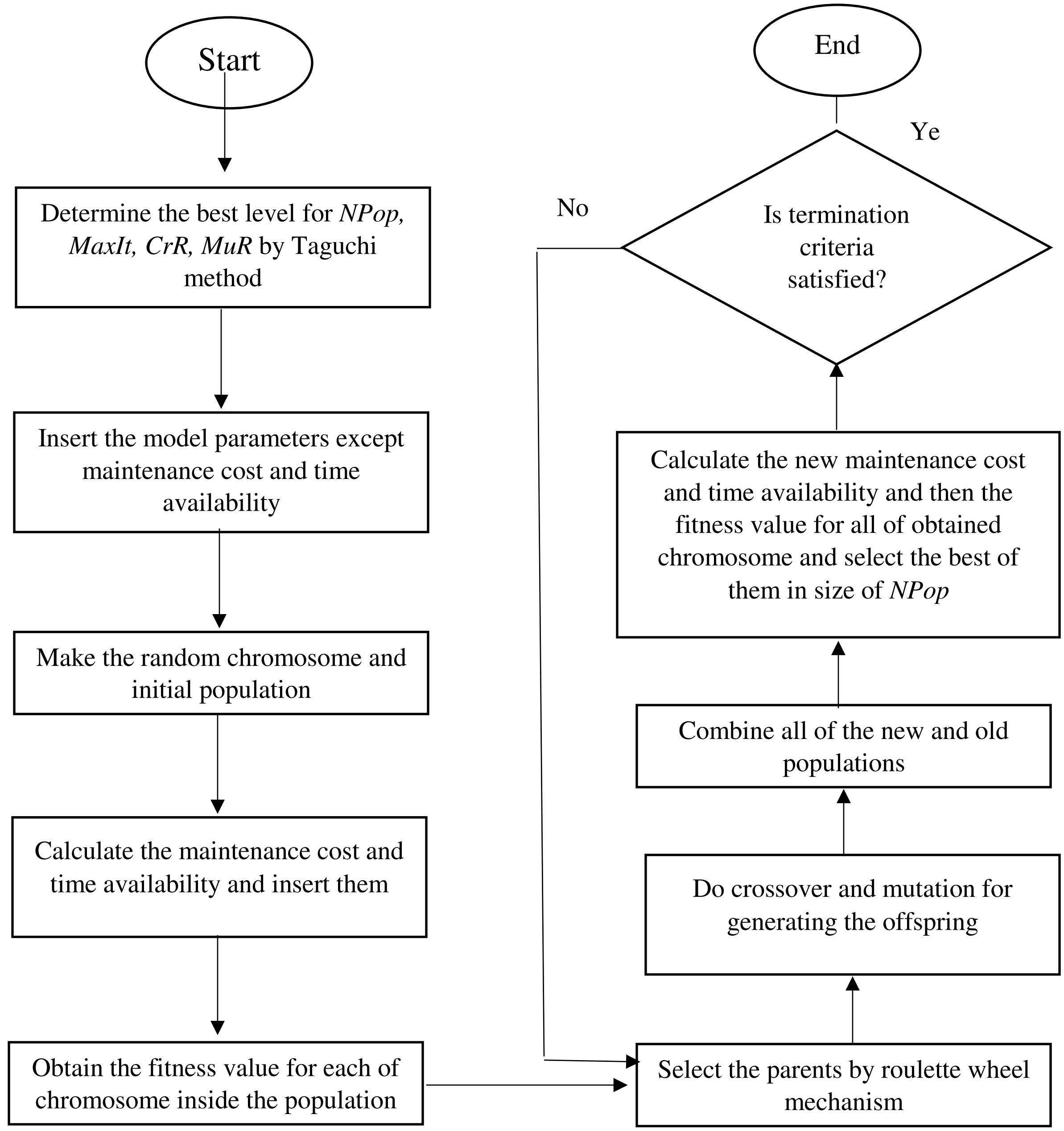


Fig. 7. The flowchart of developed GV in this study

6. Numerical example

To test the performance and efficiency of our model and solution approach, a variety of problem instances are considered. As an example, suppose there is a manufacturing system, including 5 workshops, 3 AGV types, and a horizon equal to one year with 12-period single-month ($H = 1year. \tau = 1$ month). For each of AGVs type, a specific Gamma and Weibull density function is assumed. The AGVs costs, speeds, capacities, loading and unloading times, and failure distribution are according to Table 1. In addition, it is assumed that $Z = 10^{10}$. The parameters of workshops have been given in Table 2. The nominal available in each period is 500000.400000 and 400000 for AGV type 1, 2, and 3 respectively and $\omega = 0.02, \varphi = 0.05$.

