Ant Colony Optimization Algorithm to Solve Electrical Cable Routing

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Abstract Ant colony algorithms have been applied to solve wide range of difficult combinatorial optimization problems like routing problems, assigning problems, scheduling problems and revealed remarkable solutions. In this paper we are presenting a novel approach of ant colony optimization algorithm to solve the electrical cable routing problem. We have studied the objectives to optimize the cable routing and modified the ant colony system algorithm to get better solutions. This research focused on two objectives, route optimization and the obstacle avoidance. The results of this modified algorithm show an immense improvement in optimizing the electrical circuit designing in a building.

Keywords Ant colony optimization · Electric cable routing · Obstacle avoidance

1 Introduction

Nature offers inspirations to novel solutions for science, technology and engineering. Dorigo and Stutzle introduced the Ant Colony Optimization (ACO) algorithm in 1990s by studying the foraging behavior of real ants [1]. The real ants deposit pheromone while they are walking towards a food source from their nest. With the help of the pheromone density, the rest of the ants can follow the shortest path toward the food sources. Mimicking this behavior into artificial ants has become a popular approach for resolving combinatorial optimization like Traveling Salesman Problem (TSP), quadratic assignment problem and job-shop

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scheduling problem [2, 3]. Recently advancements of ACO have been applied to complex problems with multiple objectives to be optimized and proved with remarkable solutions [4, 5].

With the rapid growth in the electrical requirement of the building construction, designing wiring layouts has become complicated. Most of the wiring laying is done manually as a trial and error method. Engineers have presented numerous designs, techniques and systems in order to design the wiring layouts for many types of applications [6]. Optimizing means discovering the best available value of an objective function, or in different types of objective functions. Optimization proves that there are valuable solutions to variables like profit, quality and time [6]. By applying the ant colony optimization to optimize cable routes, it can gain considerable amount of benefits. Optimizing the wiring routes can also help to reduce the length of the wires in the circuit, which will reduce the cost, complexity and the voltage drops of the circuits. Reducing the voltage drops can ensure the safety of the electrical equipment. Automating the wiring routes can also lead to reduction of decision-making time.

The main aim of our research is to modify the ant colony optimization algorithm to optimize the electrical wiring route in order to reduce the length of the wiring circuits and obstacle avoidance. In the recent research literature, we can find few applications of ant colony optimization algorithm in wire and cable routings and harness designing systems. J. M. Alvarado and his team introduced an ant colony systems application for electric distribution network planning [3]. They have used proportional pseudo-random transition rule to explore new paths in order to select the best route. The branches that belong to the best networks found so far were refreshed by applying global pheromone level revision rule. In addition, local pheromone level revision rule is applied, these levels are updated during the route generation process. Their main concern is to minimize the cost and the limits at voltage magnitudes in order to design complete model for the electric system.

Communication cables also need huge attention in building construction. Gianni Di Caro and Marco Dorigo presented a novel approach to adaptive learning of routing tables in wide area best-effort routing in datagram networks [5]. Their study introduced new versions of AntNet, which are AntNet-CL and AntNet-CO. Results shown in both versions had proven better performances compared to the current internet routing algorithm, such as OSPF, SPF, distributed adaptive Bellman-Ford, and recently proposed forms of asynchronous online Bellman-Ford.

Gishantha Thantulage and Tatiana Kalganova have designed a grid-based ant colony algorithm for automatic 3D horse routing [7]. They have applied the algorithm with tessellated format of the obstacles and the generated hoses in order to detect collisions. They have also proved that the algorithm can be applied to real-world hose/pipe routing problems. But when the algorithm is applied to the situations with high resolution or size of the grid, it requires having highest amount of memory and more time to compute the results.

2 Electrical Cable Routing

Cabling plays a key role in building constructions. If one cable goes down the entire system can cease. Therefore, the precise layout design of the entire cable system is very important. Cables designs should be optimized to achieve less complexity, high durability, and low cost. Since the performances of an entire electrical system depends on the cable design, there are few applications to design wire routings in a building. Although, there is no such approach used in the latest nature-inspired algorithms and drawn the results towards optimum solution. Therefore, it is significant to see the practicability and the performance of these nature-inspired algorithms in designing optimized cable layout for a building [8]. Electrical wiring design must follow the recognized standards, use standard electrical symbols and applicable codes. IET (The Institution of Engineering and Technology), which is also known as BS7671, defines the standard regulations for wiring. These regulations focus on the key factors for electrical installations as well as electrical safety [9].

