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Aircraft Landing Scheduling Based On Unavailability of Runway Constraint Through A Time Segment Heuristic Method

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ABSTRACT

Noting the problem of increasing airports congestion, it is crucial to obtain a practical and efficient scheduling for departure and landing. The problem of deciding how to land an aircraft on the airport involves assigning each aircraft to an appropriate runway, computing a landing sequence for each runway and scheduling the landing time for each aircraft. The objective was to achieve effective runway use. In this paper, a multiple runway case of the static Aircraft Landing Problem was considered. It was assumed that one of the runways is not available. A mixed integer formulation approach was proposed to deal with the problem. The approach of solving this problem was breaking down the main problem into several sub problems. To validate the model, eight test problems were extracted from the OR-Library and discussions made on their solutions.

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1. INTRODUCTION

Nowadays air traffic is an important subject which has been paid attention since 1920 [1]. According to an increasing growth of air traffic, several famous and crowded airports reached to their final capacity. But due to several limitations such as the environment, policies, aerospace limits, parasite limits and the noise pollution, it is impossible to add runways to airports. In such airports, it is required to exploit the most usage from runways to control more aircrafts. For example, airports such as Heathrow in London and Costrop in Copenhagen, they have just two runways which are replaceable to each other according to windflaw that one of them is related to the flight and the other to landing[2]. The controllers of air traffic schedule aircrafts based on FIFO(First In First Out). it means the aircraft that comes in controllers range first, it lands first. This approach is a suitable method for landing an aircraft, but it does not maximize the runways outcome. These programs are used to help the aircrafts with landing. While the aircraft landing runs scheduled out of FIFO, these programs increase the number of aircrafts per hour and thus, more runways are used. In this way, according to predictions, the number of potential landings in airports will be enhanced and therefore, they will get much more benefit. Before the aircraft lands in an airport, the rout of landing should be determined by air traffic controllers. The flight number, height and speed of aircraft are sent to the controllers in which are in watchtower, when the aircraft is entering in the area of air traffic control. Based on these information, a suitable runway is assigned to aircraft. Controllers should be ensured that landings are safe and efficient, from the time aircraft enters in the area until its landing. The capacity of a runway is an essential issue which makes it difficult and hard to schedule efficiently. It is impossible to enhance the runway capacity especially in some conditions as political and environmental one. As a result, to help controllers, it is required to develop some decision making tools. These are several questions for controllers which aircraft should be landed and at what time and on which runway? When an aircraft enters in the area of air traffic controllers, the target time, the earliest time and the latest time are assigned to that. The time between the earliest and latest time of landing, namely the time window is to be scheduled by the landing controllers. Every aircraft makes a turbulence while landing. The turbulence of bigger aircrafts' are more than the smaller ones. Moreover, the time between two sequential landings is named as separation time, since the turbulence can make some serious problems for other aircrafts. Also, bigger aircrafts can resist the bigger turbulence than others [3].

Several studies have been conducted for landing scheduling to achieve an efficient schedule. Lee and Pinedo proposed a workshop production schedule to solve landing aircraft issue which runways and aircrafts are as machines and job respectively. The earliest time related to each aircraft is the available time for a job. Based on this, the separation time in aircraft landing is the processing time in workshop production[4]. Chang, Crawford and Menon performed four different types of genetic formulation searches to solve the aircraft landing issue with several runways. The result and findings were validated through 12 aircrafts and three runways[5]. Ernest, Krishnamoorthy and Storer suggested a unique simplex algorithm which quickly measures the landing time by constraining time window validated by 50 aircrafts and four runways[6]. Moreover, to solve aircrafts landing issue, a mixed integer programming formulation including six types of additional limit for decreasing zero region was implemented. Then, the problem was optimized by linear programming based on search tree including 50 aircrafts[7]. An effective heuristic algorithm and mixed integer programming were proposed to solve the problem by scatter search and bionomic algorithm[8]. Fahle, Feldmann, Grothklags and Monien proposed different accurate and heuristic methods to solve landing scheduling issue while the aircrafts are waiting for landing. They compared 2 integer formulations with 4 accurate and heuristic methods through such factors as quality, speed and flexibility[9].