Table 1. The parameters of AGVs

AGVs type	fc	vc	**s(m/s)**	**cap**	**loading time, unloading time (seconds)**					**Function failure distribution**	**Maintenance cost**	
					workshops							
					1	**2**	**3**	**4**	**5**		pc_j	cc_j
1	700000	25	0.75	20	120, 100	145, 85	100, 150	100, 75	80, 110	Weibull (1,2)	600	400
2	640000	15	0.95	10	60, 90	160, 140	80, 60	100, 100	120, 110	Gamma (2,2)	150	50
3	970000	20	0.5	10	140,80	60, 60	90, 120	130, 110	100,90	Weibull (1,2)	1800	1000

For all AGVs, with respect to candidate cycle size; and preventive and corrective maintenance in each period, the total maintenance costs are calculated according to Eq. (4). These costs represented in Table 3 are entered into the model as parameters.

Moreover, there are the available capacities in Table 4-6 for 3 AGV types According to Eq. (18).

The problem was solved by LINGO 17.0 software with the help of the global solver tab because of the nonlinearity of the model. The proposed model has $3 \times |J| \times |N|^2 + |J|$ non-negative variable, $|J| \times |N| + |J| + |J| \times |N|^2 + |J| \times |N|^2 \times |H|$ integer variable and $|J| \times |N|^2 + |J| \times |H|$ binary variable. In addition, the model contains $7 \times |J| \times |N|^2 + |N|^2 + |J| \times |N| + |J| \times |N|^2 \times |H| + 3 \times |J|$ (excluding non-negativity, integer, and binary constraints). In the case of 3 AGVs, 5 workshops, and 12 time periods, the number of non-negative variables, integer variables, binary variables, and constraints are 228, 993, 111, and 1474 respectively. After solving, the optimal objective value is equal to 3.83×10^8. Table 7 Is related to the optimal number of AGVs assigned to workshops, the total movement times, and preventive maintenance cycles for AGVs obtained by LINGO. The optimal completed mission values for AGVs between workshops have been listed in Table 8. The optimal manufacturing system for this problem has been depicted in Fig. 8.

The above-mentioned problem known as a small-sized problem was solved by LINGO in about 30 minutes. Certainly, for problems with higher dimensions (known as a medium and large-sized problems), the computational time will be a challenging topic. Hence, a GA is applied to solve the medium and large-sized problems in a logical computational time. Here, the first above problem is solved by GA to validate and then the performance of the GA is compared with LINGO in terms of computational time and solution quality for several examples with various dimensions.

Table 2. The parameters of workshops					
Workshop (n)	**Workshop (m)**	nc	d(m)	Rm	pr
1	2	7000	80	145000	1
	3	8500	40	160000	1
	4	7300	70	0	0
	5	7000	100	152000	1
2	1	6000	80	0	0
	3	6700	50	120000	1
	4	9800	100	180000	1
	5	5500	30	100000	1
3	1	12500	40	150000	1
	2	5000	50	0	0
	4	4500	60	145000	1
	5	6000	50	172000	1
4	1	5900	70	0	0
	2	4500	100	0	0
	3	11000	60	110000	1
	5	4600	80	126000	1
5	1	7900	100	0	0
	2	6300	30	0	0
	3	10000	50	100000	1
	4	7400	80	129000	1

It is should be noted that the GA algorithm runs on MATLAB R2012a software on a PC with Intel Core i7 CPU 2.2 GHz and 6 GB RAM. Four parameters (*NPop, MaxIt, CrR,* and *MuR*) and three levels according to Table 9 take into account for setting. The Taguchi method is performed by Minitab software (version 16) and suggested an L9 orthogonal array as in Table 10. Eventually, Taguchi analysis leads to Fig. 9 which is a graphical S/N ratio. Level 3 of *NPop* i.e. 100, level 3 of *MaxIt* i.e. 150, level 2 of *CrR* i.e. 0.7, and level 1 of *MuR* i.e. 0.2 are selected for the GA algorithm to solve the previous example. Table 11 and 12 are the obtained optimal results by GA. Moreover, the optimal manufacturing by GA has been represented in Fig. 9. In this state, the objective function value is equal to 4.048×10^8.