There are considerable number of requirements to be focused on when designing the electrical wiring layout [10]. Mainly, it needs the expert knowledge, and a detail study should be carried out before starting the designing of the circuit. Quality and the requirements, with respect to the price, are also of main considerations. At the studying phase, it is necessary to examine the activities in various types of residences. When laying electrical circuit, there are few constrains to look at architectural design, accessibility, dedicated areas for laying cables, and mounting heights of the electrical accessories must be considered. In this research we have implemented the algorithm based on the radial circuits. Furthermore, the standard mounting heights and dedicated areas for laying cable have been considered according to the BS7671 standards.

3 Ant Colony System

Dorigo and Gambardella [11] derived Ant Colony System (ACS) based on the Ant System (AS) in 1996. They have proven the efficiency of the algorithm by applying it to solve the Travelling Salesman Problem (TSP). ACS is implemented by modifying three main areas of AS.

3.1 An Ant Position on City R Chooses the City S to Move by Applying the State Transition Rule (Pseudo-random-Proportional Rule) Given by Eq. 1

$$s = \begin{cases} \arg\max_{u \in J_k(r)} \left[[\tau(r,s)] \cdot [\eta(r,s)]^{\beta} \right] & \text{if } q \le q_0 \text{ (exploitation)} \\ S & \text{otherwise (biased exploration)} \end{cases} \tag{1}$$

where $\tau(r,s)$ is the pheromone density of an edge (r,s), $\eta(r,s)$ is the $[1/\text{distance}(r,s)]$. $J_k(r)$ is the set of cities that remains to be visited by ant k positioned on city r. β is a parameter, which decides the relative importance of pheromone versus distance ($\beta > 0$). q is a random number uniformly distributed in [0, 1], q_0 is a parameter ($0 \leq q_0 \leq 1$), and S is a random variable from the probability distribution given by the Eq. (2).

$$p_k(r,s) = \begin{cases} \frac{[\tau(r,s)]\cdot[\eta(r,s)]^\beta}{\sum_{u\in J_k(r)}[\tau(r,u)]\cdot[\eta(r,u)]^\beta} & \textit{if } s \in J_k(r) \\ 0 & \textit{otherwise} \end{cases} \tag{2}$$

3.2 Then the Pheromones Are Updated in the Edges of the Best Ant Tour Using Global Updating Rule in Eq. (3)

$$\tau(r,s) \leftarrow (1-\alpha)\cdot\tau(r,s) + \alpha\cdot\Delta\tau(r,s) \tag{3}$$

where $\Delta\tau(r,s) = \begin{cases} (L_{gb})^{-1} & \textit{if } (r,s) \in \textit{global-best-tour} \\ 0 & \textit{otherwise} \end{cases}$

$0 < \alpha < 1$ is the pheromone decay parameter and L_{gb} is the length of the globally best tour.

3.3 When Ants Move from One City to Another, Local Pheromone Updating Rule Is Applied as Eq. (4)

$$\tau(r,s) \leftarrow (1-\rho)\cdot\tau(r,s) + \rho\Delta\tau(r,s) \tag{4}$$

where $0 < \rho < 1$ is a parameter. And $\Delta\tau(r,s) = \tau_0$, τ_0 is the initial pheromone level.

4 Algorithm Implementation

The grid points in the wall are designed according to the BS7671 standards and followed the standards of permitted cable routing zones with the mounting heights of the electrical equipment's in dwellings. When mounting switches and socket-outlets for lighting and other equipment in habitable rooms, the appropriate heights between 450 and 1200 mm from finished floor level is considered [10]. This also facilitates the requirements of special assisting people. In addition, the mounting height of wall-mounted socket-outlets and other accessories is required to be enough to keep them suffering from getting wet or impact, which may result from floor cleaning.

Ant completes a circuit by travelling from starting point to the end point, where the socket outlet is located. Initially all the ants are positioned in a starting node, then each ant selects the next grid point to move according to the modified state transition rule in Eq. 5 and using the roulette wheel selection. This will be selected according to the closest and the highest level of pheromone. When an ant builds the tour, local pheromone updating rule in Eq. 4 is applied to the visited points. When the ant reaches to the target point where the power socket is located, then the tour is completed. Then the length of the completed tours of each ant is calculated and only the optimum path is updated with extra amount of pheromone using the global updating rule in Eq. 3.

4.1 Modifications to the Ant Colony System Algorithm to Solve Wire Routing

Modification 1—State Transition Rule

An ant position on city *r,* chooses the city *s* to move by applying the state transition rule (pseudo-random-proportional rule) given by Eq. 5

$$p_k(r,s) = \begin{cases} \frac{[\tau(r,s)]\cdot[\eta(r,s)]^{\beta}}{\sum_{u \in J_k(r)} [\tau(r,u)]\cdot[\eta(r,u)]^{\beta}} & \text{if } s \in J_k(r) \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where $\tau(r,s)$ is the pheromone density of an edge (r,s),

Heuristic information $\eta(r,s)$ is the [1/distance (s,t)], distance from point s to the target point t.