To sum up, none of those researches have considered the atmosphere condition and unavailability of runway. In this regard, this paper tries to solve the landing scheduling problem by a heuristic method under mentioned conditions. Meanwhile, in order to decrease the solution region and achieve the solution more quickly, the time window is tightened by an algorithm. The rest of this paper is organized as follows. In section 2, a mathematical model is proposed. Next, an algorithm is presented to generate an upper bound for the solution. In section 4, a heuristic method is explained. Finally, the computational results and conclusions are presented.

2. MODELLING OF THE PROBLEM

a. Description of the problem

The case study used in this paper is landing scheduling of aircrafts in an airport including several runways with the limitation as unavailability to a runway at the time period. Assumptions of this case study is as follows:

- The set of aircrafts which are waiting to be landed is known, a static model.
- There are several runways in the airport.
- The sets of aircrafts including the target time and time window are waiting to be landed on the runway.
- One of the runways is unavailable for some reasons such as the filthy floor, frozenness and repairing.
- The cost is considered for each unit of tardiness or earliness for the target time of every aircraft.
- Each aircraft is supposed to land on a determined runway, when the limitation of separation time (the time between this aircraft and previous ones which land on this runway or others) is satisfied.
- All aircrafts are not equal and similar to each other and there are different aircrafts.

The objective function of the problems is to minimize the deviation of target time for each aircraft. As when an aircraft lands sooner than the target time, it causes problems for other aircrafts flight schedules. Moreover, if the aircraft landed later than the target time, it would cause customers' dissatisfaction, decreasing the flight security and delays for other aircrafts. These problems are of optimization ones with large scale, which they frequently occur in some airports as Heathrow in London including an enhancing limitation of runway.

As soon as an aircraft enters in the area of air traffic control, it is essential for the pilot to be aware of the landing time and the runway by air traffic controllers(if there are more than one runway). The landing time should be located in determined time window of the aircraft. On one hand, it is limited to the earliest time of landing(Ei) and on the other hand to the latest time of landing(Li). This time window is different from one aircraft other.

It is clear that all aircrafts make a vortex during the flight. As a matter of fact, not only does it cause huge turbulence in the other aircrafts rout, but also it may cause some accidents in a specific situation. To ensure the aero dynamical stability of an aircraft, a separation time should be determined during aircrafts landings, which it depends on type of each aircraft. For example, a Boeing 747 can make much more turbulence than a Hawker 700.

b. The Mathematical Modeling

i. Notation and decision variables

P: the number of aircrafts waiting for landing.

R: the number of landing runways.

Ei: the earliest time of landing for the ith aircraft.

Li: the latest time of landing for the ith aircraft.

Sij: the separation time between aircrafts i and j, when aircrafts i and j land on the same runway.

sij: the separation time between aircrafts i and j, when aircrafts i and j do not land on the same runway.

fr: when the runway r is available, the value of this variable is 1 and when it is not in [t1,t2], the value is 0.

Zir: if the aircraft i lands on the runway r, the value of this variable is 1; otherwise 0.

δij: if the aircraft i lands before the aircraft j, the value of this variable is 1; otherwise 0.

γij: if aircrafts i and j land on the same runway r, the value of this variable is 1; otherwise 0.

Xi: the time of the scheduled landing for landing of ith aircraft.

Yi: if the landing time on the unavailable runway is more than t2, the value of this variable is 1. If it is less than t1, the value is 0.

ii. The mathematical model

$$\text{MIN} \sum (\alpha_i . g_i + \beta_i . h_i) \quad (1)$$

S.t

$$E_i \leq X_i \leq L_i \forall i \in \{1, \dots, p\} \quad (2)$$

$$\delta_{ij} + \delta_{ji} = 1 \qquad \forall (i,j) \in \{1, \dots, p\}^2 \quad (3)$$

$$\gamma_{ijr} = \gamma_{jir} \quad \forall (i,j) \in \{1, \dots, p\}^2 j, r \{1, \dots, R\} \quad (4)$$

$$X_j \geq [X_i + \gamma_{ijr}.S_{ij} + (1 - \gamma_{ijr}).s_{ij} - M\delta_{ji}] \quad (5)$$

$$\sum_{r=1}^{R} Z_{ir} = 1 \qquad \forall i \in \{1, \dots, p\}, r \in \{1, \dots, R\} \quad (6)$$