In order to compare and study the efficiency of solutions obtained by LINGO and GA, 15 test problems were generated and solved with both exact on global solver of LINGO and GA method mentioned in Section 4.1 for 10 runs on MATLAB. Furthermore, the mean of the objective function and CPU time, and the mean of gap% have been represented in Table 13. Also, Fig. 11 and Fig. 12 show the performance of GA against LINGO. As observed, the maximum deviation GA from LINGO in terms of the objective function is 7.4%. On the other hand, the computational times for LINGO are much more than GA for small or medium-sized examples, and for large-sized ones, Lingo is not able to find the response even within 24 h (86400s). As a result, the developed GA is more efficient than LINGO and can find justifiable and acceptable solutions for all examples especially large-sized examples.

Table 3. The total maintenance cost

Candidate maintenance cycle	AGV types		
	1	**2**	**3**
1	9284.61	2317.43	26811.53
2	7769.22	1987.23	21223.07
3	8653.84	2154.89	22834.06
4	10138.45	2144.02	26246.14
5	9791.02	2365.47	25377.55
6	13722.85	2133.06	34907.12
7	12324.9	1993.82	32263.56
8	13741.13	1942.92	34780.54
9	14122.12	2002.11	35701.04
10	15090.14	2213.41	37012.34
11	15461.33	2451.23	38569.81
12	15818.41	1328.79	39900.12

Table 4. The available capacity of AGV type 1 according to the candidate maintenance cycle

Candidate maintenance cycle	Period											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	479142	479142	479142	479142	479142	479142	479142	479142	479142	479142	479142	479142
2	479142	467427	479142	467427	479142	467427	479142	467427	479142	467427	479142	467427
3	479142	467427	445713	479142	467427	445713	479142	467427	445713	479142	467427	445713
4	479142	467427	445713	423998	479142	467427	445713	423998	479142	467427	445713	423998
5	479142	467427	445713	423998	402283	479142	467427	445713	423998	402283	479142	467427
6	479142	467427	445713	423998	402283	381369	479142	467427	445713	423998	402283	381369
7	479142	467427	445713	423998	402283	381369	358245	479142	467427	445713	423998	402283
8	479142	467427	445713	423998	402283	381369	358245	330714	479142	467427	445713	423998
9	479142	467427	445713	423998	402283	381369	358245	330714	304808	479142	467427	445713
10	479142	467427	445713	423998	402283	381369	358245	330714	304808	282095	479142	467427
11	479142	467427	445713	423998	402283	381369	358245	330714	304808	282095	258661	479142
12	479142	467427	445713	423998	402283	381369	358245	330714	304808	282095	258661	235718

Table 5. The available capacity of AGV type 2 according to the candidate maintenance cycle

Candidate maintenance cycle	Period											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	371418	371418	371418	371418	371418	371418	371418	371418	371418	371418	371418	371418
2	371418	362256	371418	362256	371418	362256	371418	362256	371418	362256	371418	362256
3	371418	362256	341309	371418	362256	341309	371418	362256	341309	371418	362256	341309
4	371418	362256	341309	328701	371418	362256	341309	328701	371418	362256	341309	328701
5	371418	362256	341309	328701	316455	371418	362256	341309	328701	316455	371418	362256
6	371418	362256	341309	328701	316455	302724	371418	362256	341309	328701	316455	302724
7	371418	362256	341309	328701	316455	302724	289293	371418	362256	341309	328701	316455
8	371418	362256	341309	328701	316455	302724	289293	273905	371418	362256	341309	328701
9	371418	362256	341309	328701	316455	302724	289293	273905	260007	371418	362256	341309
10	371418	362256	341309	328701	316455	302724	289293	273905	260007	244681	371418	362256
11	371418	362256	341309	328701	316455	302724	289293	273905	260007	244681	229555	371418
12	371418	362256	341309	328701	316455	302724	289293	273905	260007	244681	229555	217620

Table 6. The available capacity of AGV type 3 according to the candidate maintenance cycle

Candidate maintenance cycle	Period											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	383314	383314	383314	383314	383314	383314	383314	383314	383314	383314	383314	383314
2	383314	373942	383314	373942	383314	373942	383314	373942	383314	373942	383314	373942
3	383314	373942	356570	383314	373942	356570	383314	373942	356570	383314	373942	356570
4	383314	373942	356570	339198	383314	373942	356570	339198	383314	373942	356570	339198
5	383314	373942	356570	339198	321827	383314	373942	356570	339198	321827	383314	373942
6	383314	373942	356570	339198	321827	300445	383314	373942	356570	339198	321827	300445
7	383314	373942	356570	339198	321827	300445	279406	383314	373942	356570	339198	321827
8	383314	373942	356570	339198	321827	300445	279406	254272	383314	373942	356570	339198
9	383314	373942	356570	339198	321827	300445	279406	254272	231394	383314	373942	356570
10	383314	373942	356570	339198	321827	300445	279406	254272	231394	208110	383314	373942
11	383314	373942	356570	339198	321827	300445	279406	254272	231394	208110	184736	383314
12	383314	373942	356570	339198	321827	300445	279406	254272	231394	208110	184736	157938

