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序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期	类别
91	张洪海 胡明华 陈世林	博士 正高 博士	072 072 072	机场进离场流量协同分配策略	南京航空航天大学学报	2008.40.5	
92	张洪海 胡明华 王艳军	博士 正高 博士	072 072 072	Priority-Based Collaborative Aircraft Scheduling	2008 International Conference of China Logistics and Transportation Professionals	2008.2.0	
93	王艳军 胡明华 张洪海	博士 正高 博士	072 072 072	Scheduling Model and Heuristic Algorithm for Departure Management in Multiairport	2008 International Conference of China Logistics and Transportation Professionals	2008.4.0	
94	陈世林 胡明华 张洪海	博士 正高 博士	072 072 072	基于进离场容量转换的协同决策系统研究	系统管理学报	2008.17.5	
95	陈世林 胡明华 张洪海	博士 正高 博士	072 072 072	SMS系统中基于冲突探测的滑行道轨迹预测算法研究	四川大学学报	2008.45.6	
96	陈世林 胡明华 张洪海	博士 正高 博士	072 072 072	Improvement of Slot Assignment Algorithms in Ground Delay Program Enhancements	2008 International Conference of China Logistics and Transportation Professionals (ICCLTP2008)	2008	
97	陈世林 胡明华 张洪海	博士 正高 博士	072 072 072	一种新的基于贪婪法的CDM时隙分配最优化算法研究	系统工程理论与实践	2008.28.10	
98	高政 胡明华	硕士 正高	072 072	动态空域下的实时改航策略	第四届全国智能交通会议	2008	
99	张荣 胡明华 张洪海	硕士 正高 博士	072 072 072	协同式地面等待程序中时隙公平分配研究	交通与计算机	2008.26.144	
100	赵磊	硕士	072	飞机进港时隙分配机制的有效性与公平性研究	第四届全国智能交通会议	2008	
101	瞿英俊 胡明华	硕士 正高	072 072	动态航迹推测改进模型	第四届全国智能交通会议	2008	
102	窦荣 胡明华 王艳军	硕士 正高 博士	072 072 072	基于飞行需求的航路动态管理	航空计算技术	2008.38.6	
103	陈星 胡明华	硕士 正高	072 072	动态空域下的飞行流量自适应调配模型	第四届全国智能交通会议	2008	
104	张全 胡明华	硕士 正高	072 072	基于协同空域的飞行流量管理	第四届全国智能交通会议	2008	
105	刘欢 胡明华	硕士 正高	072 072	模拟退火算法求解区域航班规划模型	第四届全国智能交通会议	2008	

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期	类别
106	丁毅萍 韩松臣	硕士 正高	072 072	Research on the airport taxiways optimization modelingbased on metagraph	Logistics	2008.4.0	
107	张慧 韩松臣	硕士 正高	072 072	窄距平行跑道配对进近的构型边界研究	第7届亚太交通运输发展会议暨第21届国际华人交通运输协会	2008.5	
108	崔国山 韩松臣 朱新平	硕士 正高 硕士	072 072 072	基于Agent的机场应急资源动态调配研究	2008全国工业控制计算机年会会议论文集	2008.11	
109	钟育鸣 韩松臣 张旭婧	硕士 正高 硕士	072 072 072	机场容量评估中仿真飞机流的设计与实现	交通与计算机	2008.26.6	
110	尤杰 韩松臣	硕士 正高	072 072	MAS在机场路面路径优化中的应用研究	交通与计算机	2008.26.6	
111	张慧 王喆	硕士 硕士	072 072	机场吞吐量预测方法探讨	中国民用航空	2008.0.10	
112	梁世华 韩松臣 朱新平	硕士 正高 硕士	072 072 072	基于CBR的机场应急救援规模决策研究	交通与计算机	2008.26.6	
113	明朝辉	博士	072	基于多层次FEM的过程进度测算	江苏教育学院学报	2008.25.4	
114	汤新民 钟诗胜	中级 正高	072 外校	基于确定时间连续Petri网的航空发动机总装资源调度	计算机集成制造系统	2008.14.9	
115	汤新民 钟诗胜	中级 正高	072 外校	基于离散时间最优控制的航空发动机装配序列规划	控制与决策	2008.23.11	
116	汤新民 韩松臣	中级 正高	072 072	民航发动机车间维修能力近似平均值分析方法	交通运输工程学报	2008.8.4	
117	田勇 董云龙	中级 硕士	072 072	基于进离场容量转换的航班地面等待程序	系统工程理论与实践	2008.28.9	
118	田勇 宋柯 顾英豪	中级 硕士 硕士	072 072 072	空中交通流量管理中的改航策略研究	数学的实践与认识	2008.10	
119	白杨	中级	073	对加强民航经营管理人才培养的思考	现代企业教育	2008.11	
120	白杨 朱金福	中级 正高	073 073	基于价值网的航空物流企业经营模式分析	商业时代	2008.9	
121	吴薇薇	中级	073	Evaluation of the reliability of transport networks based on the stochastic flow of moving objects.	Reliability engineering and system safety	2008.93.6	

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期	类别
122	吴薇薇	中级	073	民航运输管理专业运筹学课程教学改革研究	科技信息	2008.0.28	
123	杨文东 朱金福 李雯 王文芳	中级 正高 硕士 硕士	073 073 073 073	长江三角洲航空运输网络一体化研究	长三角区域经济社会协调发展理论研讨会	2008	
124	杨文东 张璟	中级 博士	073 073	Simulation Research on Cargo Process of Airport Logistics Park	中国物流与运输国际会议	2008	
125	赵秀丽 朱金福 郭梅	博士 正高 博士	073 073 073	不正常航班延误调度模型及算法	系统工程理论与实践	2008.0.4	
126	赵秀丽 朱金福	博士 正高	073 073 073	Grey Programming for Irregular Flight Scheduling	Proceedings of 2007 IEEE International Conference on Grey Systems and Intelligent Services	2007.18-20	
127	赵秀丽 朱金福 郭梅	博士 正高 博士	073 073 073	Application of Grey Programming in Irregular Flights Scheduling	Proceedings of the 2007 IEEE IEEM	2007	
128	姚韵 朱金福 郭梅	博士 正高 博士	073 073 073	基于可拓关联函数的不正常航班管理预警模型	西南交通大学学报	2008.0.2	
129	张玮 朱金福	博士 正高	073 073	Research on Multi-Attribute ecision-Making Method Based on Fuzzy Set Theory	International Symposium on Intelligent Information Technology Application	2008	
130	张玮 朱金福	博士 正高	073 073	Using Fuzzy wavelet Neural Network to solve MCDM problem	International Symposium on Computer Science and Computational Technology	2008	
131	张玮 朱金福	博士 正高	073 073	我国交通运输业发展区域差异性研究	企业经济	2008.0.6	
132	张玮 朱金福	博士 正高	073 073	城市公交网络复杂性实证研究	商业时代	2008.0.7	
133	张玮 朱金福	博士 正高	073 073	从枢纽机场建设谈“临空经济”发展	商业时代	2008.0.25	
134	张文欣 罗亮生	硕士 高工	073 073	航空公司客户价值管理	民航管理	2008.0.6	
135	演克武 朱金福	博士 正高	073 073	决策树分类法中D3算法在航空市场客户价值细分中的应用	商业研究	2008.0.3	
136	朱星辉 朱金福	中级 正高	073 073	基于杂交模型及逻辑分解算法的JSSP研究	系统工程与电子技术	2008.30.9	
137	朱星辉 朱金福	中级 正高	073 073	MIP/CP综合考虑的车间作业调度问题研究	小型微型计算机系统	2008.29.4	