$J_k(r)$ is the set of cities that remains to be visited by ant k positioned on city r. $\eta(r,u)$ is also taken as [1/distance (s,t)].

β is a parameter, which decides the relative importance of pheromone versus distance ($\beta > 0$).

Modification 2—Roulette Wheel Selection

Using the roulette wheel selection, the probabilities are calculated by the state transition rule in Eq. 5 to select the next city to be move, mapped into contiguous segments of a line span within [0 1]. Therefore, each individuals' segment is equally sized to its fitness. A random number is generated and the individual, whose segment spans the random number is selected.

4.2 Pseudo-code of the Ant Colony System Algorithm – Solve Wire Routing

```
Initialization
  turn = 0
Loop
  Release new set of ants from the starting point
  Loop
    turn =turn +1
    For each ant 'a' in the current set
  If ant 'a' does not reach to the target point
          Move to the next point using ACS pseudo random-proportional rule
          (eq. 5) and roulette wheel selection
          Apply local pheromone update rule (eq. 4) to the selected point
      else
          Ant 'a' stops exploring
  Until (reaches the target)
  Apply the global pheromone update rule (eq. 3) to the best path
  using the ants that reached to the target point
  Remove the current set of ants from the civilization
Until (turn <= MAX_TURNS)
```

5 Experimentation

To analyze the behavior of the new algorithm, three experiments were carried out. Through these experiments, we have applied the algorithm to optimize the distance between start and the end point with obstacle avoidance and then analyzed the behavior of the algorithm in extended grids with multiple obstacles.

The parameter settings for the algorithm were.

The pheromone decay parameter $\rho = 0.1$, $\alpha = 0.1$, $\beta = 2$, $q_0 = 0.9$, $\tau_0 = (n\ L_{nn})^{-1}$ where L_{nn} is the tour length produced by the nearest neighbour heuristic and n is the number of the cities. The heuristic distance $\eta(r, s)$, the $[1/\text{distance}((\text{s,t}))]$ is the distance from point s to the target point (socket outlet). This will make the solution more effective and feasible. The simulation is conducted on a PC with Intel Core i5-6200U processor (Processor speed = 2.4 GHz, Memory = 8 GB) in the Windows 10 Home operating system using MATLAB (Version R2012b).

5.1 Experiment 1—Wire Routing from Start to a Target Point

The algorithm is initially implemented to the wall design shown in Fig. 1. The grid is designed by adhering to the BS7671 standards height with 15 grid points. In this initial experiment, we have changed the number of ants and the number of the iterations to analyze the behavior of the algorithm to reach towards the optimum length. All the other parameter values are set to the initial values proposed by Dorigo [11] when introducing the ACS algorithm to solve TSP. As shown in Fig. 1 initially, we have improved the algorithm to optimize the distance between start (7.5, 9) and end (4, 0.5) points. We have studied the behavior of the algorithm and recorded the best, average and worst distances and time taken to different combinations of number of ants and the iterations. This has been tested using 25 trials. To analyze the accuracy of the algorithm, we have introduced the same changes to another pair of starting (2.5, 9) and ending (7.5, 0.5) points.

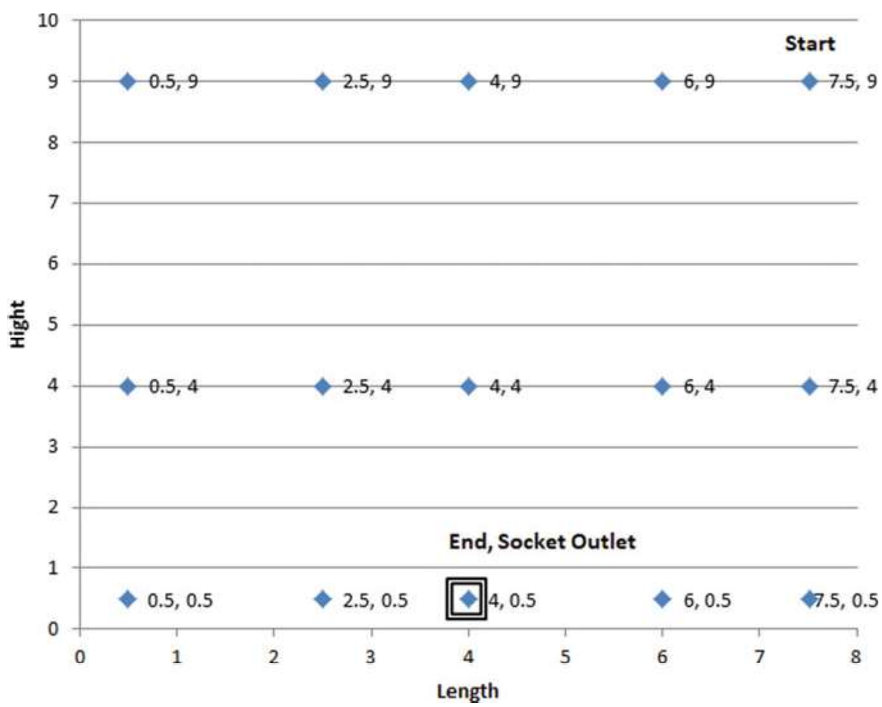

Fig. 1 Model 1–15 point wall design with starting point and the ending point (socket outlet)