Table 7. The optimal number of AGVs assigned to workshops, total movement times, and preventive maintenance cycles obtained by LINGO

AGV type	N_{jn} in workshops					Tm_j	x_{jt}
	1	2	3	4	5		
AGV_1	-	1	-	-		1.71×10^6	2
AGV_2	-	-	2	-	2	3.15×10^6	12
AGV_3	3	-	-	1		6.64×10^6	2

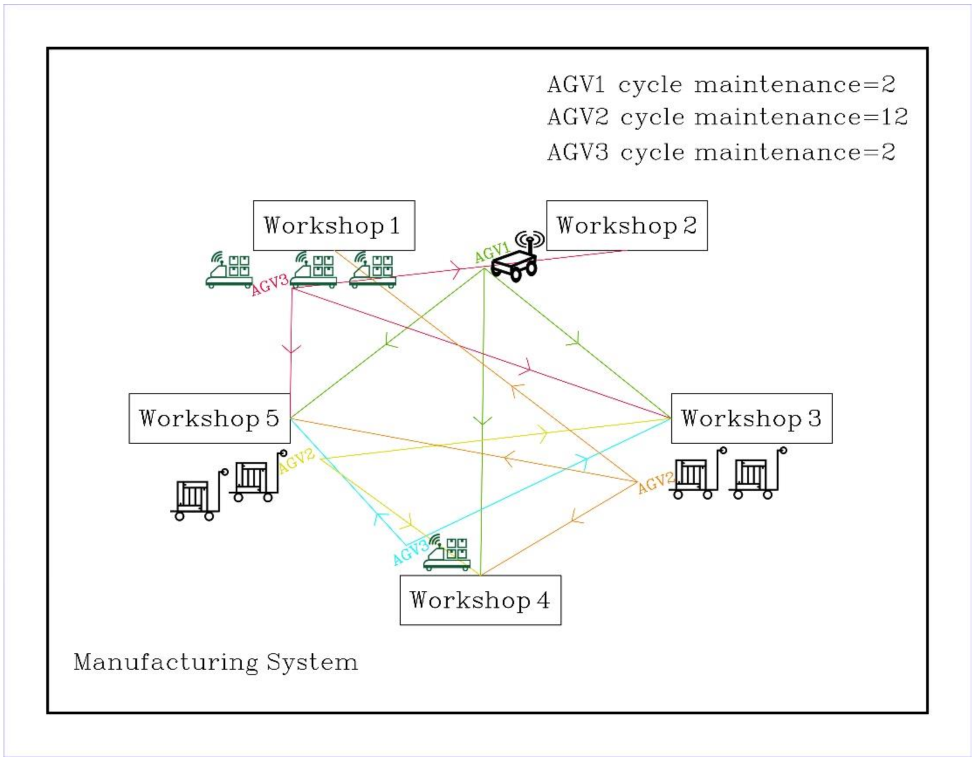


Fig. 8. The optimal manufacturing system view obtained by LINGO

Table 8. the optimal completed and uncompleted mission value obtained by LINGO

$Cm_{123} = 6000$	$Cm_{145} = 6300$	$Cm_{253} = 10000$	$Cm_{313} = 16000$
$Cm_{125} = 5000$	$Cm_{231} = 15000$	$Cm_{254} = 12900$	$Cm_{315} = 15200$
$Cm_{143} = 5500$	$Cm_{234} = 17200$	$Cm_{312} = 14500$	$UCm^{*}_{124} = 9000$
$UCm^{*}_{234} = 14500$			

*: uncompleted mission ($UCm^{*}_{jnm} = \max(0, Dc_{nm} - Cm_{jnm})$)

Table 9. GA parameters and their levels

Level	*NPop*	*MaxIt*	*CrR*	*MuR*
1	40	50	0.5	0.2
2	80	100	0.7	0.3
3	100	150	0.8	0.5

Table 10. L9 orthogonal array formed in Minitab and objective function value obtained by GA