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期	类别
138	刘晓明 夏洪山	博士 正高	073 073	基于航空旅客OD流的重力模型逆向算法	西南交通大学学报	2008.43.3	
139	刘晓明 夏洪山	博士 正高	073 073	机场选择研究综述	数理统计与管理	2008.27.5	
140	刘晓明 夏洪山	博士 正高	073 073	基于粗糙集理论的省区航空客运需求生成预测	海峡两岸智能运输系统学术研讨会	2008..	
141	刘晓明 夏洪山	博士 正高	073 073	基于重力模型逆向算法的航空节点客运量估计	交通运输工程学报	2008.8.2	
142	王喆 夏洪山	硕士 正高	073 073	基于熵权法的新机场货邮吞吐量预测	郑州大学学报	2008.12.4	
143	曾小舟 江可申	副高 正高	073 073	诚信视角下战略联盟稳定性影响因素研究	价格月刊	2008.0.2	
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145	张明 韩松臣 裴成功	中级 正高 初级	074 074 074	空中交通管制员工作负荷研究综述	人类工效学	2008.14.4	
146	张明 韩松臣	中级 正高	074 074	Integrated Evaluation of air Traffic Controller workload Based on Matter-Element Analysis	Journal of Southwest Jiaotong University(English Edition)	2008.16.2	
147	司海青 王同光	中级 正高	074 074	Grid-Optimized Upwind Dispersion-Relation-Preserving Scheme on Non-uniform Cartesian Grids for Computational Aeroacoustics	Aerospace science and technology	2008.12.8	
148	司海青 王同光	中级 正高	074 074	Calculation of the Unsteady Airloads on Wind Turbine blades under yawed flow	2nd International Symposium on Physics of Fluids	2008	
149	司海青 王同光	中级 正高	074 074	Grid-Optimized Upwind Dispersion-Relation-Preserving Scheme on Curvilinear Grids for Computational Aeroacoustics	37th International Congress and Exposition on Noise Control Engineering	2008	
150	李桂芳 刘星	中级 副高	074 074	一类非线性系统的鲁棒无源性综合问题	系统工程与电子技术	2008.30.10	
151	李桂芳 李会莹	中级 博士	074 外校	Delay-dependent robust passivity control for uncertain time-delay systems	Journal of Engineering and Electronics	2007.18.4	

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机场进离场流量协同分配策略

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摘要：为充分利用机场容量、减少航班延误，把进离场视为互相影响的两个过程，研究机场流量与容量匹配问题，给出了一种进离场流量协同分配模型。基于机场容量动态限制，模型以最小化进离场航班总延误损失为目标，协同优化进离场流量分配策略；通过引入航班延误损失系数，作为航空公司协同决策的偏好信息以兼顾其利益。针对模型特点设计了遗传算法予以实现。实例仿真结果表明，模型不仅能使流量与容量协调匹配，而且能够使延误损失降到最小且能兼顾航空公司的利益，验证了所提策略的有效性。

关键词：空中交通；流量分配；遗传算法；协同优化

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Collaborative Distribution Strategy of Airport Arrival and Departure Traffic Flow

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Abstract: To use airport capability and reduce filght delay, an optimization model for the flow distribution is proposed. The model takes arrivals and departures as two interdependent processes. The model minimizes the total delay cost to find optimal flow distribution strategy. It also introduces delay cost coefficients as decision-preferential information to consider the airlines interest. A genetic algorithms is designed for the model. Experimental results show that the model has a balance between airport flows and capabilities, and minimizes the delay cost with airline preferences. So the distribution strategy is verified to be effective.

Key words: air traffic; flow distribution; genetic algorithms; co-optimization

引　言

空中交通流量管理的根本目的在于调整交通需求与供给，使之协调匹配。随着航空运输的蓬勃发展，不断增长的空中交通需求与供给之间的矛盾日益突出，由机场容量的限制带来的交通拥挤、航班延误问题已日益严峻，机场成了空中交通管制的瓶颈[1-3]。航班延误不仅会造成巨大的经济损失，而且还会直接影响航空公司的信誉。因此，合理分配机场流量、优化利用容量，使之协调匹配，对于减缓空中等待和地面延误、提高航空公司信誉等，既具有经济价值又具有现实意义。

机场流量分进场流量和离场流量，与之相应的机场容量分别为进场容量和离场容量。目前大多数流量管理、优化决策的研究都将进离场视为相互独立的两个过程，而且将机场容量视为一个恒定值。然而，由于国内大多数机场只有一条跑道，进离场实际上是互相影响制约的两个过程。研究表明，机场进场容量和离场容量一般表现为如图1所示的机场容量曲线[4]。

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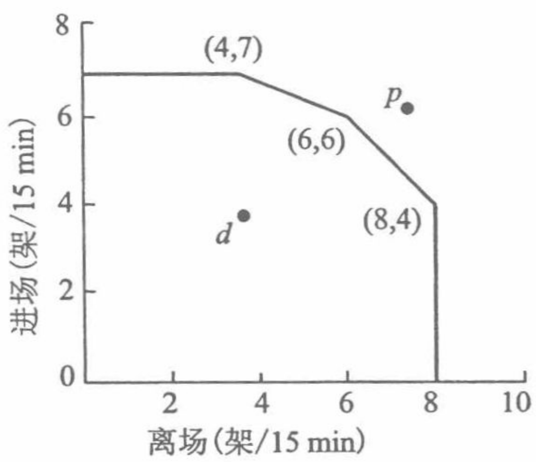

图1 机场容量曲线(VFR条件下)

显然,机场容量不是恒定的,而且随机场天气的变化而显著变化,甚至与飞机类别、组合比例及顺序都直接相关。一般情况下机场按两种规则运行:目视飞行规则(VFR)和仪表飞行规则(IFR),前者在天气较好时使用,容量较大;后者在天气较差时使用,容量较小。本文主要研究VFR条件下的流量与容量匹配问题。此外,机场还有一些调度规则,如停机坪、滑行道等的使用,后勤服务等。研究表明这些因素对延误影响较小[3],因此本文暂不考虑这些因素。

机场终端区流量分配或容量配置问题的研究已受到国内外学者的日益关注。Gilbo、余江、马正平等人通过最小化机场进离场列队中延误的航班量建立优化模型,配置容量、分配流量[5-7];Gilbo又基于CDM(Collaborative decision making)研究了机场进离场流量管理协同优化策略[8],通过加入优先级队列使具有优先权的航班免遭延误,考虑了航空公司的利益;Dell'Olmo通过最小化航班延误时间建立优化模型,并采用动态规划的方法研究容量配置问题[9]。然而由于航班类型、重要程度等性质不同,其延误损失也会不同。因此无论延误航班的数量最小,还是延误时间最小,延误损失未必达到最小。因此,本文在上述研究的基础上,提出一种进离场流量协同分配优化策略,通过以最小化进离场航班总延误损失为目标,并借鉴CDM思想,结合航班类型、重要程度等因素,引入航班延误损失系数作为决策偏好信息,建立优化模型寻求最佳的流量分配方案。所求方案既能使延误损失到达最小又能兼顾航空公司的利益,因而更趋合理。