5.2 Experiment 2—Wire Routing from Start to Target Point with Obstacle Avoidance

In the next stage, we have introduced an obstacle to this scenario as a door in the wall as shown in Fig. 2. In this scenario, the point behind the door is removed and considered only 11 points around the door. The coordinates of the door are x [5 8 8 5], y [0 7 7 0]. In this scenario, we have introduced a utility matrix shown in Table 1, to avoid the obstacle when selecting the optimum path. Utility matrix was constructed to avoid obstacles and indicate feasible paths ants can move to, if the path is feasible, that is represented as '1', else '0'. Therefore, when the ant is selecting the next point, utility matrix is considered to check if the point is feasible to move or not.

We have studied the behaviour of the algorithm and record the best, average, worst distances and time taken to different combinations of number of ants and the iterations. This has been tested using 25 trials. To analyse the accuracy of the algorithm, we have introduced the same obstacle to the left side of the grid, door is x [0 3 3 0], y [0 7 7 0]. A modified utility matrix is introduced to obstacle

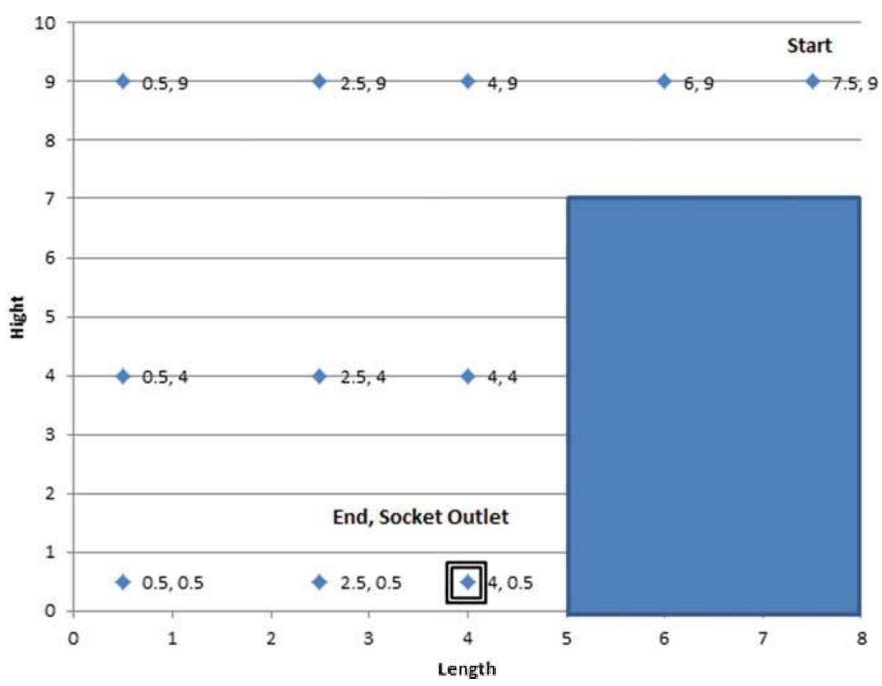

Fig. 2 Model 2–11 point wall design with starting point and the ending point (socket outlet) with a door

Table 1 Utility matrix for model 1

Grid point	1	2	3	4	5	6	7	8	9	10	11
1	0	1	1	1	1	1	1	1	1	1	0
2	1	0	1	1	1	1	1	1	1	0	0
3	1	1	0	1	1	1	1	1	1	0	0
4	1	1	1	0	1	1	1	1	1	1	1
5	1	1	1	1	0	1	1	1	1	1	0
6	1	1	1	1	1	0	1	1	1	0	0
7	1	1	1	1	1	1	0	1	1	1	1
8	1	1	1	1	1	1	1	0	1	1	1
9	1	1	1	1	1	1	1	1	0	1	1
10	1	0	0	1	1	0	1	1	1	0	1
11	0	0	0	1	0	0	1	1	1	1	0

avoidance. In addition, we have introduced another pair of starting (2.5, 9) and ending (7.5, 0.5) points and then recorded the best, average and worst distances and time taken to different combinations of number of ants and the iterations.

