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# Cooperative coalition for formation flight scheduling based on incomplete information

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**Abstract** This study analyzes the cooperative coalition problem for formation scheduling based on incomplete information. A multi-agent cooperative coalition framework is developed to optimize the formation scheduling problem in a decentralized manner. The social class differentiation mechanism and role-assuming mechanism are incorporated into the framework, which, in turn, ensures that the multi-agent system (MAS) evolves in the optimal direction. Moreover, a further differentiation pressure can be achieved to help MAS escape from local optima. A Bayesian coalition negotiation algorithm is constructed, within which the Harsanyi transformation is introduced to transform the coalition problem based on incomplete information to the Bayesian-equivalent coalition problem based on imperfect information. The simulation results suggest that the distribution of agents' expectations of other agents' unknown information approximates to the true distribution after a finite set of generations. The comparisons indicate that the MAS cooperative coalition algorithm produces a significantly better utility and possesses a more effective capability of escaping from local optima than the proposal-engaged marriage algorithm and the Simulated Annealing algorithm.


## 1. Introduction

The continuous growth of air traffic flow has created an energy and environmental crisis, which has aroused global concerns. According to the international airport association, the passenger demand is expected to reach 9.1 billion and cargo demand 214 million tons in 2025, which in turn will result in 1.4 billion tons of $CO_2$ emissions,[1] increasing concerns for energy demand and environment crisis. In 2009, the European Union created its long-term vision on reducing $CO_2$ emissions to half of the 2005 level by 2050.[2] The Chinese government has also promised to reduce $CO_2$ emissions to 45%–50% of the 2005 level by 2020. The aviation sector will inevitably be forced to reduce its share of emissions. Formation flight has been widely recognized as one of the most promising coping strategies due to its potential for reducing fuel use. NASA, Airbus, Boeing

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and other researchers have pioneered studies regarding aerodynamic theory and the fuel economy of extended formation flying in the commercial aviation sector.[3–8]

Formation scheduling problems have become the focus of these studies. Scheduling is typically described as when, where and with whom flights are scheduled to join a formation, with the objective being to minimize overall fuel costs. The formation flight paths must be created in advance to evaluate the fuel economy of a specific schedule. Therefore, the formation scheduling and path planning problems are highly correlated and solved simultaneously. The formation scheduling problem is based on the recursive weighted geodesic steiner minimum tree (WGSMT) constructing problem. However, because no exact analytical solution of the WGSMT Steiner point problem exists,[9] a numerical solution technique will cause the problem to become exponentially complex. Ribichini and Frazzoil formulated the problem as three related sub-problems, presented a multi-agent coalition algorithm and solved it via the greedy method.[10] Bower et al. optimized the formation path by using the Nelder–Mead Simplex algorithm.[11] Kent and Richards built a mixed integer programming model for large-scale formation scheduling and solved it based on Simulated Annealing.[12] Later, they incorporated wind impacts into the model.[13] Recently, Xu et al. developed a bi-level formation flight path planning framework in which heterogeneous aircraft drag models are involved. They also significantly reduced the problem's complexity by restricting the search space inside the intersections of all the candidate flight performance and fuel-efficiency envelopes.[14,15] Xu et al. presented a mathematical model of the formation path planning problem along with related geometric deductions.[16]

Previous research has mainly been conducted under the assumption of complete information. The inherent complexity of the problem, which is induced by geodesic measurements, is seldom considered. In this paper, we focus on the intercontinental commercial formation scheduling problem based on incomplete information. In Section 2, we give the problem description and model it using a recursive WGSMT construction problem. An approximate analytical solution of the WGSMT Steiner point problem is derived to reduce the problem's complexity. In Section 3, a cooperative coalition framework is developed to treat the problem in a decentralized manner. We also propose a coalition negotiation algorithm based on incomplete information. We then make comparisons to verify the validity and efficiency of our algorithm. Finally, we present our conclusions and suggestions for future work in Section 5.