Experiment	Coded level				Uncoded level				Objective function value
	Npop	*MaxIt*	*CrR*	*MuR*	*Npop*	*MaxIt*	*CrR*	*MuR*	
1	1	1	1	1	40	50	0.5	0.2	4.69×10^{8}
2	1	2	2	2	40	100	0.7	0.3	4.58×10^{8}
3	1	3	3	3	40	150	0.8	0.5	4.40×10^{8}
4	2	1	2	3	80	50	0.7	0.5	4.53×10^{8}
5	2	2	3	1	80	100	0.8	0.2	4.15×10^{8}
6	2	3	1	2	80	150	0.5	0.3	4.16×10^{8}
7	3	1	3	2	100	50	0.8	0.3	4.22×10^{8}
8	3	2	1	2	100	100	0.5	0.3	4.15×10^{8}
9	3	3	2	1	100	150	2	1	4.06×10^{8}

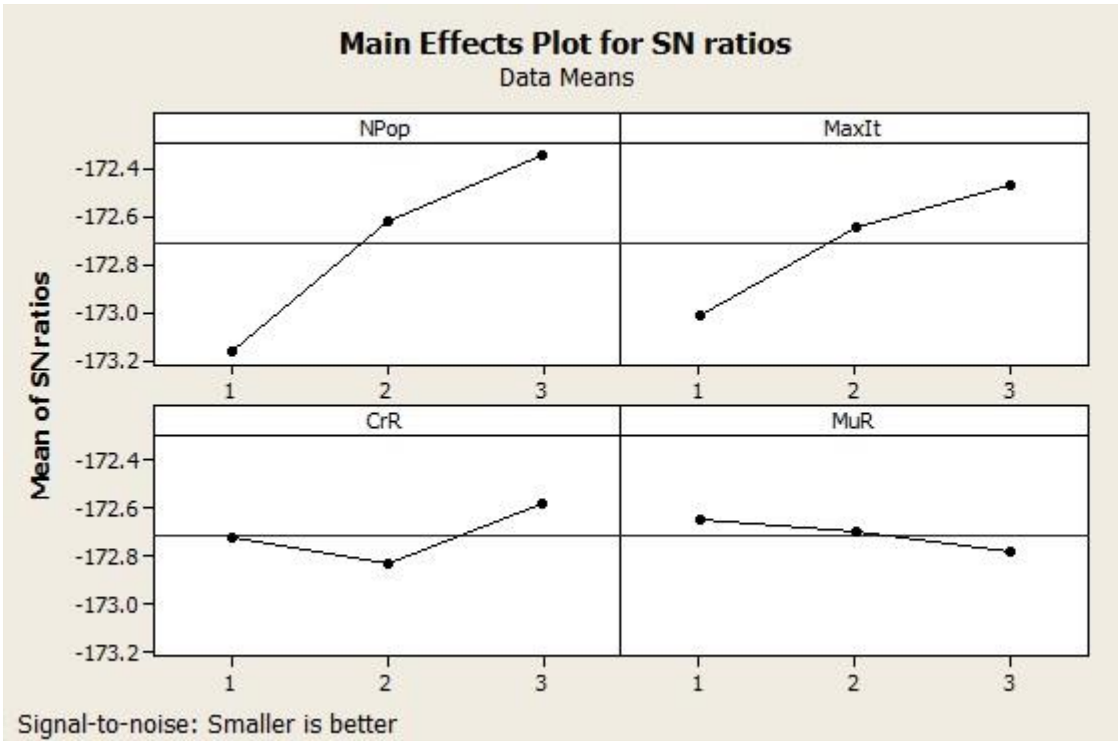


Fig. 9. Signal to noise ratio in Taguchi method

Table 11. The optimal number of AGVs assigned to workshops, total movement times, and preventive maintenance cycles obtained by GA in MATLAB.

AGV type	N_{jn} in workshops					Tm_j	x_{jt}
	1	2	3	4	5		
AGV_1	2	3	-	2	2	3.89×10^6	1
AGV_2	-	-	3	-	-	1.59×10^6	2
AGV_3	-	-	-	-		0	-