5.3 Experiment 3—Wire Routing from Start to Target Point with Extended Grid with Multiple Obstacles

The behaviour of the new algorithm is analysed by introducing to two complex models of expanded grids of more points with multiple objects. As shown in Fig. 3, model 3 consists 44 points and two obstacles. The coordinates of the obstacles are, door x [0 3 3 0], y [0 7 7 0] and the window x [2 12 12 2], y [3 8 8 3]. We have applied the improved algorithm to find the optimized distance between starting point 44 (19.5, 9) and ending point 5 (4.5, 0.5), and then, recorded the best, average and worst distances and time taken through 25 trails. To conduct this experiment, we have considered 20 ants and 1000 iterations.

Model 4 in Fig. 4, consists 48 points and four obstacles. The coordinates of the obstacles are, door x [0 3 3 0], y [0 7 7 0], window1 x [2 4 4 2], y [2 8 8 2], window2 x [7 9 9 7], y [2 8 8 2] and window3 x [12 14 14 12], y [2 8 8 2]. We have applied the improved algorithm to find the optimum distance between starting point 48 (19.5, 9) and ending point 2 (1.5, 0.5) and then recorded the best, average and worst distances and time taken through 25 trails. To conduct this experiment, 20 ants and 1000 iterations were considered.

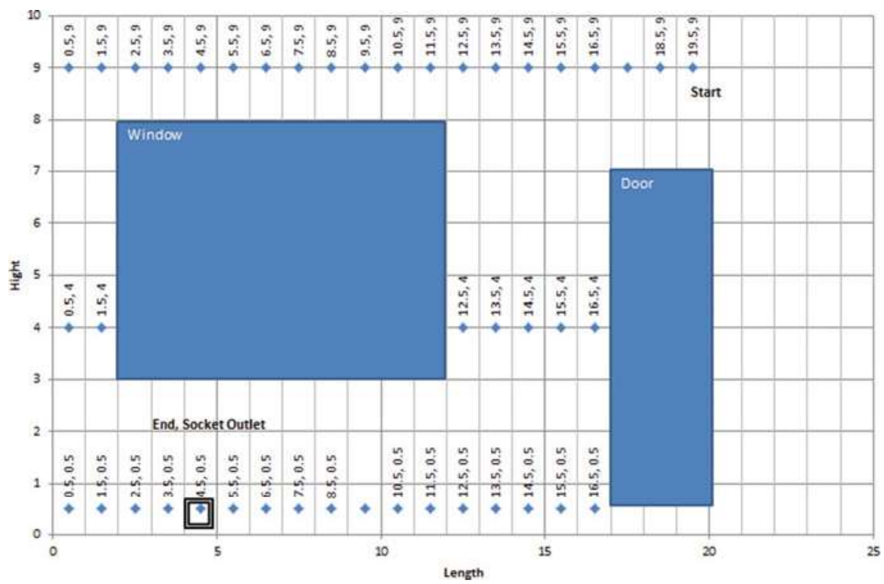

Fig. 3 Model 3–44 points wall design with starting point and the ending point (socket outlet) with 2 obstacles

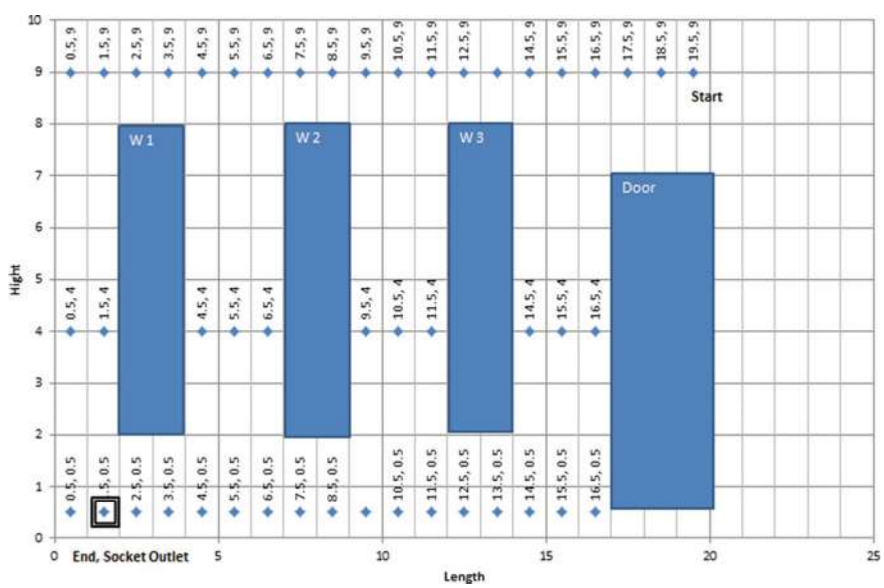

Fig. 4 Model 4–48 points wall design with starting point and the ending point (socket outlet) with 4 obstacles