1 协同分配策略

1.1 流量分配原理

机场交通流量分配的根本在于平衡航班需求和机场供给,需求与供给失衡势必造成航班延误。机场供给一般表现为如图1所示的容量曲线,图中的点称为进离场航班需求点。当需求小于或等于供给,即图中需求点处于容量曲线内或上(如d点),则进离场需求均被满足,无航班延误;当需求大于供给,即图中需求点处于容量曲线之外(如p点),则造成某些航班延误,此时须合理分配进离场流量,使之与容量协调匹配,即在容量曲线上寻求Pareto最优的容量配置点(称为最优流量分配点),使延误损失降到最小。

本文提出的分配策略是把要进行流量分配的时间区间划分为若干时段,根据每时段的初始交通需求和动态容量限制,在实现容量最优利用的基础上,寻求进场和离场航班的总延误损失最小,协同优化配置进离场容量,为每时段分配最优的进离场流量;通过引入航班延误损失系数作为决策偏好信息,使航班所属的航空公司能够协同决策,最小化航班延误的同时尽可能地满足航空公司的利益,使流量分配策略更趋合理。

1.2 已知与假设

为实现上述分配策略,需要给出以下几点假设:

(1)预分配流量的时间区间的航班需求及容量曲线已知,所有航班的地面或空中的单位时间延误损失已知,这是策略得以实现的先决条件。

(2)在时间区间内无法分配的需求,都可在下一个额外的时段内完成,即假设该时段容量无限;该条件用以确保所有航班都可以实现进或离场,即确保所研究问题具有可行解。

(3)所有航班不能在其预计离场(进场)时间之前离场(进场),即航班不能提前起飞(降落)。该条件使研究问题线性化,可以简化模型,在实际应用中也是合理的。

1.3 数学模型描述

模型参数及其符号意义:

T:预分配流量的时间区间,由若干时段组成,$T=\{t_1,t_2,\cdots,t_N,t_{N+1}\}$,时段为一定长时间(如15 min),定义$t_{N+1}$为额外时段,其容量无限,$t\in T$。

D:T时间内的离场航班d集合,$d\in D$。

A:T时间内的进场航班a集合,$a\in A$。

F:T时间内的所有航班f集合,$F=D\cup A$,$f\in F$。

e_f:航班f预计最早进场或离场时间。

T_f:航班f可能的进场或离场时段集合,$T_f=\{t\in T\mid t\geqslant e_f\}$,$T_f\subset T$。

$C_f(t)$:航班f在t时间进场或离场的延误损失函数,$C_f(t)=c_f\cdot(t-e_f)^{1+\epsilon}$。其中$c_f$指航班$f$的延误损失系数,是由其机型、重要程度或优先级等因素决定,代表单位时间的航班延误损失或延误程度,作为决策偏好信息调整最优策略;参数ϵ用来

表示航班延误成本的缓慢超线性增长，它是协同决策公平原则的体现，能避免过多地延误某一航班[10]，$0<\varepsilon<1$。

$$x_d(t)=\begin{cases}1 & \text{航班 } a \text{ 在 } t \text{ 时间离场}\\ 0 & \text{否则}\end{cases}$$

$$y_a(t)=\begin{cases}1 & \text{航班 } a \text{ 在 } t \text{ 时间进场}\\ 0 & \text{否则}\end{cases}$$

u_t:机场在 t 时段内的离场流量

$$u_t=\sum_{d\in D}x_d(t)\qquad \forall\, t\in T$$

v_t:机场在 t 时段内的进场流量

$$v_t=\sum_{a\in A}y_a(t)\qquad \forall\, t\in T$$

U_t,V_t 分别为 t 时段的最大离场容量和进场容量。

目标函数

$$f(t)=\min\sum_{f\in F}\sum_{t\in T_f:t\geqslant e_f}C_f(t)\cdot x_f(t)=$$

$$\min\sum_{d\in D}\sum_{t\in T_d:t\geqslant e_d}c_d(t-e_d)^{1+\varepsilon}\cdot x_d(t)+\sum_{a\in A}\sum_{t\in T_a:t\geqslant e_a}c_a(t-e_a)^{1+\varepsilon}\cdot y_a(t)\tag{1}$$

约束条件

$$0\leqslant u_t\leqslant U_t,0\leqslant v_t\leqslant V_t,t\in T,t\neq t_{N+1}\tag{2}$$

$$\alpha_t\cdot u_t+\beta_t\cdot v_t\leqslant\gamma_t,t\in T,t\neq t_{N+1}\tag{3}$$

$$x_d(t)=\{0,1\},\sum_{t\in T_d}x_d(t)=1,d\in D\tag{4}$$

$$y_a(t)=\{0,1\},\sum_{t\in T_a}y_a(t)=1,a\in A\tag{5}$$

约束条件(2,3)为容量限制约束，它们构成容量限制下的流量分配点域(容量曲线以内或上)，在点域内寻求最优分配点，从而确保容量与流量协调匹配；其中 $\alpha_t,\beta_t,\gamma_t$ 为容量曲线系数，如图1中，由 $0\leqslant u_t\leqslant 8$，$0\leqslant v_t\leqslant 7$，$u_t+2v_t\leqslant 18$ 和 $u_t+v_t\leqslant 12$ 构成流量分配点域。约束条件(4,5)为流量分配约束，用以确保每个航班有且仅有一个进场或离场时段。

2　遗传算法求解

模型实际决策变量为二进制值，属于0-1整数规划。由于在流量分配及调度中，通常要配置几个小时的流量及其调度，航班需求量较大，传统的0-1整数规划算法较难求解。本文采用遗传算法寻求模型最优解。

2.1　编码

本文遗传算法中个体的染色体表示采用矩阵描述，构成如图2中所示的染色体个体。$m\times n$ 的矩阵 $\boldsymbol{Y}=[y_{ij}](i=1,\cdots,m,j=1,\cdots,n$，其中 m 为机场需求中进离场航班总量，n 为每个航班可能的进场或离场时段集合 $T_i)$，y_{ij}表示航班 i 在时段 j 内的进场或离场情况(若 $y_{ij}=1$，则航班 i 在时段 j 内的进场或离场；若 $y_{ij}=0$，则不在该时段内进场或离场)。y_{ij}值随机产生，所有 y_{ij}取值后，行和列都有相应的约束，矩阵行要满足流量分配约束，矩阵列要满足容量限制约束。满足约束的个体代表一种可行的流量分配方案。随机编码生成一个可行解的步骤如下：

