A discrete particle swarm optimization algorithm for rectilinear branch pipe routing

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A discrete particle swarm optimization algorithm for rectilinear branch pipe routing

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Abstract

Purpose – The purpose of this paper is to develop a new rectilinear branch pipe-routing algorithm for automatic generation of rectilinear branch pipe routes in constrained spaces of aero-engines.

Design/methodology/approach – Rectilinear branch pipe routing that connects multiple terminals in a constrained space with obstacles can be formulated as a rectilinear Steiner minimum tree with obstacles (RSMTO) problem while meeting certain engineering rules, which has been proved to be an NP-hard and discrete problem. This paper presents a discrete particle swarm optimization (PSO) algorithm for rectilinear branch pipe routing (DPSO-RBPRA) problems, which adopts an attraction operator and an energy function to plan the shortest collision-free connecting networks in a discrete graph space. Moreover, this paper integrates several existing techniques to evaluate particles for the RSMTO problem in discrete Manhattan spaces. Further, the DPSO-RBPRA is extended to surface cases to adapt to requirements of routing pipes on the surfaces of aero-engines.

Findings – Pipe routing numeral computations show that, DPSO-RBPRA finds satisfactory connecting networks while considering several engineering rules, which demonstrates the effectiveness of the proposed method.

Originality/value – This paper applies the Steiner tree theory and develops a DPSO algorithm to plan the aero-engine rectilinear branch pipe-routing layouts.

Keywords Aircraft engines, Pipe routing, Rectilinear paths, Branches, Particle swarm optimization, Steiner tree, Programming and algorithm theory

Paper type Research paper

Introduction

Routing pipes, in particular branch pipes with multiple terminals, poses a considerable challenge to complex product developments such as aero-engine engineering. Given that manual routing usually leads to numerous revisions and waste, pipe-routing algorithms that enable automation for pipe routes extensively draw attention from both academic researchers and practitioners in engineering disciplines. However, during the past decades, while the two-terminal pipe-routing problems are widely studied (Lee, 1961; Hightower, 1969; Kang *et al.*, 1999; Ito, 1999; Sandurkar and Chen, 1999; Guirardello and Swaney, 2005; Fan *et al.*, 2006; Van Der Velden *et al.*, 2007; Roh *et al.*, 2007; Liu and Wang, 2010; Yin *et al.*, 2010; Liu and Wang, 2011a), only a few researches have been conducted on the branch pipe-routing problems due to its complexity.

As a more general case of two-terminal pipe-routing problems, branch pipe routing with multiple terminals that can be formulated as a Steiner minimal tree problem (detailed analysis will be conducted in section "Problem description") is NP-hard even in 2D spaces, which means that no exact algorithm can solve this problem in polynomial time. For instance, without consideration of obstacles, the shortest pipe path between two terminals is the straight line connecting both terminals; however, the multi-terminal routing problem is much more complex even in this case since the Steiner points (branch point) are difficult to be determined. And, the obstacle-avoidance multi-terminal routing problem is more complicated.

Park and Storch (2002) take branch pipes into consideration in the cell-generation method, where a branch pipeline is regarded as a compound of two simple forms: end forked and middle forked. Fan *et al.* (2003) present a branch pipe-routing algorithm based on maze algorithm, where he first connects two terminals and then connects the remainders one by one. Asmara and Nienhuis (2006) apply the particle swarm optimization (PSO) (Kennedy and Eberhart, 1995) and Dijkstra's (1951) algorithm in conjunction to connect the terminals sequentially. Even though these methods can provide feasible solutions, few rectilinear branch pipe-routing algorithms are studied by using the Steiner tree theory which reflects the mathematical model of rectilinear branch pipe-routing problems, i.e. the RSMTO. Liu and Wang (2011b) present a PSO-based routing algorithm for

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solving Euclidean Steiner minimal tree with obstacles (ESMTO) problem to plan non-rectilinear branch pipes in Euclidean spaces, however, the rectilinear pipe-routing problems need to use the concept of Manhattan distance in a discrete space, which makes it much difficult (if not impossible) to directly implement planning algorithms commonly used in Euclidean spaces to solve rectilinear problems in discrete Manhattan spaces (detailed differences between ESMTO and RSMTO problems will be described in section "Problem formulation").