$$\gamma_{ijr} \geq \frac{Z_{ir} + Z_{jr} - 1}{2} \quad \forall (i,j) \in \{1, \dots, p\}^2 \; i \neq j, r\{1, \dots, R\} \quad (7)$$

$$\gamma_{ijr} \leq \frac{Z_{ir} + Z_{jr}}{2} \quad \forall (i,j) \in \{1, \dots, p\}^2 \; i \neq j, r \in \{1, \dots, R\} \quad (8)$$

$$X_i \leq t_1 . z_{ir} . (1 - f_r) + L_i . f_r + L_i . (1 - z_{ir}) + M' . Y_i \quad (9)$$

$$X_i \geq t_2 . z_{ir} . (1 - f_r) + E_i . f_r - M" . (1 - Y_i) \quad (10)$$

$$X_i = T_i - \propto_i + \beta_i \qquad , \forall i \in \{1, \dots, p\} \quad (11)$$

$$0 \leq \propto_i \leq T_i - E_i \qquad , \forall i \in \{1, \dots, p\} \quad (12)$$

$$0 \leq \beta_i \leq L_i - T_i \qquad , \forall i \in \{1, \dots, p\} \quad (13)$$

$$\propto_i \geq T_i - X_i \qquad , \forall i \in \{1, \dots, p\} \quad (14)$$

$$X_i \geq 0 \qquad \beta_i \geq X_i - T_i \qquad , \forall i \in 1, \dots, p\} \quad (15)$$

(16)

The objective function of the problem is to minimize costs related to the tardiness and the earliness of aircrafts. α_i and β_i are the values of the earliness and the tardiness of the target time for the ith aircraft respectively.

$$\propto_i = \max(0, T_i - X_i), \forall i \in \{1, \dots, \text{p}\} \quad (17)$$

$$\beta_i = \max(X_i - T_i, \cdot), \forall i \in \{1, \dots, p\} \quad (18)$$

If values of αi and βi were set in the equation, the problem would be converted from a linear condition to a none-linear one. For having the problem in linear condition and making a relation between αi and βj with decision variable Xi, constraints (11) to (15) are added to replace constraints (16) to (17). Constraint (2) shows that the landing time for each aircraft should be set in a determined time window (as between the earliest and the latest time of the allowable landing). Also, the separation time depends on the landing order of aircrafts and the runway which is assigned to the aircraft. To determine the landing order and the fact that whether the aircraft i lands before j or not, constrain (3) is used. Constraint (4) is to show that there is no difference whether aircrafts i and j land on runway r or aircraft j and i land on runway r. The separation constraint should ensure that the aircraft j lands in the unit of time Sij, when aircrafts i and j land on the same runway and i lands before j. But if they land on different runway, then, the aircraft j lands in the unit of time sij. This condition is set in constrain (5) which M is a large positive amount to ensure that the inequality becomes redundant if aircraft j lands before i. The value of M is suggested as: $M = L_i + S_{ij} - E$

Constrain (6) shows if aircrafts i and j are assigned to a same runway, $\gamma_{ijr}=1$; otherwise 0, which constrains (7) and (8) show this. It is assumed that the r_{th} runway is not available in interval period [t_1, t_2]. In this way, the landing time of the ith aircraft should be earlier than t_1 or later than t_2, if it lands on this runway. According to the variable Y_i, one of constrains (9) or (10) is active if rth runway becomes unavailable. It means if rth runway is unavailable and the aircraft needs to be landed on this runway, it should land before t_1 or after t_2. The value of M' and M" for constraints (9) and (10) are (Li) and (t_2 + Li) respectively, values for M' and M" are set empirically.

c. Complexity of the Problem

The complexity of scheduling landing problems growsas the size of the problem becomes large. Some authors such as Balakrishnan and Chandran[10] and Bianco, Dell'Olmo and Giordani[11] pointed at NP-hardness of such problems. Due to consideration of more than one runway in this problem, it is considered as an NP-hardness problem. Decreasing the solution space of the problem may decrease the time of solving it. hence, we propose an algorithm in order to tight the time window of each aircraft.