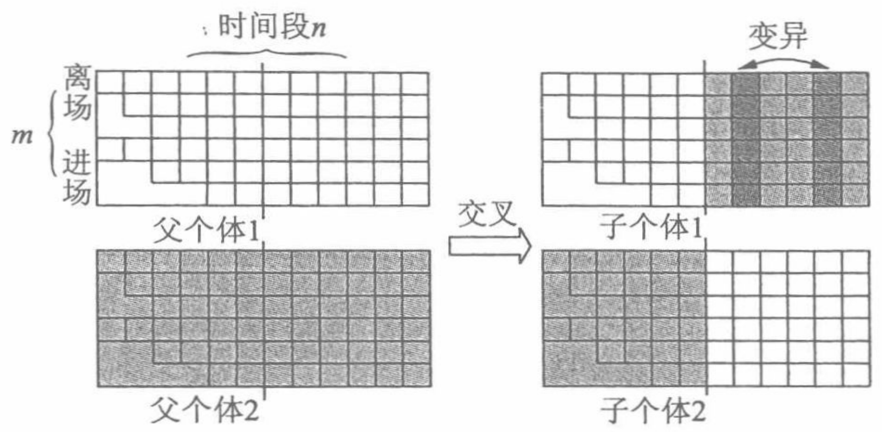

图2　染色体编码及遗传操作示例

(1)为离场航班初始编码。初始化离场航班 i 的所有元素，令 $y_{ij}=0$；然后在 T_i 内随机选择一个时段 j，令 $y_{ij}=1$。

(2)最大离场容量约束修正。离场航班编码若满足约束条件(2)中的前者则进行步骤(3)；否则转至步骤1。

(3)为进场航班初始编码。初始化进场航班 i 的所有元素，令 $y_{ij}=0$；然后在 T_i 内随机选择一个时段 j，令 $y_{ij}=1$。

(4)最大进场容量约束修正。进场航班编码若满足约束条件(2)中的后者则进行步骤(5)；否则转至步骤(3)。

(5)进离场容量曲线约束修正。个体编码若满足约束条件式(3)则该个体编码完毕；否则转至步骤(1)重新编码。

2.2　选择

采用基于最优保留策略的排序选择方法:首先计算种群中的每个个体的适应度，并将个体按其适应度值降序排列；然后根据预先设定的淘汰率，淘汰适应度值较小的个体，并复制相同比例的最优个体(适应度值较大的个体)，以保证种群大小不变。

2.3　交叉

采用单点交叉方式对两个体进行交叉(图2中的父个体1和2)。首先在 $1,\cdots,n$ 的时段列中，随机选择一列位置作为交叉点，如选择图2中加黑直线的位置作为交叉点，则把染色体矩阵分成左右两部分；然后交换父个体1和2的染色体矩阵右侧部分的 y_{ij}值，从而生成子个体1和2。

由于代表个体的矩阵在行和列上均有相应的约束，采用单点交叉方式，交叉后的子个体可以满

足列约束(容量限制约束),但行约束(流量分配约束)或多或少不能满足,因此,再对交叉后的子个体约束修正处理。

约束修正处理方法。行约束不满足时会出现两种情况:(1)行中有两个进场或离场时段,(2)行中没有进场或离场时段。若某行出现前者情况,则随机去掉一个(仍然满足列约束);若出现后者情况,则在该行可能的进场或离场时段集合中随机选择一个作为进场或离场时段,此时该时段对应的列约束可能不再满足,若不满足则在集合中重新随机选择。如果选择完该集合中所有时段后仍不满足列约束,则该子个体存在致死的遗传基因,应给予淘汰,为保证群体大小不变,保留该子个体对应的父个体。

2.4 变异

采用随机选择两列互换产生新个体的方式。互换操作可以满足行约束,但可能不满足列约束,若不满足列约束,则重新随机选择其他两列互换,直至满足列约束为止。

3 实例及分析

以国内某机场12:00～14:00时间段内的交通流量分配为例,交通初始需求中共有92架次航班(其中离场49,进场43),交通需求及其与机场容量的匹配情况如图3所示。显然,其中有若干时段的进场或离场需求超出了其最大容量,且相互影响的进离场需求也超出了机场容量(图3中有4个需求点在容量曲线之外),这种与容量不相匹配的需求势必造成航班延误。为减小或消除延误,应对需求再分配,使之与容量协调匹配。

针对该机场的交通需求及其容量曲线,应用遗传算法协同优化进离场流量分配方案。仿真优化之前,先确定延误损失系数值。根据国际民航组织(ICAO)的标准,按照飞机的尾流强弱将飞机分为重型、中型和轻型3类[10],文献[10]中对延误成本的分析,设定普通航班各类型飞机的延误损失系数见表1;此外,有关研究表明,进场航班的单位时间延误损失是离场航班的3倍[11],因此可设定同等类型的具有优先权的航班(包括进场和重要离场航班)的延误损失系数是普通航班的3倍。遗传操作时,选取种群规模为100,最大世代数为400,选择淘汰率为0.2,交叉率为0.9,变异率为0.1。经计算得到该问题的最优解,即最佳的流量分配方案。优化后各时段的流量及其与容量的匹配情况如图4所示。

表1　普通航班各类飞机的延误损失

机型	代表符号	最大起飞质量/t	延误运营成本/(元·h^{-1})	延误损失系数
重型	H	>136	4 000	4
中型	M	7～136(含)	2 000	2
轻型	L	≤7	1 000	1