The rectilinear Steiner tree problem is also addressed in integrated circuits design areas; however, according to Hu (2005), only a few existing multi-terminal routing algorithms take obstacles into consideration, which is more complicated than the cases of the two-terminal obstacle-avoidance routing and multi-terminal routing without consideration of obstacles.

In this paper, the rectilinear branch pipe-routing problem is studied in the context of an aero-engine development. We first analyze the mathematical models of two commonly used descriptions of branch pipe-routing problems and then show that their common mathematical model is the RSMTO problem. Then, we present a discrete PSO algorithm (DPSO-based rectilinear branch pipe-routing algorithm, DPSO-RBPRA) that adopts an attraction operator and an energy function to solve the RSMTO problem and to plan aero-engine rectilinear branch pipes. Moreover, this paper combine several existing techniques, the method (Liu and Wang, 2011a) for solving two-terminal rectilinear pipe paths and the method (Liu and Wang, 2011b) for solving the ESMTO problem in continuous Euclidean spaces, to make this integrated strategy be available for evaluating particles for the RSMTO problem in discrete Manhattan spaces. To the best of our knowledge, in this paper the Steiner tree theory is used for the first time to solve rectilinear branch pipe-routing problems. Finally, several numerical computations for rectilinear branch pipe routing are conducted to demonstrate the effectiveness of the proposed method.

Mathematical model

Problem description

According to computational geometry, the Steiner minimal tree with obstacles (SMTO) can be formulated as finding a shortest collision-free network interconnecting a number of given terminals while allowing for addition of auxiliary points called Steiner points, which are called ESMTO and RSMTO problems when using Euclidean and Manhattan metrics, respectively.

Even though Fan *et al.* (2003) has shown that the branch pipe-routing problems can be mathematically formulated as a Steiner minimal tree problem, so far few Steiner tree theory-based rectilinear branch pipe-routing algorithms are developed, which may result from the fact that there is not a uniform description of branch pipe-routing problems. In branch pipe-routing areas, the most commonly used descriptions are "multi-point pipe routing" and "one to multi-point pipe routing". In this section, we will analyze the mathematical models of these two descriptions in detail, which can be described as Theorem 1.

Theorem 1. Both the "multi-point pipe routing" and "one to multi-point pipe routing" problems have the same mathematical formulation – a Steiner tree problem.

Proof. Given a branch pipe with $(n+1)$ terminals $v_0, v_1, v_2, v_3, \ldots, v_n$, without loss of generality, we assume that the "one to multipoint pipe routing" problem means that v_0 needs to be connected to all the other points $V_t = \{v_1, v_2, v_3, \ldots, v_n\}$. □

First, the "multi-point pipe routing" problem can be formulated as planning a shortest collision-free network connecting the terminals so that arbitrary two points can be connected, while allowing for addition of auxiliary points called Steiner points, which obviously satisfies the definition of SMTO.

Consequently, a "multi-point pipe routing" connecting network must meet the objective "one to multipoint" since arbitrary two points can be connected, which naturally means that v_0 can be connected to the other points $v_1, v_2, v_3, \ldots, v_n$. Therefore, we have, a "multi-point pipe routing" connecting network must be a "one to multipoint pipe routing" connecting network.

Further, a "one to multi-point pipe routing" connecting network where v_0 can be connected to the points $V_t = \{v_1, v_2, v_3, \ldots, v_n\}$ means that, $\forall v_i \in V_t, v_j \in V_t$, there must exist a path $v_i \rightarrow v_0 \rightarrow v_j$ shown in Figure 1, so that v_i can be connected to v_j. Thus, we have, a "one to multi-point pipe routing" connecting network must be a "multi-point pipe routing" connecting network.