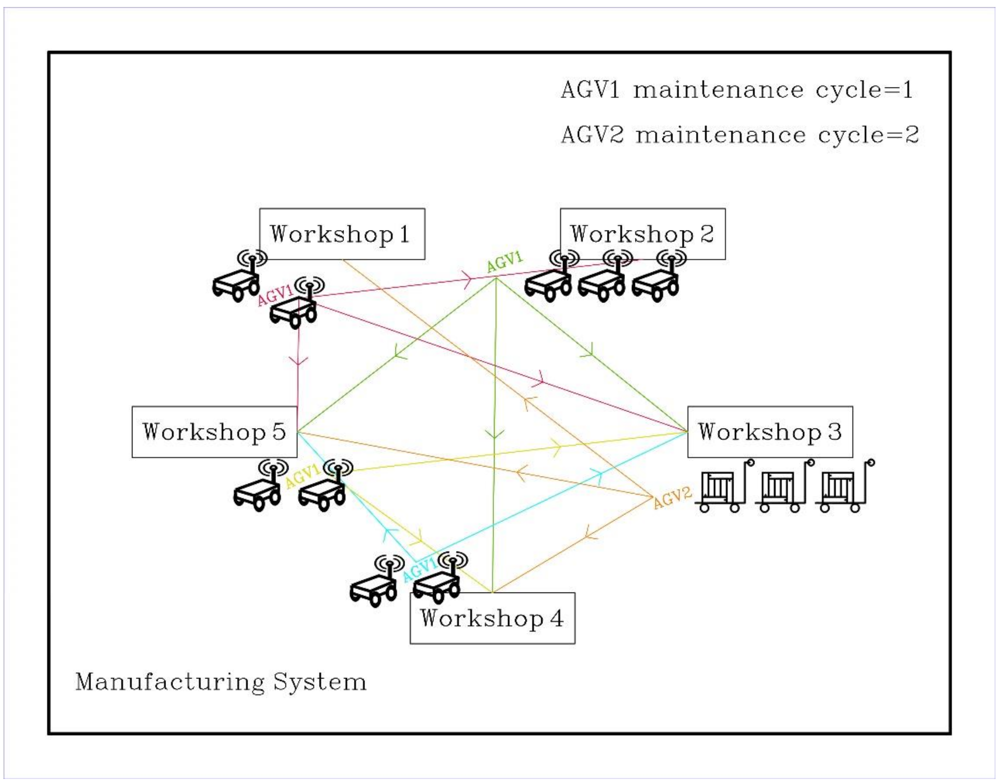


Fig. 10. The optimal manufacturing system view obtained by GA

Table 12. the optimal completed and uncompleted mission value obtained by GA in MATLAB

$Cm_{112} = 7256$	$Cm_{143} = 6076$	$Cm_{154} = 6462$	$UCm_{113} = 8000$
$Cm_{123} = 7081$	$Cm_{145} = 6400$	$Cm_{231} = 16383$	$UCm_{115} = 7600$
$Cm_{125} = 8192$	$Cm_{153} = 6904$	$Cm_{235} = 17096$	$UCm_{124} = 9000$
$UCm^{*}{}_{234} = 14500$	$UCm^{*}{}_{235} = 104$	$UCm^{*}{}_{334} = 25$	

Table 13. Comparison of the objective function obtained by LINGO and GA in MATLAB (10 runs)

Example no.	LINGO			GA in MATLAB		Mean gap%
	No. of AGV type/workshop/period	Objective function	CPU time(s)	Mean Objective function	Objective function CPU time(s)	
1	2/5/6	2.12×10^8	208	2.16×10^8	0.13	1.8%
2	3/5/6	1.91×10^8	852	2.01×10^8	28	5.2%
3	3/5/12	3.83×10^8	1731	4.05×10^8	132	5.4%
4	5/8/6	2.41×10^8	1340	2.59×10^8	44	7.4%
5	5/8/12	4.67×10^8	5995	4.70×10^8	215	0.6%
6	7/9/6	2.18×10^8	11490	2.24×10^8	187	2.7%
7	7/10/12	5.53×10^8	8367	5.89×10^8	560	6.5%
8	8/10/12	5.72×10^8	28860	5.81×10^8	931	1.5%
9	8/12/16	7.24×10^8	48621	7.45×10^8	718	2.9%
10	10/12/16	7.59×10^8	78876	7.86×10^8	1024	3.5%
11	10/12/20	-	>86400	1.06×10^9	1419	-
12	12/12/20	-	>86400	1.23×10^9	1806	-
13	12/12/24	-	>86400	1.51×10^9	1542	-
14	13/15/12	-	>86400	9.33×10^8	1114	-
15	13/15/24	-	>86400	1.75×10^9	2141	-