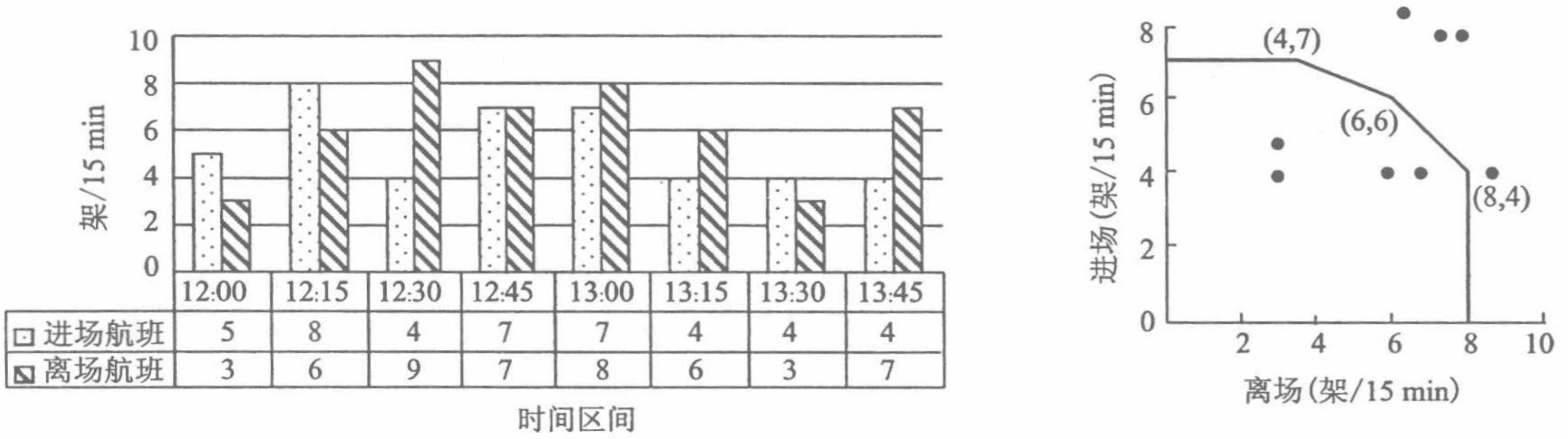

图3　交通初始需求及其与机场容量的匹配情况

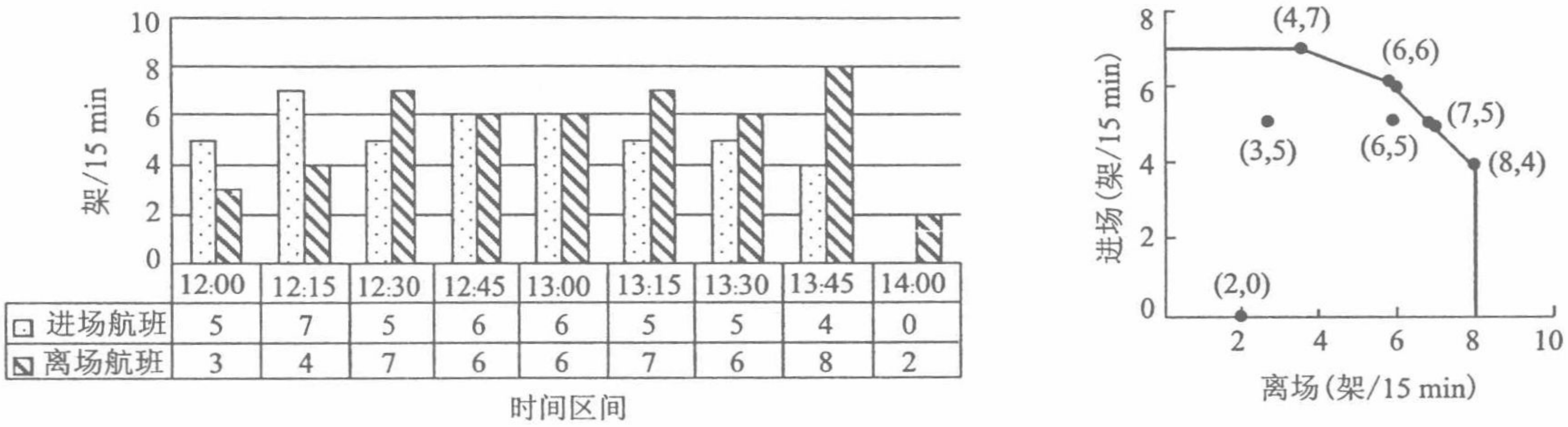

图4　优化后的流量及其与机场容量的匹配情况

显然，优化后的流量与容量能较好地协调匹配（所有分配点都处于容量曲线上或内，其中内点(3，5)是由于属于第1个时段且其初始需求小于容量所致，(6,5)是由于整数约束所致)。虽然造成了2个离场航班延误到该时间区间外，但能最大限度地减小具有优先权的所有进场航班的延误，使该时间区间内的总延误损失达到最小。以12:15～12:30时段为例分析说明，优化前(图3)虽然该时段的离场需求6小于其最大容量8，但进场需求8超过其最大容量7，而且进离场需求点偏离容量曲线之外，航班延误不可避免。该时段优化后的流量分配方案如表2所示，从中看出：具有优先权的所有进场航班几乎都能在本时段内进场，由于最大进场容量约束，因A7航班属于轻型机且最早进场时间较晚，而被分配到以后的时段；虽然离场需求小于其最大容量，但为了尽量减小损失较重的进场航班的延误（仅1架被延误到以后的时段)，致使2架离场航班(D4，D5)被分配到以后的时段，最早离场时间相对较晚的D6航班由于具有优先权而被保留。显然，这种分配不仅能尽量减小总延误损失，而且满足了航空公司的利益，因为航空公司可能宁愿以延误某些次等航班为代价换取其重要航班的准时进离场。

表2 12:15～12:30时段的进离场流量分配方案

进场航班					离场航班				
序号	类型	优先级	预计最早进场时间	该时段进场与否	序号	类型	优先级	预计最早离场时间	该时段离场与否
A1	M	优先	12:15	1	D1	M	一般	12:15	1
A2	M	优先	12:15	1	D2	M	一般	12:15	1
A3	L	优先	12:20	1	D3	M	一般	12:20	1
A4	M	优先	12:20	1	D4	L	一般	12:20	0
A5	H	优先	12:20	1	D5	M	一般	12:25	0
A6	M	优先	12:20	1	D6	L	优先	12:25	1
A7	L	优先	12:25	0					
A8	M	优先	12:25	1	优化分配的离场流量				4
优化分配的进场流量				7					

4 结束语

本文把进离场视为互相影响的两过程，在其容量互相转换和动态约束的条件下，研究流量与容量的协调匹配问题。论文提出了一种进离场流量协同分配策略，给出了分配模型，并采用遗传算法予以实现。模型不仅考虑了总延误损失，而且通过引入航班延误损失系数作为决策的偏好信息，优化的同时兼顾了航空公司的利益，使流量分配具有一定的灵活性和自主性。实例分析表明所提的分配策略切实可行。如果结合跑道构型、滑行道、停机坪及飞机安全间隔等因素，可进一步研究进离场航班的协同调度、时隙分配等问题。

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PRIORITY-BASED COLLABORATIVE AIRCRAFT SCHEDULING

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Abstract: This is a study of aircraft scheduling problems based on the idea of CDM. Taking the interests of ATC, airlines, and airports into consideration, we propose a priority scheduling model that integrally schedules arrivals and departures using airlines' preferences. The model minimizes the total flights' weighted delay costs to find best landing times for the arrivals or take-off times for the departures and their expected runways. We also design a genetic algorithm to solve the proposed problem. Finally, with actual schedule data from an airport with 3 runways, the model has been verified to work well. The experiment shows a 77% time delay savings compared with the current FCFS schedule, and equity among airlines is achieved. The designed genetic algorithm is able to solve the instance with 15 flights in a few seconds.

Keywords: air traffic control, priority scheduling, genetic algorithm

1 Introduction

Aircraft Scheduling Problem (ASP) has aroused widespread concern [1-6]. However, the majority of research didn't take the preferences of and fairness to airlines into account. In fact, air traffic controllers adopt a First-Come-First-Served (FCFS) for scheduling landing and departing aircrafts. It doesn't depend on scientific methods, but basically on the controllers' experience and judgment. Under a Collaborative Decision Making (CDM) mechanism, Air Traffic Control (ATC) cooperates with airlines and airports to manage and control aircrafts, the collaborative ATC is responsible for guiding aircraft in a safe, equitable and efficient manner. With consideration of ATC, airlines, and airports' interests, we present a Collaborative Aircraft Scheduling (CAS) method based on priority to make safe, fair and efficient tactical decisions.

2 Priority Scheduling Model

2.1 Cost Function

Due to performance limitations, each flight has an earliest landing or take-off time, a latest landing or take-off time and target (preferred) landing or take-off time, we will call them the earliest time, the latest time and the target time. Clearly, the cost of flight is mainly caused by ahead of or behind the target time; the cost function is required to be convex and piecewise increasing and to have a minimal cost of zero at the preferred time. This implies the non-negative cost function is in fact describing the extra cost for deviations from the timetable. Moreover, with the fairness consideration, we define the cost function as a piecewise super-linear increasing function. The function generally seems to be a realistic description of the costs: A larger delay means a larger increase in cost per time unit. The function can also help to avoid penalizing a flight too much by assigning to it most of the total delay, and this is also a purpose of the fairness principle.