6 Results and Discussion

6.1 Experiment 1—Wire Routing from Start to a Target Point

As shown in Table 2, experiment 1 is carried out for three different combinations of population of ants and number of iterations to optimize the distance between point 15 and 3. Each combination is tested using 25 trials. Best distance is the direct distance between the points (9.1924 feet) and this is achieved with modified algorithm. 80% of the results proved the direct distance as the best distance. When the population size is 20 and the iterations are 2000, algorithm shows better results, but the time has increased. Since accuracy of the algorithm is also the same for the population size 20 and the iterations were 1000 and the results were produced faster, this is the most suitable combination for the modified algorithm. This has been proved using another set of starting 12 and ending 5 points in the same grid as shown in Table 3. Figures 5 and 6 show the best distance of both instances.

Table 2 Results of experiment 1 model 1—Start point—15, End point—3

Number of ants/ iterations Start point—15, End point—3	Best distance (feet)/time (s)	Average distance (feet)/time (s)	Worst distance (feet)/time (s)
Number of ants—10 Iterations—1000	9.1924/0.8919	10.5418/3.0664	12/6.0115
Number of ants—20 Iterations—1000	9.1924/1.9631	9.6993/5.5841	10.8073/9.5608
Number of ants—20 Iterations—2000	9.1924/9.5649	9.4130/14.4145	10.2321/22.1703

Table 3 Results of experiment 1 model 1—Start point—12, End point—5

Number of ants/ Iterations Start point—12, End point—5	Best distance (feet)/time (s)	Average distance (feet)/time (s)	Worst distance feet)/time (s)
Number of ants—10 Iterations—1000	9.8615/4.5457	11.4485/6.0383	15.1313/9.2218
Number of ants—20 Iterations—1000	9.8615/5.0889	10.8398/6.1229	13.5/6.0094
Number of ants—20 Iterations—2000	9.8615/12.0895	10.02768/14.0554	10.6924/16.5066

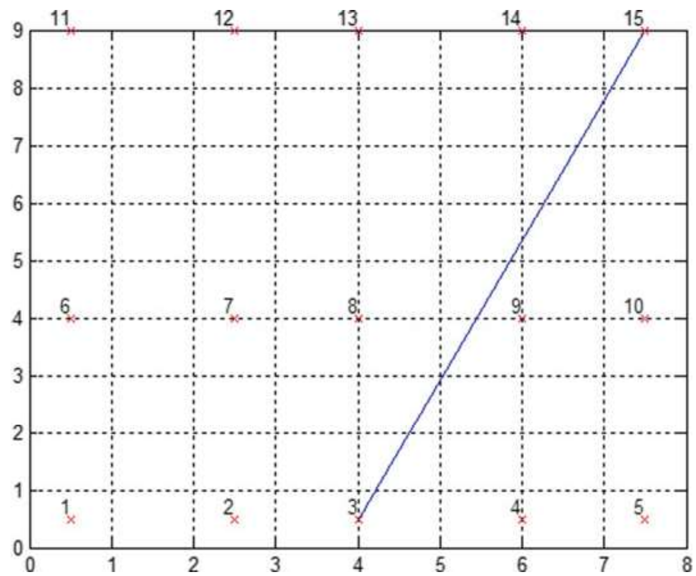

Fig. 5 15 points wall design with starting point 15 and the ending point 3 (socket outlet) output = optimized distance 9.1924

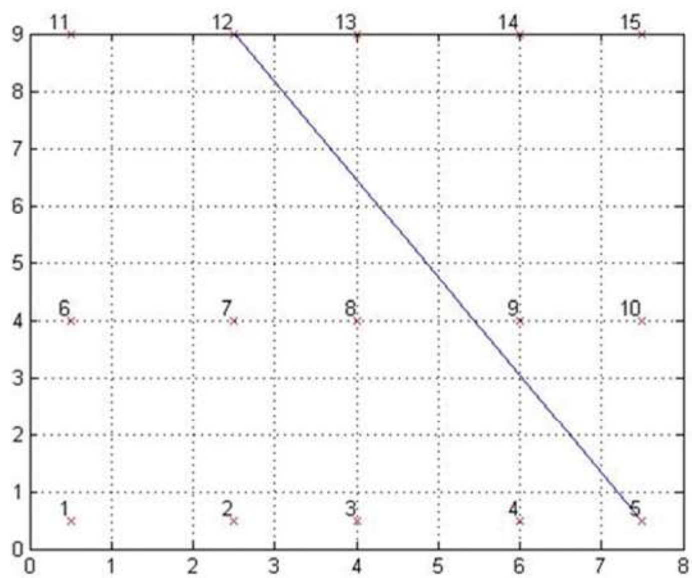

Fig. 6 15 points wall design with starting point 12 and the ending point 5 (socket outlet) output = optimized distance 9.8615

6.2 Experiment 2—Wire Routing from Start to Target Point with Obstacle Avoidance

In this experiment, a single obstacle was introduced to the grid and the modified algorithm was analysed with obstacle avoidance in two scenarios; One with the door in the right side and the other in the left side. As the results show in the Table 4, the best distances given for both scenarios are the same as the shortest distances given by the Dijkstra algorithm. The solution is tested through 20 trials and proved the success rate of 85–90% for both scenarios (Figs. 7 and 8).