Thus, both the "multi-point pipe routing" and "one to multi-point pipe routing" descriptions have the same the mathematical formulation, i.e. the RSMTO problem.

Problem formulation

For the RSMTO problem, Ganley and Cohoon (1994) have shown that there is an optimal routing for any multi-terminal net that uses only escape segments, which can be described by the following theorem.

Theorem 2 (Ganley and Cohoon, 1994). If an instance of the RSMTO problem is solvable, then there is an optimal solution composed only of escape segments, where the escape graph (as shown in Figure 2) can be constructed by the lines extended form terminals and obstacle vertices in both horizontal and vertical directions until blocked by any obstacle or boundary of the design.

For solving an RSMTO problem, a main task is to determine the Steiner points. Theorem 1 shows that the RSMTO problem

Figure 1 A path: $v_i \rightarrow v_0 \rightarrow v_j$

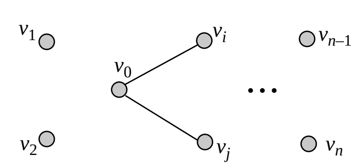
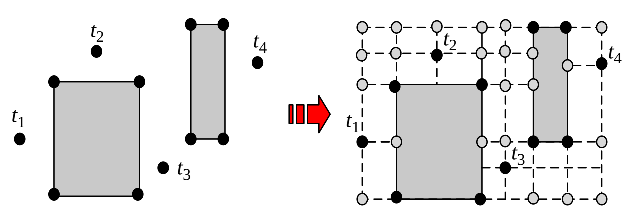


Figure 2 An escape graph



is clearly a discrete problem such that the possible Steiner points must belong to the set of nodes of the escape graph, which is different from the ESMTO problem in continuous Euclidean spaces. Moreover, the RSMTO problem has to use the concept of Manhattan distance other than the Euclidean distance, which further makes it much difficult (if not impossible) to directly implement planning algorithms commonly used in Euclidean spaces (Liu and Wang, 2011b) to solve rectilinear branch pipe-routing problems.

The DSPO-RBPRA

As an intelligent optimization technique, the PSO algorithm proposed by Kennedy and Eberhart (1995) extensively draws attention from both academic researchers and practitioners due to its good global search ability, robustness and simple structure. In this paper, the basic idea of DPSO-RBPRA is to apply the PSO algorithm to seek the Steiner points in a discrete space determined by an escape graph by presenting an attraction operator, defining the extended pipe length and integrating several existing techniques.

Particle encoding

One key problem of solving an RSMTO problem is to determine the number and positions of the Steiner points, this naturally leads to an encoding method that views the number and the coordinates of the Steiner points as a particle encoding, as did by Yang (2006) and Liu and Wang (2011b), which, respectively, solve the ESMT and ESMTO problems. More specially, for an n-terminal pipe-routing problem, a particle can be represented as an encode with a fixed length $2(n\text{-}2) + 1$, which is determined by the full-tree with (n-2) points:

$$\{m, x_1, y_1, x_2, y_2 \ldots, x_m, y_m \ldots, x_{n-2}, y_{n-2}\}$$

where:

m	the number of Steiner points, $0 \leq m \leq n-2$
$\{x_1, y_1, x_2, y_2 \ldots, x_m, y_m\}$	the coordinates of the m Steiner points.
$\{x_{m+1}, y_{m+1} \ldots, x_{n-2}, y_{n-2}\}$	the $(n-2-m)$ potential Steiner points. Note that, the potential Steiner points mean that the points may become the Steiner points as the system iterates.

As mentioned in section "Problem formulation", Theorem 2 has shown that the possible Steiner points must belong to the set V_G of nodes of the escape graph, then the Steiner points represented by this encoding method thus need to be appropriately transformed to adapt to this discrete spaces after initiation and update. To this end, this paper presents an attraction operator to make the original PSO algorithm can handle this discrete case, which will be introduced in detail in the following section.