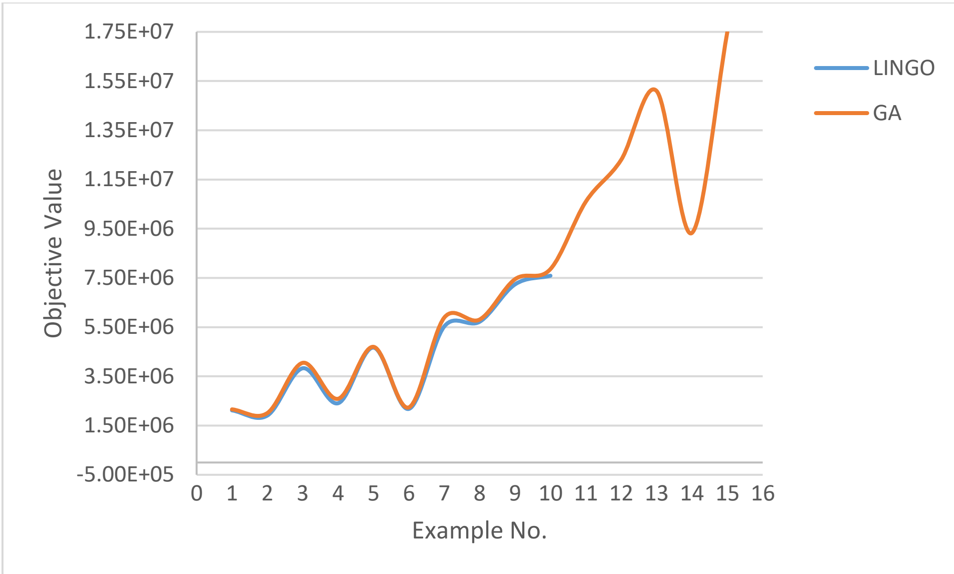


Fig. 11. The objective value obtained by LINGO and GA

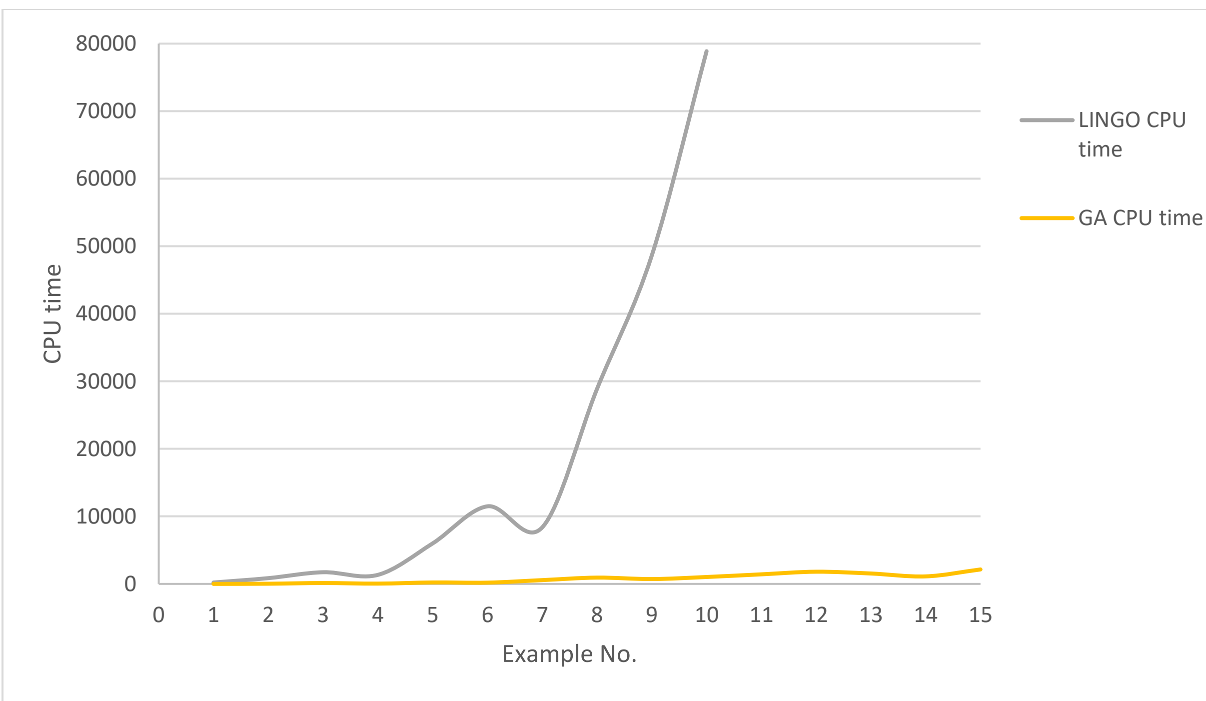


Fig. 12. The CPU time obtained by LINGO and GA

7. Sensitivity analysis

In this section, variation of three parameters including the AGV speed, the AGV capacity, and workshops distance have been investigated on values of the objective function for example 3 given in Table 3. As it is depicted in Fig. 13, the objective function value has an oscillating behavior subject to the speed of AGVs as well as the distance between workshops. This behavior is absolutely logical because these two parameters influence on both cost of total movement time for AGVs and the cost of uncompleted missions through the horizon planning in the objective function at the same time. On the other hand, the objective function value has a descending trend with increasing the capacity of AGVs. It is obvious that the greater the capacity of AGVs, the less number of AGVs, the less movement time, and the less uncompleted mission is needed and therefore this leads to lesser costs.