Table 4 Results of experiment 2

Model	Best distance (feet's)/ time (s)/accuracy	Average distance (feet's)/time (s)	Worst distance (feet's)/time (s)
Right door—Model 2 Start—11, End—3	11.4112/6.6228 90%	11.5289/7.1989	12/6.9741
Left door—Model 2 Start—7, End—1	10.8852/6.0014 85%	10.9165/6.5522	11.053/5.5213

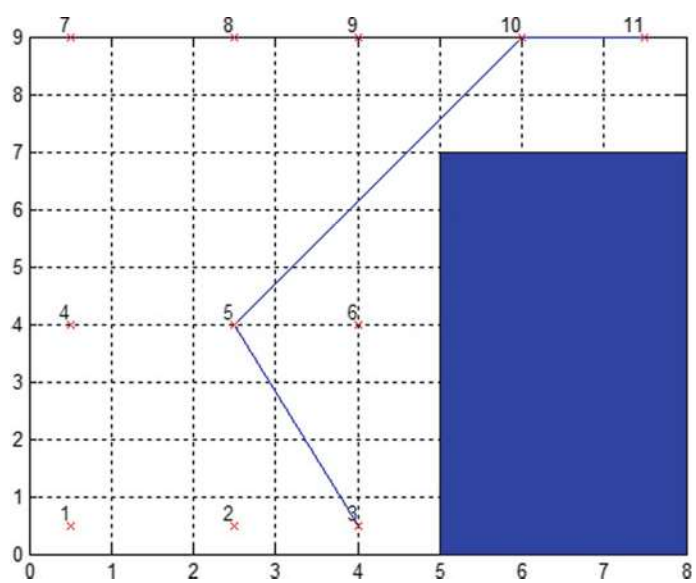

Fig. 7 11 points wall design with starting point 11 and the ending point 3 (socket outlet) with right door. Output = optimized distance 11.4112 feet

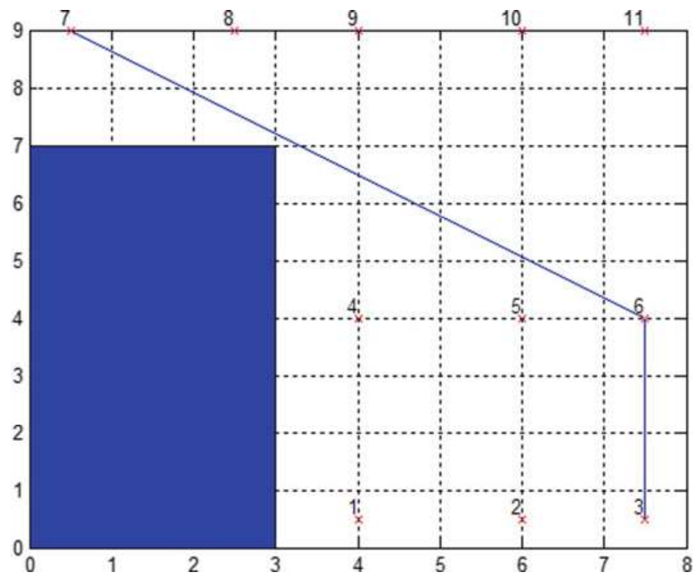

Fig. 8 11 points wall design with starting point 7 and the ending point 3 with left door. Output = optimized distance 9.603 feet

6.3 Experiment 3—Wire Routing from Start to Target Point with Extended Grid with Multiple Obstacles

In the third experiment, the modified algorithm was introduced to two grids in model 3 and 4 with few obstacles. In addition, the shortest distances were calculate using the Dijkstra Algorithm, for model 3 from point 44 to 5, the shortest distance is 18.3794 feet and for the model 4, the shortest distance from point 48 to 2 is 20.0139 feet. The modified algorithm also produced the same result as the best distance from same points and it proved 80–85% accuracy from 25 trials as shown in Table 4 (Figs. 9, 10; Table 5).