3. AN ALGORITHM TO GENERATE AN UPPER BOUND

It is noticeable that if we can find out a suitable upper bound for the solution of the problem, the time window of each aircraft will be tightened[7]. An algorithm is suggested in the following this upper bound. The steps of the algorithm is as follows:

1- Ar (r=1,2,…,R) is defined as the order for the set of aircrafts which land on runway r. This value is null for all runways at the beginning i.e., $A_r = \emptyset \ \forall \ r$.
2-All aircrafts are sorted in the non-decreasing manner, based on the target time for landing, Tj.
3-The aircraft j is selected based on the sorted order.
4- Function Bjr is defined for each runway of the aircraft j, when the aircraft j on the runway r, which as follows:

$$B_{jr} = \max \left[T_j, \max\left[X_k + S_{kj} \middle| \forall k \in A_r\right], \right.$$

$$\left. \max\left[X_k + s_{kj} \middle| \forall k \in A_u \ u = 1, \dots, R \ \ u \neq r\right]\right] \quad (20)$$

5-The values of B_{jr} generated for aircraft j is sorted undescendingly.
6-the value of K is 1 at the beginning.
7-At the sorted order, Kth value(actually in the order which its cost function is less) is selected.
8-If the value of selected Bjr is not in interval [t1, t2] (t1 ≤ Bjr ≤ t2), the aircraft j is assigned to the runway r and move to the next step. Otherwise if the value of selected Bjr is in interval [t1, t2] and the runway r is available, aircraft j is assigned to the runway r; if the value Bjr is in interval[t1, t2] and the runway r is unavailable, we add one unit to K and move back to step 7.
9-Set the value of Bjr equal to the landing time of the jth aircraft Xj=Bjr and add the aircraft j to the list of Ar and move back to step 2. And continue until all aircrafts are assigned to determined runways.

In fact, in this way the suitable runway is determined with respect to the best landing time. Since the landing time generated from the algorithm is not before the target time as it is always in or after the target time, a better upper bound will be generated , the landing time is again calculated based on a fixed runway and land of aircrafts is as the above order. In other words, in the model, variables Zir, δij and γijr stay fixed and the landing time is calculated again. According to mentioned conditions, hereafter the value generated for the objective function is named Zub. Figure 1 shows the flowchart of the algorithm. The time window can be updated based on an upper bound and equations (21) and (22).