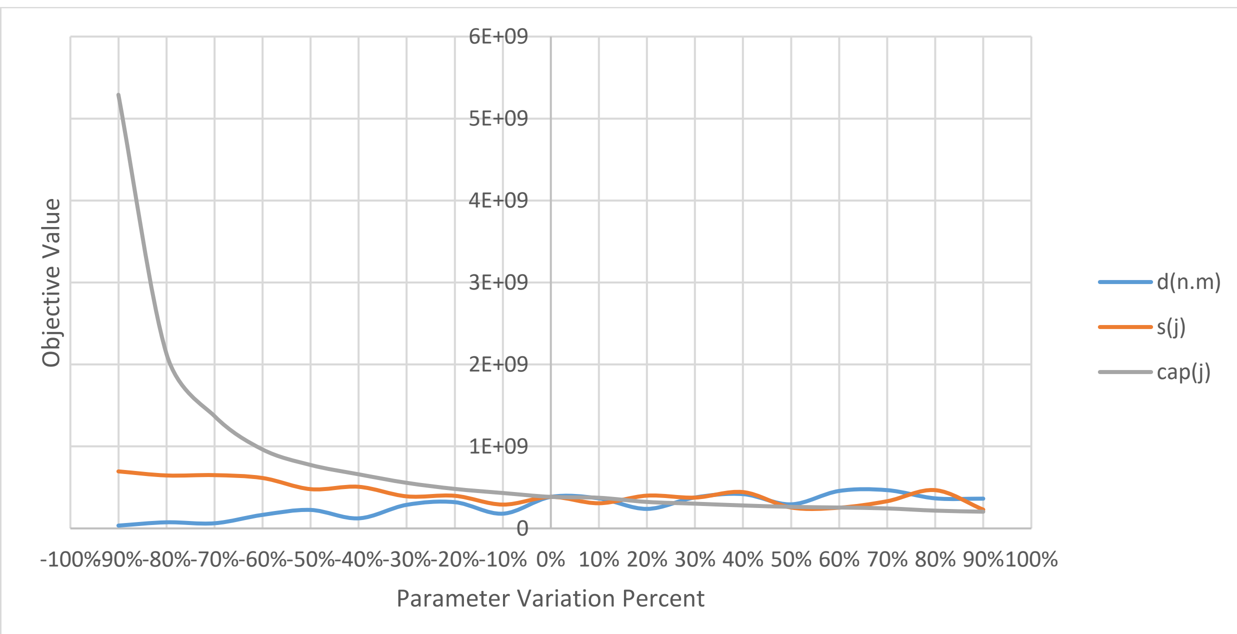


Fig. 13. The sensitivity analysis for three parameters $d(n,m), s(j)$ and $cap(j)$

8. Conclusion

In this paper, a nonlinear mathematical model for an automated guided vehicle (AGV) design problem with considering the preventive maintenance policy of AGVs has been developed. In other words, the main goal of this paper is to find the optimal fleet sizing of AGVs and assign them to workshops together with determining the optimal preventive maintenance cycle. Our proposed model minimizes the constant and variable cost of AGVs, uncompleted mission cost, and maintenance cost. The performance of the model is verified by a numerical example solved in LINGO software. Since the considered problem is a hard problem to solve, a genetic algorithm (GA) together with the Taguchi method for tuning the GA parameters was represented. In order to check the efficiency of GA, 15 examples were generated and solved by both GA and global solver in LINGO software. By comparing the obtained objective function value for all examples, is concluded that GA has a maximum 7.4% percentage gap in terms of the objective function value. Also, GA solves these examples at much lower times (on average about 50 times smaller). These results show the efficiency of the proposed GA for solving the problems, especially for large-sized ones where Lingo is not able to achieve a feasible solution even in 24 hours. Finally, a sensitivity analysis was performed on some key parameters and investigated the effects of those parameters on objective value.

The future extension of this study can be to consider the job shop scheduling together with the above problem, development of the multi-objective model and solution approach, apply the uncertainties in parameters and integrate other AGVs design or control problem such as battery management, navigation strategies, AGVs routing, and dispatching, etc.

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