7 Conclusion

In this study, a new version of ACS has been introduced to generate optimal path between start and the target point. The algorithm is implemented in MATLAB environment. The new algorithm is developed to optimize the length of cables in electrical wiring in a building with obstacle avoidance. Initially, it has considered a 2D single wall with a door. The grid was designed according to the BS7671 standards following the standards of permitted cable routing zones. Results gained through experimenting different models and number of trials were compared again,

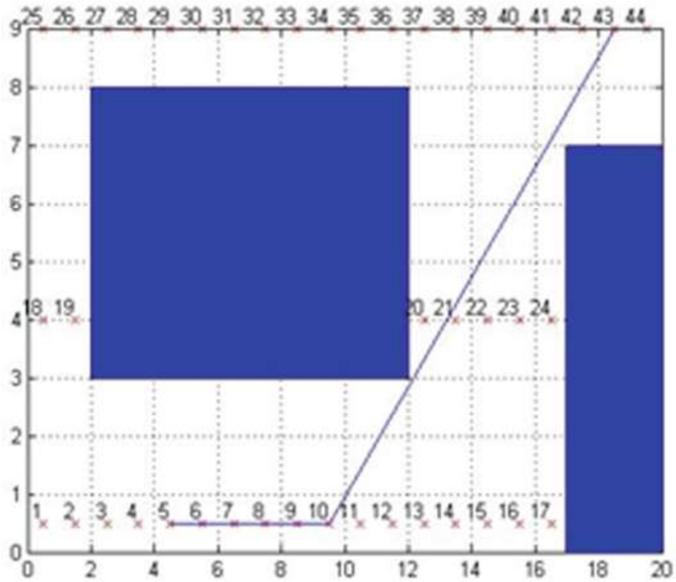

Fig. 9 Model 3–44 points wall design with starting point and the ending point (socket outlet) with 2 obstacles. Optimized distance: 18.3794 feet

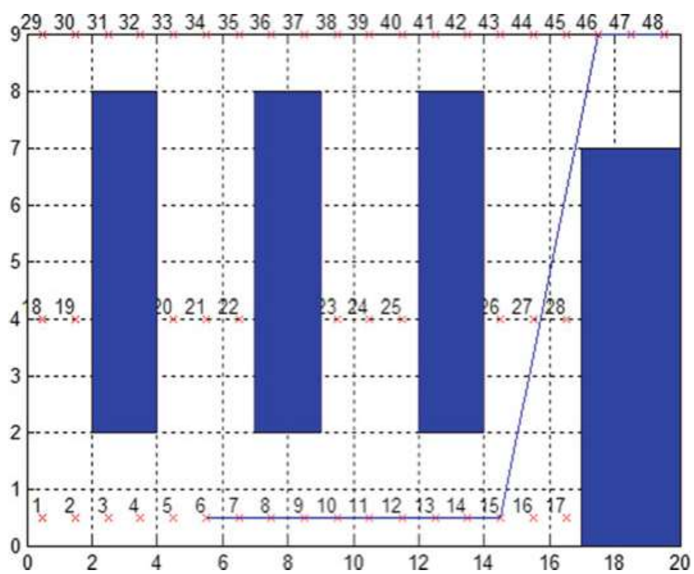

Fig. 10 Model 4–48 points wall design with starting point and the ending point (socket outlet) with 4 obstacles. Optimized distance: 20.0139 feet

Table 5 Results of experiment 3

Model	Best distance (feet's)/ time (s)/accuracy	Average distance (feet's)/time (s)	Worst distance (feet's)/time (s)
Model 3—44 points, 3 objects Start—44, End—5	18.3794/18.679 80%	18.6551/19.3385	19.2424/18.0354
Model 4—48 points, 4 objects Start—48, End—2	20.0139 24.1364 85%	20.38462/24.7678	20.7321/25.24631

for the shortest distances calculated, using a distance matrix. The comparison of results proved that the results given by the modification were the same as the results gained from the Dijkstra algorithm and the modification gave the optimized distance between start and the target point. By applying the above improved ant colony optimization to optimize cable routes, it can gain considerable amount of benefits. Optimizing the wiring routes can help to reduce the length of the wires in the circuit, which will reduce the cost, complexity and the voltage drops of the circuits. Reducing the voltage drops can ensure the safety of the electrical equipment. This also helps to follow electrical wiring standards as well as obstacle avoidance. The results can be finally shown in cable layout map for the engineers to lay circuits efficiently.

The first stage of the research focused on two objectives as optimizing the distance between starting and ending point, as well as avoiding obstacles in the path. At the next stage, the algorithm can be further developed to optimize the path of one starting point to multiple target points. This can be applied to situations in an electrical cabling, where a circuit should cover multiple points. This also can be improved to be used in 3D grid environments. In future, this method can be applied to multi-objectives optimization in order to optimize the number of bends in a circuit with the optimized length, where the graph based deterministic algorithms like Dijkstra and A* are not acceptable.

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