$$E_i = \max[E_i, T_i - (Z_{UB}/g_i)] \qquad i = 1, 2, \ldots, P \quad (21)$$

$$L_i = \min[L_i, T_i + (Z_{UB}/h_i)] \qquad i = 1, 2, \ldots, P \quad (22)$$

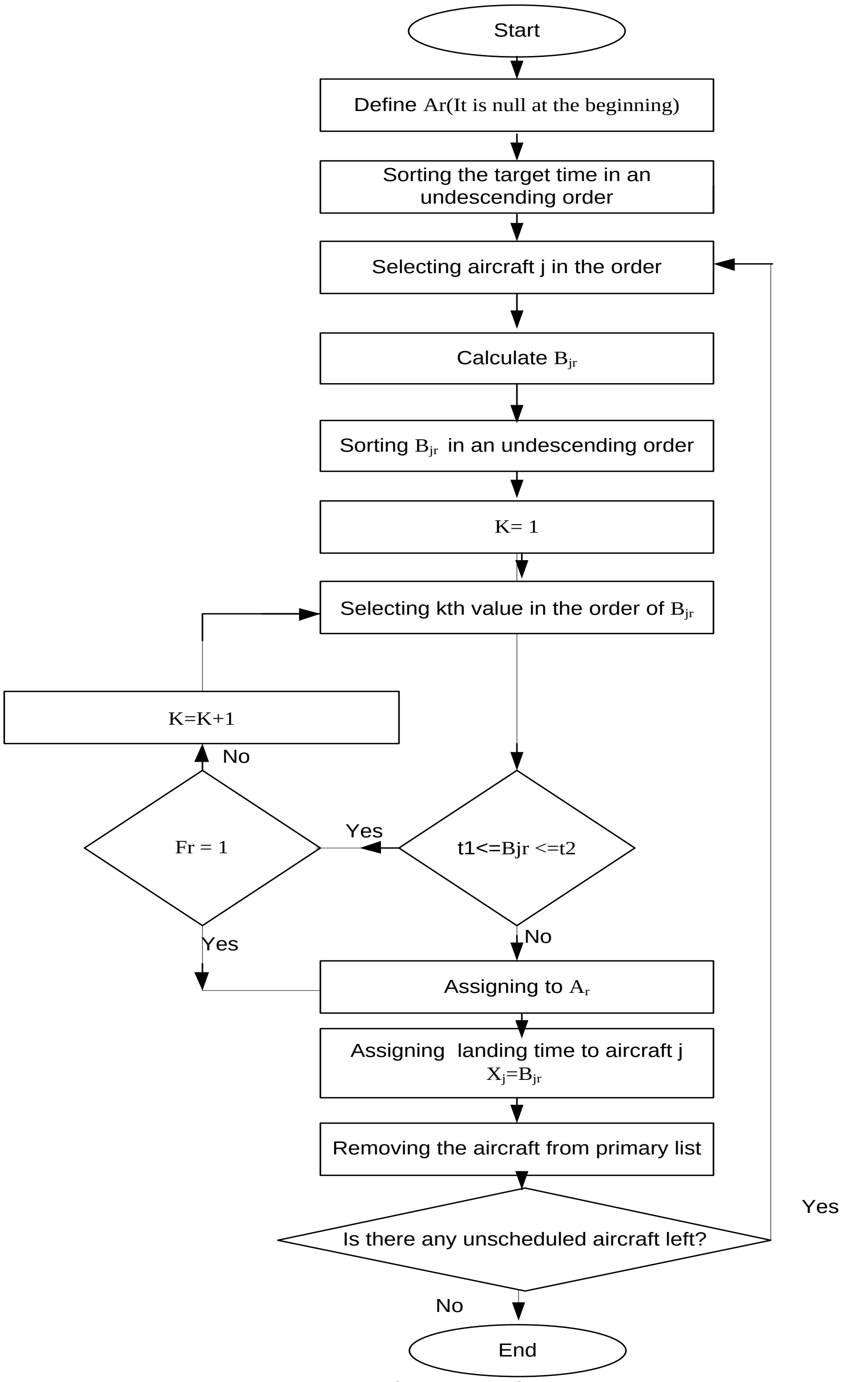

Figure 1. The flowchart of algorithm to generate upper bound

Hence, by using this algorithm, the solution space will be smaller through decreasing Li and increasing Ei for each time window [Ei , Li].

4. THE TIME SEGMENT HEURISTIC METHOD

This approach is based on dividing the main problem to sub-problems and finding the final solution by solving sub-problems. In this algorithm, the whole time horizon is broken down into different segments. At the beginning, it is assumed that the time interval is smaller than time horizon. Based on NP-hardness of the problem, the solution region of the problem exponentially the number of aircrafts increases. In this regard, if the number of aircrafts decreases, then the solution time decreases based on an negative exponential.

a. The Solution Method

The major idea of this method is segmenting the primary problem into sub-problems[12]. Sub-problems are resulted from segmenting time horizon to several segments so that each segment contains several aircrafts. In addition, the solution of primary problem is generated from the combination of other sub-problems solutions. Therefore, the first step is to determine and set the time interval related to each segment. Here the difficulty of solving each sub-problem is related to the number of aircrafts existing in the related segment which they should land in. Also, rules which are used to break down the time horizon into suitable segments, are defined. For example, at the beginning point of each segment, the place which contains the least aircrafts is selected. Generally, the number of aircrafts in each segment influences the solution of the problem as an important parameter. In order to use this algorithm, it is essential to define two parameters Ik and Bk for classifying the aircrafts.

Ik: the set of aircrafts in segment k.

Bk: the set of marginal aircrafts between segment k and k+1.

Ik: is the set of aircrafts which their earliest time is longer than their beginning time of segment k and their target time is shorter than the marginal time of that segment.

Bk: is the set of aircrafts which their time window coincides with the marginal time. In other words, the aircraft i is in the set Bk if the marginal time of the segment k is in time window [Ei , Li].

In addition, set EBTk as the minimum Ei related to the set of aircrafts which are the member of Bk.

$$EBT_k = (\min E_i \quad | \, i \in B_k)$$

Our contribution is segmenting the time for multi-runway condition with some constraints such as unavailability to formulate the sub-problems. In our research, it is required to find out the landing time and the runway related to each aircraft as an output of sub-problems.