## 2. Mathematical formulation

### 2.1. Problem formulation

In our previous work, the formation flight scheduling problem was developed from the WGSMT construction problem, as was a detailed description of the mathematical model.[16] A formation path includes departures, rendezvous points, breakaway points and arrivals, which are connected by geodesic lines[11] (Fig. 1). Based on the assumption that only two fleets are scheduled to join the formation at a rendezvous point and separate from the formation at a breakaway point,[12] the degree of all rendezvous points and breakaway points is exactly 3. Therefore, the formation path can be represented by a WGSMT tree, $T(D,R,B,A,W)$, spanning the departure set, $D=\{d_i|i=1,2,\ldots,m\}$, and the arrival set, $A=\{a_j|j=1,2,\ldots,n\}$ (Fig. 2)[12,16]. The rendezvous point set, $R=\{r_i|i=1,2,\ldots,m-1\}$, and the breakaway point set, $B=\{b_j|i=1,2,\ldots,n-1\}$, are Steiner point sets. $W$ is the arc weight set, which is determined by fleet size. The objective is to minimize the total weighted geodesic distance of $T(D,R,B,A,W)$ by optimizing the formation schedule.

Based on the topological features of the formation path, the construction of $T(D,R,B,A,W)$ can be redefined as recursively constructing $T(k)=\{(o_i(k),g_i(k),q_i(k)),i\in F(k)\}$ until $T(k)$ converges. In $T(k)$, $o_i(k)$ is $i$'s current position, $g_i(k)$ is $i$'s goal-reachable position, $q_i(k)$ is $i$'s fleet size, $F(k)=\{1,2,\ldots,n(k)\}$ is the formation set and $n(k)$ is the number of formations at generation $k$.

To quantify the fuel economy of formation flight, we introduce the equivalent range as[16]

$$d_{\mathrm{ff}}(o_i(k),g_i(k))=w_i(k)d(o_i(k),g_i(k)) \tag{1}$$

where $d(o_i(k),g_i(k))$ is the geodesic distance from $o_i(k)$ to $g_i(k)$; $w_i(k)=1/\varepsilon_i(q_i(k))$, $\varepsilon_i(q_i(k))$ is the relative range defined by the ratio of the fuel mileage flying in a formation relative to that flying solo;[17] $d_{\mathrm{ff}}(o_i(k),g_i(k))$ is the equivalent range from $o_i(k)$ to $g_i(k)$ and "ff" represents "formation flight".

$$\varepsilon_i(q_i(k))=2q_i(k)/(q_i(k)+1) \tag{2}$$

At $k=0$, $T(k)=\{f_i(k)=(o_i(k),g_i(k),q_i(k))|i=1,2,\ldots,n(k),\ o_i(k)\in D,\ g_i(k)\in A,\ q_i(k)\in\mathbf{N}\}$.

At $k>0$, all possible 2-member formations in $T(k)$ are scheduled to minimize the overall equivalent range:

$$\begin{aligned}\min f=\sum_{i,j\in F(k)}\delta_{\langle i,j\rangle}(k)[&q_i(k)(d_{\mathrm{ff}}(o_i(k),r_{\langle i,j\rangle}(k))\\&+d_{\mathrm{ff}}(r_{\langle i,j\rangle}(k),b_{\langle i,j\rangle}(k))+d_{\mathrm{ff}}(b_{\langle i,j\rangle}(k),g_i(k)))\\&+q_j(k)(d_{\mathrm{ff}}(o_j(k),r_{\langle i,j\rangle}(k))+d_{\mathrm{ff}}(r_{\langle i,j\rangle}(k),b_{\langle i,j\rangle}(k))\\&+d_{\mathrm{ff}}(b_{\langle i,j\rangle}(k),g_j(k)))]\end{aligned} \tag{3}$$

where

$$\delta_{\langle i,j\rangle}(k)=\begin{cases}1 & \text{if formation } \langle i,j\rangle \text{ is formed}\\0 & \text{if formation } \langle i,j\rangle \text{ isn't formed}\end{cases} \tag{4}$$

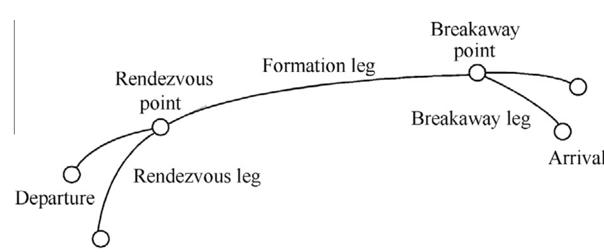


**Fig. 1** Representation of a formation path.

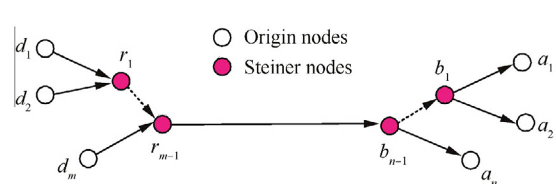


**Fig. 2** WGSMT formation path.