The DPSO for solving RSMTO

In the original PSO (Kennedy and Eberhart, 1995), particles are defined as candidate solutions and the movements of particles are regarded as the search process. The position and velocity of the ith particle at t iteration are represented by $x_i(t) = (x_{i1}(t), \ldots, x_{il}(t), \ldots, x_{iD}(t))$ and $v_i(t) = (v_{i1}(t), \ldots, v_{il}(t), \ldots, v_{iD}(t))$, respectively. Each particle adjusts its position according to its previous optimal position denoted by $p_i = (p_{i1}(t), \ldots, p_{il}(t), \ldots, p_{iD}(t))$ and the group's optimal position denoted by $p_g = (p_{g1}(t), \ldots, p_{gl}(t), \ldots, p_{gD}(t))$. During the iterations, particles are updated by equations (1) and (2).

$$v_{il}(t+1) = \omega \cdot v_{il}(t) + c_1 \cdot r_1 \cdot [p_{il}(t) - x_{il}(t)] + c_2 \cdot r_2 \cdot [p_{gl}(t) - x_{il}(t)] \quad (1)$$

$$x_{il}(t+1) = x_{il}(t) + v_{il}(t+1) \quad (2)$$

where ω is the inertia weight, $c_1$and c_2 are the acceleration coefficients. r_1 and $r_2$are two random numbers in [0, 1].

The original PSO described above is proposed for solving the continuous optimization problems; however, it cannot deal with the discrete RSMTO problem. To breakthrough this technical barrier, we present a DPSO in order to seek the rectilinear Steiner minimum tree in a discrete space determined by the nodes of a constructed escape graph.

Define 1: attraction operator. As shown in Figure 3, in an l-dimensional space, given a set $V_G$of nodes determined by an escape graph and a particle $p(x_{p1}, x_{p2}, \ldots x_{pl})$, then the attraction operator can be defined as a transformation that transforms p into the point $q(x_{q1}, x_{q2}, \ldots x_{ql}) \in V_G$, which has the shortest distance to p. More specially, the *attraction operator* can be mathematically formulated as follows:

$$x_{p1} \leftarrow x_{q1}, x_{p2} \leftarrow x_{q2}, \ldots, x_{pl} \leftarrow x_{ql}$$
$$q \in V_G \,\&\, d(p,q) = \min\{d(p,q_i)\}, i = 1, 2, \ldots, n$$

where $d(p,q)$ denotes the distance between the points $p(x_{p1}, x_{p2}, \ldots, x_{pl})$ and $q(x_{q1}, x_{q2}, \ldots, x_{ql})$, which can be formulated as the Euclidean distance:

$$d_E(p,q) = [(x_{p1} - x_{q1})^l + (x_{p2} - x_{q2})^l + \cdots + (x_{pl} - x_{ql})^l]^{1/l} \quad (3)$$

or the Manhattan distance:

$$d_M(p,q) = |x_{p1} - x_{q1}| + |x_{p2} - x_{q2}| + \cdots + |x_{pl} - x_{ql}| \quad (4)$$

By using this definition, the PSO can adapt to the discrete rectilinear branch pipe-routing problem. The main flowchart of DPSO (Figure 4) is described as follows.

Evaluate particles

Beside the collision-free shortest pipe lengths, another objective (engineering rule) for pipe routing is to place pipes close to some equipment, or to keep distance from some regions (i.e. electrical regions) for safety consideration. Considering this, Ito (1999) has proposed the concept of "potential energy" for a planning space divided into cells, where cells close to obstacles (equipment) are endowed with lower energy values, which means that one route is more favorable if it goes along obstacles.