The convex piecewise super-linear function $C_f(t)$ of flight f landing/departing at time t can be written as two super-linear functions on two connected intervals:

$$C_f(t)=\begin{cases} c_{1f}\left(T_f-t\right)^{1+\varepsilon_1} & E_f \le t \le T_f \\ c_{2f}\left(t-T_f\right)^{1+\varepsilon_2} & T_f \le t \le L_f \end{cases} \qquad (1)$$

Where

c_{1f}: The penalty cost (per time unit) for flight f with landing or take-off before its target time T_f. c_{2f}: The penalty cost (per time unit) for flight f with landing or take-off after its target time T_f. ε : The parameter for the super-linear slow growth reflects the principle of fairness under CDM philosophy [7], the purpose of which is to avoid penalizing a flight too much by assigning to it most of the total delay. $0 \le \varepsilon \le 1$. E_f: The earliest time of flight f. L_f: The latest time of flight f. T_f: The target time of flight f. So, $C_f(t)$ is defined on the interval $\left[E_f, L_f\right]$.

2.2 Priority Weight

Airlines take part in the scheduling by naming priority-ranks for their own flights in the CAS. Airlines name priority-ranks for landing/departing in advance. We allow airlines as much flexibility as possible in naming priority-ranks. Normalization must be performed, of course, to prevent an airline from gaming the process by naming all of its flights higher priorities: We normalize these priority-ranks into priority weights in an equitable manner, and then let them be delay cost weights. So flights with higher priority would be given a higher weight, and its cost would be less.

Let us make this more precise. Let A be the set of airlines $i \in A$ $|A| = m$; let F_i be the set of flights for airline i $j \in F_i$. Let R be the set of priority-ranks and r_{ij} be the priority-rank of flight j in F_i $r_{ij} \in R$: r_{ij} are arbitrarily named by airline i with preference on flight j.

Let p_{ij} be the unitary priority weight of the flight j in F_i, p_{ij} is defined such that:

$$p_{ij}=\frac{r_{ij}}{\max\left\{r_{i1}, r_{i2} \dots, r_{i|F_i|}\right\}}$$

To obtain equity, we define a converting factor for each airline. These converting factors are determined for each airline based on its flights' priority-ranks. This not only ensures the ratios between priority weights of their own fights are preserved, but also ensures the average priority weights (per flight) of all airlines are approximately the same. So whatever airlines name priority-ranks for their flights, this can only affects the ratios between priority weights of their own fights, but not the weights of other airlines. Therefore delays can only be exchanged in an airline's own set of flights without interfering with flights of other airlines.

Let α_i be the converting factor of airline i, α_i is defined such that:

$$\frac{\alpha_i \sum_{j\in F_i} p_{ij}}{|F_i| \sum_{i\in A}\sum_{j\in F_i} p_{ij}} = 1. \text{ So, } \alpha_i = \frac{|F_i| \sum_{i\in A}\sum_{j\in F_i} p_{ij}}{\sum_{j\in F_i} p_{ij}}$$

Then an equitable priority weight ω_{ij} for flight j of airline i can be standardized:

$$\omega_{ij}=\frac{\alpha_i \cdot p_{ij}}{\sum_{i\in A}\sum_{j\in F_i}\alpha_i \cdot p_{ij}}.$$

2.3 Optimization Formulation

The following notations are needed to determine the validity of schedules for a Multi-runway Collaborative Aircraft Scheduling Problem (M-CASP).

F: The set of all the arriving and departing flights $f \in F$ $F = \bigcup F_i$ $|F| = n$. RW: The set of runways $w \in RW$ $|RW| = l$. S_w : The sequence of flights landing and departing on runway w $k \in S_w$. $t[S_w(k)]$: The landing or take-off time for the flight in position k of sequence S_w. $E[S_w(k)]$: The earliest time for the flight in position k of sequence S_w. $L[S_w(k)]$: The latest time for the flight in position k of sequence S_w. $T[S_w(k)]$: The target time for the flight in position k of sequence S_w. $O[S_w(k)]$: The runway occupying time for flight in position k of the sequence S_w. $s(c(S_w(k)), c(S_w(k+1)))$: The minimal safety separation time required between the flights in the successive positions k and $k+1$ of the sequence S_w, where $c(f)$ is the weight class of flight f. There are usually 3 categories: Heavy (H), Large (L) and Small (S).

The main decision variables are the assigned runways and landing times for the arrivals and the assigned runways and take-off times for the departures. We will call the landing time and the take-off time the scheduling time. Further the formulation requires some additional decision variables: let δ_{fw} be 1 if flight f landing/departing on runway w, otherwise be 0.

The objective function is the minimization of total weighted delay cost and can be written in as follows:

$$f(t) = Min \sum_{w\in RW}\sum_{k\in S_w} \omega_k C_k(t_k) \qquad (2)$$

And it is subject to the following constraints:

$$E[S_w(k)] \le t[S_w(k)] \le L[S_w(k)], \forall w \in RW, \forall k \in S_w \qquad (3)$$

$$\delta_{fw} = \{0,1\},\ \sum_{w \in RW} \delta_{fw} = 1,\ \forall f \in F, \forall w \in RW \tag{4}$$

$$t[S_w(1)] = T[S_w(1)],\ t[S_w(k)] = \max\{E[S_w(k)],\ t[S_w(k-1)] + \max\{s(c(S_w(k-1)), c(S_w(k))), O[S_w(k-1)]\}\},\ \forall w \in RW, \forall k \in S_w \tag{5}$$

Constraint (3) ensures that each flight f must land or take off during its specified interval; we will call it the interval constraint. Constraint (4) guarantees that each flight f is assigned a single runway that is in RW; we will call it the runway constraint. Constraint (5) makes sure that each flight f lands or takes off in a safe way which accords with the minimum time separations on a cleared runway; we also determine the scheduling time for flight f using it, and let the scheduling time of the first one in S_w be its target time. We will call it the separation constraint.

3 Genetic Algorithms

3.1 Coding based on Flight ID and Runway Assignment

We designed two-string gene codes based on flight ID and runway assignment for the M-CASP, an example for an individual chromosome is depicted in figure 1. The first string codes express flights ID, we call it flight chromosome; the second string codes express assigned runways for these flights, we call it runway chromosome: suppose that there are 3 runways signed in 0, 1 and 2 respectively. While coding we selected a single runway for a flight in a stochastic way. To obtain an initial feasible solution, constraints (3) and (4) must be satisfied.

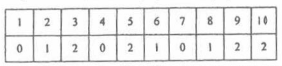

Fig.1 Coding based on flight ID and runway assignment

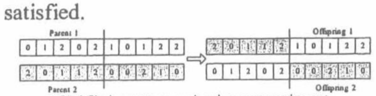

Fig.2 Single point crossover based on runway assignment

3.2 Selection based on Excellence Reservation

To implement easily, we selected optimal individuals using an excellence reservation strategy. Firstly, we compute the fitness value for each individual in population, and arrange individuals in descending sequence according to their fitness values. Secondly, we eliminate those individuals whose fitness values are less through selection in a pre-established eliminating probability (Pe), and copy the same proportional excellence individuals to ensure the size of population is invariable.