2.4. The algorithm of time segment heuristic method

The steps of this algorithm are as follow:

1- Determine the number of segments(m)

2- Go to the following steps for k=1, …, m

2-1- Consider a primary time interval for the segment k.

2-2- Calculate Ik, Bk and EBTk.

2-3- Select the aircraft for the segment of the sub-problem.

2-4- Set a time interval, if required.

2-5- Move to step 2-2 if the time interval is changed.

2-6- Call the solver of sub-problem and generate the landing time of the selected aircraft in step 3-2.

2-7- Assign permanently landing time which are earlier than EBTk to the related aircraft.

Generate the solution

5. COMPUTATIONAL RESULTS

In this study, 8 typical problems from OR-Library[13] were extracted to validate the method. Table 1 shows the computational results and outputs of the model for solving the problem. In this table, the solution of Beasely et al. (2006) has been compared with the solution of the model generated from relaxed problem by time segment method[8]. Also, the number of aircrafts and runways are shown in table 1.

According to the optimization theory, by increasing the number of constrains, the solution does not improve. It means that the solution does not improve, but it may be worsen. The outputs of table 1 ensures this fact.

Table 1. Computational results

The number of problem	The number of aircraft	The number of runway	The solution generated from relaxation problem by TSH	Beasly et al's solution	Unavailable time window	The solution generated by TSH	Computational time(sec)
1	10	1	700	700	[100 150]	1120	0.7
		2	90	90		420	0.11
		3	0	0		90	0.09
2	15	1	1480	1480	[250 350]	2240	1.37
		2	210	210		230	0.4
		3	0	0		0	0.22
3	20	1	820	820	[250 350]	2830	0.9
		2	60	60		70	0.56
		3	0	0		0	0.31
4	20	1	2520	2520	[100 150]	-	-
		2	640	640		1120	50.5
		3	130	130		340	22.6
		4	0	0		60	1.7
5	20	1	3100	3100	[250 350]	4010	28.5
		2	650	650		830	73.2
		3	170	170		390	33.5
		4	0	0		90	0.01
6	30	1	24442	24442	[1100 1200]	-	-
		2	554	554		618	0.6
		3	0	0		60	0.03
7	44	1	1550	1550	[1100 1200]	2020	0.05
		2	0	0		0	0.01
8	50	1	1950	1950	[1100 1200]	1950	0.44
		2	135	135		135	41.9
		3	0	0		0	0.09

Thus, by adding a constrain such as unavailability of the runway to Beasely et al.'s problem, the solutions would not improve. In addition, often considering different unavailable times give different solutions for the problem. For example, for a problem including 15 aircrafts and one runway which is not available in the time interval from 100 to 200, the solution is 14140. Because the target time of most of aircrafts are in this interval and one runway is not enough to approximate landing time to target time. It results in enhancing the penalty of target time deviation. The computational time required is shown in the last column of table 1 to solve the problem through time segment method.

6. CONCLUSION

The main purpose of this paper was to propose an algorithm to solve landing aircrafts problem including some conditions as climate limits and unavailability of the runway in a definite time interval. At first, the problem was described and the related literature review was done. Next, we solved the problem by formulating and using a heuristic method. The results and outcomes of the paper are: (i) Considering constraints of unavailability of runways and climate limitations is one of our contributions to make the problem more realistic. (ii) An algorithm was proposed to generate a suitable upper bound and tighten time window of aircrafts. Next, the problem was solved by time segment method. (iii) The sufficiency and quality of the solutions of eight typical problems including almost 50 aircrafts and four runways, for the relaxed problem are compared with the solutions presented by Beasely et al.'s. At last, results showed that the solution is equal to theirs in the decreased solution space. (iv) The solution and the time of solving typical problems were calculated by the proposed algorithm. Results and outcomes showed that the solutions have not been improved than Beasely et al.'s, due to adding additional constraints which make the problem be more close to the reality.

The result showed that different unavailable time have an effect on the solution of the problem as a parameter. It means sometimes it is possible that the target time of many aircrafts have some overlap on the unavailable time. It results in enhancing the penalty of deviation from the target time.

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