Figure 3 Attraction operator

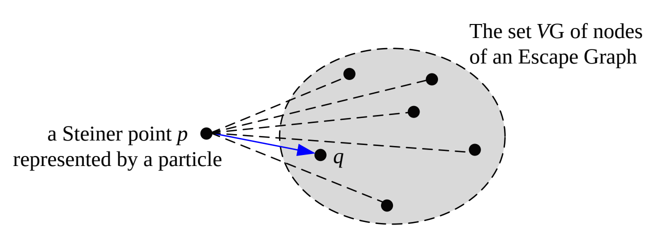
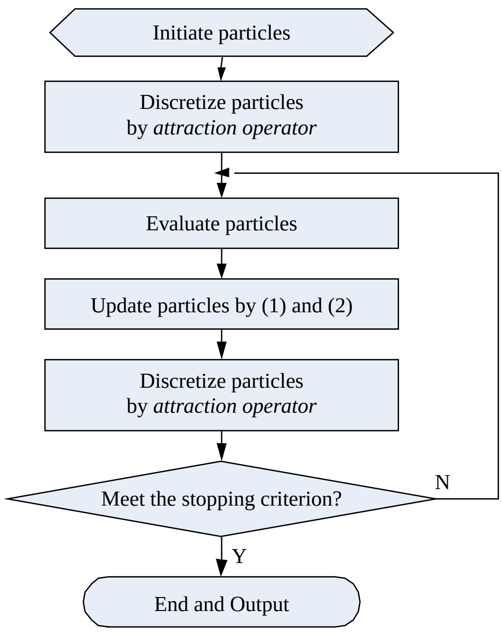


Figure 4 The flowchart of DPSO



To make the "potential energy" be available for the Escape graph-based planning spaces, this paper defines an energy function to endow the nodes and edges of the escape graph with appropriate energy values. More specially, we classify related obstacles into two sets: $O_c = \{o_{c1}, o_{c2}, \ldots, o_{cm}\}$ and $O_d = \{o_{d1}, o_{d2}, \ldots, o_{dn}\}$, which, respectively, represent the obstacles that pipes should be placed close to and the obstacles that pipes should keep distance from. And, each obstacle is designated a point p_{ci} or p_{dj} to represent the obstacle o_{ci} or o_{dj}, where $i = 1,2\ldots,m$; $j = 1,2\ldots,n$.

Further, the engine value of a point p can be determined as follows:

- *Step 1.* Select a point $p_{c\min}$ from $P_c = \{p_{c1}, p_{c2}, \ldots, p_{cm}\}$ such that $p_{c\min}$ has the shortest distance to p.
- *Step 2.* Select a point $p_{d\min}$ from $P_d = \{p_{d1}, p_{d2}, \ldots, p_{dn}\}$ such that $p_{d\min}$ has the shortest distance to p.
- *Step 3.* Compute the engine value of the point p (denoted by $E(p)$) by equation (5):

$$\begin{aligned} E(p) &= E_c(p) + E_d(p) \\ &= d(p, p_{c\min}) + [M - d(p, p_{d\min})] \end{aligned} \tag{5}$$

where $E_c(p)$ and $E_d(p)$, respectively, denote the engine values determined by O_c and O_d; M is a positive constant.

Then, the generalized pipe length $L'(pipe)$ can be defined as:

$$L'(pipe) = \alpha \cdot L(pipe) + \beta \cdot E(pipe) \tag{6}$$

where $L(pipe)$ is the pipe length; $E(pipe)$ is the engine value; α and β are constants, $0 \leq \alpha,\beta \leq 1$, $\alpha + \beta = 1$.

Now, we will introduce several existing techniques in ESMTO and two-terminal rectilinear routing areas, and then combine and extend these methods to RSMTO cases to meet the requirements of evaluating particles in the discrete escape graph space using Manhattan distance. In the method (Liu and Wang, 2011b) for solving the ESMTO problem, given a set of terminals S, a set of obstaclesΩ, and a particle S' (i.e. several Steiner points), the objective function is determined by the following steps:

- *Step 1.* Construct a visibility graph $VG(S \cup S', \Omega)$, and then the ESMTO problem becomes one of the Steiner minimum tree in graphs (SMTG), as did by Provan (1988).
- *Step 2.* The SMTG problem can be further solved by using the well-known method proposed by Lawler (1976), which first constructs a Complete Graph $CG(S \cup S')$ and then solves the minimal spanning tree (MST) of $CG(S \cup S')$ by using Prim's algorithm. Detailed introduction of Prim's algorithm can be found in the reference (Brassard and Bratley, 1996).
- *Step 3.* Then, the length of MST will be viewed as the fitness of the particle S'.