3.3 Crossover based on Runway Assignment

We adopted a single point crossover method to generate offspring in a crossing probability (Pc). An example of such a crossover is depicted in Figure 2. Firstly, we select a crossing point stochastically and swap these genes before the crossing point in parent's runway chromosomes. Secondly, we rearrange flights in ascending sequence according to their target times for each runway sequence. Lastly, we compute the scheduling time for each flight with constraints amending: if the computed scheduling times of all flights can meet their interval constraints, end the crossover; otherwise reselect a crossing point and do it again.

3.4 Mutation based on Flight Swapping

To speed up the algorithm, we do the mutation operator by swapping the flight genes of runway sequences in a mutation probability (Pm). We developed two swapping mutation operators as follows: (a) swapping flight genes in two consecutive positions of one runway sequence; (b) swapping flight genes in two stochastic positions of two different runway sequences. A simple example is depicted in figure 3. There are 3 runway sequences (S0, S1 and S2) each with several flights.

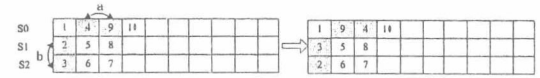

Fig.3 Sketch map of the two swapping mutations

4 Simulation Results

We implemented the described optimization methods and ran tests on an instance of collaborative arrivals scheduling. The minimum safety separation we used was the standard without wind recommended by the International Civil Aviation Organization. We used actual schedule data from an airport with 3 runways, and some of the original data are listed in Table 1. There are 15 flights waiting for landing from 3 airlines (A, B and C) each with 5 flights. Where T_0, T_1 and T_2 (in mmss) respectively denote the target times of runway 0, runway 1 and runway 2.We pre-established 5 priority-ranks of landing: $R = \{1,2,3,4,5\}$; Let c_{1f} equal to c_{2f}, and supposed they are 4, 2 and 1 for the Heavy, Large and Small aircrafts; $\varepsilon_1 = \varepsilon_2 = 0.5$.

The GA programs were implemented in Visual Basic.NET under Windows XP. Let the size of the population 20, the max-generation 50, Pe 0.4, Pc 0.8 and Pm 0.4. The scheduling results of the optimization method are shown in Table 1. The results from FCFS and our method are given in the table. The result consists of assigned runway (RW), landing time (LT, in mmss) and delayed time (DT, in second) for each flight. Where "+"denotes behind schedule and "−"denotes ahead of schedule.

Tab.1 The result of scheduling simulation

Partial original data of flight							FCFS			CAS		
f	c	r	w	T_0	T_1	T_2	RW	LT	DT	RW	LT	DT
A1	H	5	0.111	0012	0036	0024	0	0012	0	1	0036	0
B1	L	1	0.022	0112	0118	0048	2	0048	0	0	0112	0
C1	S	1	0.022	0118	0142	0106	1	0142	0	2	0106	0
A2	L	4	0.089	0236	0218	0242	0	0236	0	0	0226	-10
B2	L	2	0.044	0330	0348	0254	2	0254	0	2	0254	0
C2	H	2	0.044	0348	0336	0406	1	0336	0	1	0336	0
A3	H	3	0.067	0430	0454	0418	2	0418	0	2	0418	0
B3	H	3	0.067	0536	0548	0606	0	0536	0	1	0536	-12
C3	L	3	0.067	0606	0618	0554	1	0618	0	0	0554	-12
A4	S	2	0.044	0612	0624	0630	0	0823	+131	2	0705	+35
B4	S	4	0.089	0642	0636	0718	2	0718	0	0	0708	+26
C4	S	4	0.089	0730	0836	0648	1	0836	0	1	0844	+8
A5	L	1	0.022	0806	0754	0730	0	0937	+91	1	0730	-24

B5	H	5	0.111	0836	0754	0912	2	0912	0	0	0836	0
C5	H	5	0.111	0842	0824	0812	1	1010	+106	2	0819	+7

Table 1 show that improvements are obtained using the CAS compared with FCFS. The total time delays are reduced remarkably: the total delay time using FCFS is 328 seconds and ours is only 76 seconds (sum of "+" times), 77% time delay savings. The maximal delay time of FCFS reaches 131 seconds and ours is 35 seconds, so the CAS can avoid assigning too much delay to one flight and tend to be fairer. Furthermore, the average delay costs (per flight) of the airlines are approximately the same. This indicates each airline has a tradeoff and equity is achieved. Besides we can also find that the delays of flights with higher priority are less. What's more, the scheduling times of most flights are equal to or near their target times. This accords with requirements of the airlines and its users.

5 Conclusions

We propose a priority scheduling model to schedule arrivals and departures at a multiple runway airport. Delay costs are used as the objective. Safety, efficiency and equity are considered. We also provide an effective genetic algorithm, capable of considering some operational constraints. We analyze model and algorithm performances on actual data. The experimental analyses show that huge improvements are obtained compared with the current FCFS; the algorithm is capable of solving the experiment in a few seconds so as to fit into a dynamic operating environment.

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STUDY ON VARIATIONAL INEQUALITY MODEL OF SUPPLY CHAIN NETWORK EQUILIBRIUM

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Abstract: On the basis of an analysis of the decision-making behaviors of manufacturer, retailer and customer, this paper presents a three-level equilibrium network model for supply chains. Then, the variational inequality model equivalent to the equilibrium conditions supply chain network is established by the relationship between variational inequality and a mathematical programming model. Third, the characteristics of the solution to the model are discussed and a heuristics algorithm is developed. This provides a useful tool for further analysis and evaluation of the performance of the supply chain network.

Keywords: supply chain; network; equilibrium; variational inequality

1. Introduction

Modeling and analysis of supply chains (SC) have received great attention in the fields including information, control and management. Gunasekaren (2000) summarized the related studies on modeling and analysis on SC. Tayur (2003) provided many different aspects of the modeling of SC, especially the problems of optimization and control. Chen et al. (2001) analyzed some optimization models and presented interesting fields about SCM. Liu (2002) studied the problem on synergic supply in SC and discussed the integration of system software of the model. Pan (2004) studied decision-making in manufacturing and the optimization of a flexible SC with uncertain demand, and developed a decision-making model on manufacturing in the environment of flexible SC by making the minimum of expected cost of SC as the objective function. Kinderlehrer et al. (1991) gave an introduction to variational inequations and their applications. Nagurney et al. (2002) studied the model for an SC network by network economy theory. However, there is little research on applying variational inequation to an SC network.

Combined with a theory of the equilibrium distribution of space price, according to the network economy, a three-level equilibrium network model for SC is established. The model deals with independent behavior of different decision-makers as well as the reciprocity between them. This provides a useful platform to evaluate price and product flux and a new way for the further research on the dynamic process of SC.