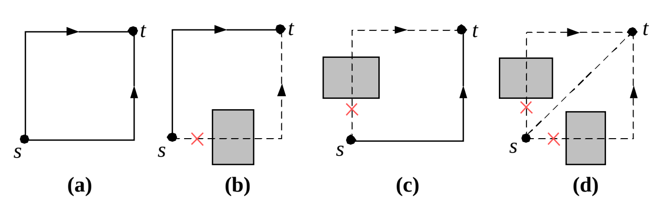
However, in cases of RSMTO problem, the above method becomes inappropriate since the original visibility graph (Lozano-Pérez and Wesley, 1979) used for Euclidean spaces is not suitable for the rectilinear problems. To breakthrough this technical barrier, this paper modifies the above method by replacing the original visibility graph with the Manhattan visibility graph (MVG) method proposed by Liu and Wang (2011a), where the basic idea of MVG is to replace the straight lines in Euclidean spaces with the defined Manhattan visible lines in Manhattan spaces. As shown in Figure 5, all the cases are defined as Manhattan visible except the case shown in Figure 5(d). Further, the MVG can be extended to the surface cases of aero-engines by replacing the Manhattan lines with meridians and parallels.

By integrating the above methods, we can evaluate particles for RSMTO problem in Manhattan spaces. Note that, in this paper the lengths of Manhattan visible lines are computed according to the generalized pipe length formulated by equation (6).

Pipe-routing simulations

In this paper, the rectilinear branch pipe-routing problem is studied in the context of an aero-engine development, where the pipes need to be installed close to surface of engine jackets to guarantee better stability and reliability. Numerical computations for pipe routing are implemented on a workstation (Quad CPU 2.83 GHz, 8 GB RAM) with conventional developments of Matrix Laboratory (MATLAB) and Unigraphics NX (UG) systems. The date transmission between both systems is performed by TXT files. More specially, first, the geometric information of the pipe-routing space of a simplified aero-engine model is extracted by using UG/Open GRIP. Then, the DPSO-RBPRA is performed in MATLAB system. Finally, the computation results will be transferred back to the UG system for visualization. The parameters of DPSO are set according to the suggestions (Clerc and Kennedy, 2002): $\omega = 1.414$, $c_1 = c_2 = 0.747$;

Figure 5 Manhattan visible lines



Source: Liu and Wang (2011a)

$N = 15$, $T = 20$, where N is the population size and T is the number for iterations.

By using DPSO-RBPRA, an eight-terminal routing computation on a simplified aero-engine piping model is performed. Figure 6 shows a satisfactory solution from several computations, which runs in about 2.7 min, and the convergence curve of the optimal particle is shown in Figure 7. The routing layout shows that, a near shortest collision-free network keeping distance from an electrical region $o_{d1}$and being placed close to o_{c1} on the surface of the aero-engine is found, which demonstrates the effectiveness of *DPSO-RBPRA*.

To further demonstrate the effectiveness of DPSO-RBPRA, we compare DPSO-RBPRA with the traditional methods which connect the terminals sequentially, where the MVG method and Dijkstra algorithm are used in conjunction to connect pipe terminals sequentially. A four-terminal pipe-routing problem is, respectively, solved by using both methods. The routing layouts and computation results are, respectively, shown in Figure 8 and Table I. As far as this example is concerned, DPSO-RBPRA finds shorter connecting networks than the traditional methods, which may benefit from using the Steiner tree theory to solve branch pipe-routing problems.

Conclusions

In this paper, the rectilinear branch pipe-routing problem is studied. We analyze the mathematical model of the rectilinear

Figure 6 Branch pipe-routing layouts

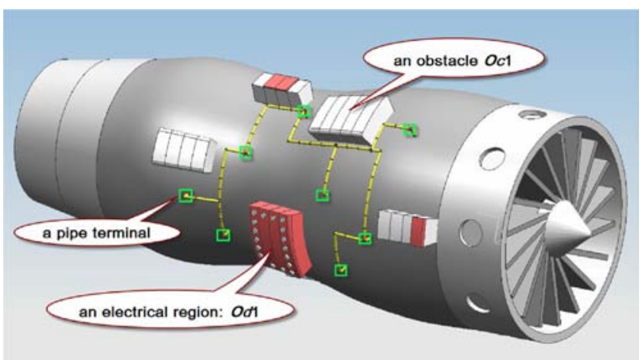


Figure 7 The convergence curve of the optimal particle

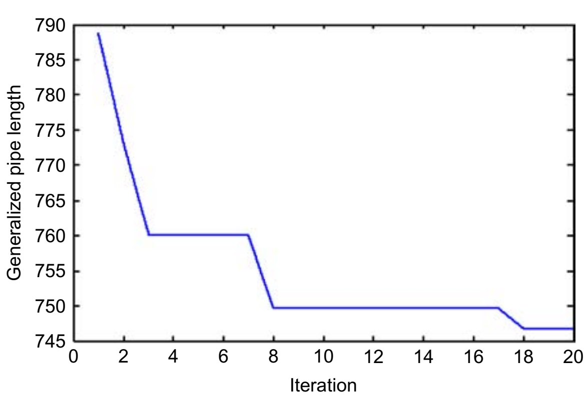
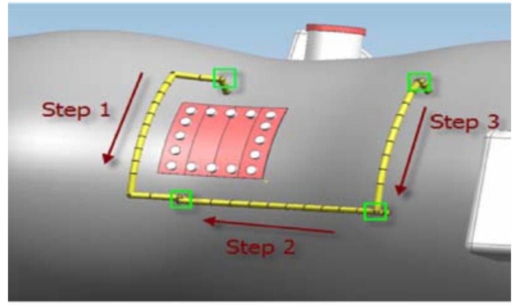
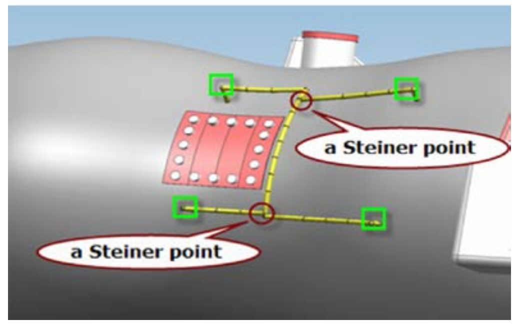


Figure 8 Routing examples for comparisons



(a) Connecting terminals sequentially



(b) Routing by *DPSO-RBPRA*

Table I Pipe lengths of routing layouts

	Connect sequentially	DPSO-RBPRA
Pipe lengths	218	198

branch pipe-routing problems and then develop a discrete swarm optimization algorithm (DPSO-RBPRA) which adopts an attraction operator and an energy function to solve RSMTO problem and to plan rectilinear branch pipe-routing problem, while considering several engineering rules: avoiding collision with obstacles, minimizing pipe lengths, placing pipes on the surface of aero-engines, placing pipes close to some equipment or keeping distance form some regions.

Unlike the traditional methods that connect the terminals sequentially, the Steiner tree theory is used to plan the rectilinear branch pipe-routing problems. Moreover, DPSO-RBPRA may have the advantages in terms of global characteristic, robustness and implementation easiness since it applies the population-based intelligent optimization technique. The final pipe-routing computations on a simplified aero-engine piping model demonstrate the effectiveness of the proposed method. Future research should be on taking more engineering rules into consideration such as minimization of the number of pipe bends.

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