2. Problem description

As shown in Figure 1, the first level, the second level and the last level represent m

SCHEDULING MODEL AND HEURISTIC ALGORITHM FOR DEPARTURE MANAGEMENT IN MULTIAIRPORT

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Abstract: A mathematical model is presented for sequencing departure flights in different airports within one terminal area. Both airport runways and departure routes are considered in the model. Practical issues that affect the implementation of the schedule are carried out by Constraint Position Shifting (CPS). Then a tabu search algorithm is developed and implemented to obtain reasonable solutions within acceptable computation times. Simulation results validate the model and show the algorithm's advantage. Efficient scheduling flights for takeoff can reduce the total separation between aircraft and thus increase the output of each airport.
Keywords: *air traffic flow management, multiairport system, departure scheduling, tabu search algorithm*

1 Introduction

The important aspects of air traffic flow management (ATFM) are the management of departure flow and arrival flow in the terminal area, which are known as departure management and arrival management. Papers relevant to arrival scheduling problems were published by Beasley et al. (2000), and Bianco et al. (2006). Bolender (2000) in his dissertation studied two major problems relating to

departure management. Avid search algorithms and related algorithms were designed to minimize the total time needed to dispatch a set of aircraft. A brief summary of some of relevant work in departure scheduling is presented in Atkin et al. (2007). They applied hybrid metaheuristics to aid in runway scheduling at London Heathrow Airport. However, the previous studies mainly focused on a single airport's departure scheduling problem. In this paper, we develop a new model and an efficient algorithm for computing an optimal departure sequence in order to minimize the time span in multi-airport terminal areas.

2 Problem Definition

The purpose of multi-airport departure scheduling is to determine an optimal sequence of takeoff times under different conditions. Besides the constraints listed in Bal Krishnan (2007), an important factor in the multi-airport scheduling problem is the traffic interaction between airports. In a terminal area, departure routes of each airport may intersect at a fixed point or even have a similar route segment. The Airport Controller will keep a safe separation for aircraft flying over intersection point. Therefore departure traffic from one airport may have impact on flights from other airports. With intersection limitations, departure scheduling must take the whole flow under consideration, otherwise it will cause airspace congestion and increase controller workload.

3 Model Formulation

Let $A=\{1,2,...,l\}$ be the set of airports' indices, where l is the number of airports under consideration. Let $P=\{0,1,2,...,m\}$ be the set of intersection points' indices, where m is the number of the points. Let $F=\{1,2,...,n\}$ be the set of departure flights' indices, where n is the total number of flights under consideration. Let $a_i \in A$ be the airport that flight i departs from. Let $p_i \in P$ represent the intersection point in the route of flight i. Particularly, $p_i=0$ stands for there is no intersection point of flight i. Here we chose variable c_i to be an integer to represent the position of flight i in the departure order, and assigned d_i as the calculated take off time of flight i. Other variables are defined as follows:

e_i: Earliest take off time of flight i

o_i: Position of flight i in the First Come First Service (FCFS) schedule

k: A predetermined number of Maximum Position Shifting (MPS)

f_i^q: Flying time of flight i between its origin airport and route point q.

τ^q: Required time separation imposed on two consecutive flights that pass route point q

S_{ij}: The required time separation for aircraft i and aircraft j.

We aim to minimize the time-span of all the aircraft in the sequence. The objective function is introduced below:

$$\min(\max_{i\in F}(d_i)-\min_{i\in F}(d_i)) \tag{1}$$

Subject to:

$$d_i \geq e_i \quad i\in F \tag{2}$$

$$d_i = e_i \qquad \text{if } c_i = 1,\ i\in F \tag{3}$$

$$|c_i - o_i| \leq k \quad i\in F \tag{4}$$

$$d_j \geq \max_{i\in F|c_i<c_j, a_i=a_j}(d_i + S_{ij}) \tag{5}$$

$$\left|(d_i + t_i^q) - (d_j + t_j^q)\right| \geq \tau^q \quad i,j\in F, q\in P\,|\, c_i > c_j, p_i = p_j = q \tag{6}$$

Constraint (2) ensures that no flight can take off before its ready. In this model, the earliest takeoff time is equal to the estimated time of departure (ETD).

We assume that the takeoff time of the first flight is its earliest take off time by constraint (3).

Constraint (4) implies that rescheduling flights will satisfy the CPS.

Constraint (5) and (6) together indicate that all flights must comply with the required separation rules. Constraint (5) guarantees that flights from the same airport will fulfil the minimum takeoff separation requirement. Constraint (6) imposes a safe separation on flights over flying a route point q.

The terms from (1) to (6) make up the optimization model for resolving a multi-airport departure scheduling problem. We will design a heuristic algorithm to solve the proposed model in the next section.

4 Tabu Search Algorithm

The basic idea of a tabu search (TS) (Glover 1989, 1990) is to explore the search space of all feasible scheduling solutions by a sequence of moves. There are a total of five essentials for a TS algorithm: (1) Initial solution; (2) Neighborhood searching; (3) Tabu list; (4) Measuring function; (5) Stop condition.

4.1 Initial Solution

FCFS policy is used to get the initial solution. For all flights under consideration, a sequence x_0 in order of ascending ETD will be the starting point for TS.

4.2 Neighborhood Searching

Our neighborhood $N(x)$ is defined as a constrained 2-opt. A neighbor is generated by swapping the positions of two aircraft in x while complying with the CPS. A candidate set $V(x)$ is used to alleviate the computational burden. If the number of members in $N(x)$ exceeds 100, we randomly generate 100 new neighbors to make up $V(x)$, or else we select the whole neighborhood $N(x)$ as candidate set $V(x)$.

4.3 Tabu List

The last 10 moves of each aircraft are stored in the tabu list. Any moves that place the aircraft back to its initial position remembered in the list are rejected.

Two criteria will be used in the process of iteration. One criterion is that when all solutions in a candidate set are forbidden, then the solution with the minimal objective value is freed. The other is that although one solution is forbidden but its measuring function value is better than the value of the current best solution, then this solution can be unbound and returned to the candidate set.

4.4 Measuring Function

A new starting point will be selected from candidate set through the measuring function. Here we take the objective function $f(x)$ as the measuring function.

4.5 Stop Condition

The TS algorithm stops after it has run for a predetermined number of iterative steps MAX_ITER. Another condition that algorithm terminated is when the objective value does not decrease in limited steps MAX_OPT. In our implementation, $MAX\_ITER = 1000$, and $MAX\_OPT = 200$.

4.6 The algorithm procedure

Step 1. Get an initial solution x^{now} as described in 4.1. Let the iteration number $N_{iter} = 0$, the number of optimal solution occurs $N_{opt} = 1$, the current optimal solution $x^* = x^{now}$, and set tabu list $T = \Phi$.

Step 2. (a) If $N_{iter} = MAX\_ITER$ or $N_{opt} = MAX\_OPT$, terminate the algorithm and output for the optimized solution.

(b) Randomly select 100 new solutions in $N(x^{now})$ or the whole $N(x^{now})$ to form the candidate set $V(x^{now})$. These solutions are not forbidden or unbound formed under aspiration criteria.

Step 3. For all solutions in $V(x^{now})$, get the optimal one and denote it by x^{next}, and let $x^{now} = x^{next}$, $N_{iter} = N_{iter} + 1$.

Step 4. (a) If $f(x^{now}) < f(x^*)$, let $x^* = x^{now}$, $N_{opt} = 1$; (b) Else let $N_{opt} = N_{opt} + 1$.