# On The Characterizations of The Interval Sequential Equal Contributions Rule

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Abstract: This paper deals with the research area of cooperative interval games arising from airport situations with interval data. The major topic of the paper is to present and introduce the interval sequential equal contributions rule. The main result of this study is to give an axiomatic characterization of the interval sequential equal contributions rule.
Key words: airport situations, sequential equal contributions rule, interval data.

Aralıklı Ardışık Eşit Dağıtım Kuralının Karakterizasyonları Üzerine

Özet: Bu makale aralıklı havaalanı durumlarından ortaya çıkan işbirlikçi aralıklı oyunları araştırmak üzerine yazılmıştır. Bu makalenin en büyük katkısı aralıklı ardışık eşit dağıtım kuralından ilk defa bahsetmektir. Bu çalışmanın en önemli sonucu ise aralıklı ardışık eşit dağıtım kuralının aksiyomatik olarak karakterize edilmesidir.
Anahtar Kelimeler: havaalanı durumları, ardışık eşit dağıtım kuralı, aralık kavramı.

1. Introduction

Generally, in literature the following class of airport problems are considered. In these situations, different airlines use airstrips of different lengths. Here, a larger plane needs a longer airstrip. Further, if a plane can be served by an airstrip, then all smaller planes can be served by the same airstrip. To accommodate all planes, the airstrip must be long enough for the largest plane. Now the question is how the cost of the airstrip could be shared among the airlines. These problems are first introduced by [11] and have been studied from different perspectives (by [15]).
Airport situations have paid much attention in the literature. We refer here to [1, 6, 9, 11, 12, 14]. In this context, we focus on the sequential equal contributions rule introduced by [6]. This rule requires that all airlines using a given part of the airstrip contribute equally to the cost of this part. Each airline's contribution is the sum of terms, one for each part of the airstrip that it uses.
Uncertainty is a daily presence in real life. It affects our decision making and may have influence on cooperation. Recently, various economic and Operations Research situations under uncertainty are studied. We refer here to [1, 3, 10] who present and identify the interval Baker-Thompson rule for solving the aircraft fee problem of an airport with one runway

when there is uncertainty regarding the costs of the pieces of the runway; [5, 13] for cost allocation problems arising from connection situations where edge costs are closed intervals of real numbers; [2] for sequencing situations with interval data and [7] for bankruptcy situations under uncertainty.

The main contribution of this paper to characterize the sequential equal contributions rule. In this paper, we introduce interval sequential equal contributions rule by using interval uncertainty for costs. Our intuition is from [6] who study the axiomatic characterization of the classical sequential equal contributions rule.

The rest of the paper is organized as follows. We recall in Section 2 basic notions and facts from airport situations and the theory of cooperative interval games. Section 3 is devoted to the interval sequential equal contributions rule and the airport interval games. In Section 4, we give the properties of interval sequential equal contributions rule. In Section 5 we give an axiomatic characterization of this rule by using minor axioms and major axioms. We conclude in Section 6 with some final remarks.

2. Preliminaries

In this section, we give some preliminaries from interval calculus [4]. We denote by $I(\mathbb{R})$ the set of all closed and bounded intervals in $\mathbb{R}$, and by $I(\mathbb{R})^N$ the set of all n-dimensional vectors with elements in $I(\mathbb{R})$. Let $I(\mathbb{R}_+)$ be the set of all closed intervals in $\mathbb{R}_+$, and by $I(\mathbb{R}_+)^N$ the set of all n-dimensional vectors with elements in $I(\mathbb{R}_+)$.

Let $I, J \in I(\mathbb{R})$ with $I = [\underline{I}, \overline{I}]$, $J = [\underline{J}, \overline{J}]$, $|I| = \overline{I} - \underline{I}$ and $\alpha \in \mathbb{R}_+$. Then, $I + J = [\underline{I} + \underline{J}, \overline{I} + \overline{J}]$; $\alpha I = [\alpha \underline{I}, \alpha \overline{I}]$. In this paper we also need a partial substraction operator. The partial subtraction operator $I - J$ is defined, only if $|I| \geq |J|$, by $I - J = [\underline{I} - \underline{J}, \overline{I} - \overline{J}]$. We say that I is weakly better than J, which we denote by $I \succcurlyeq J$, if and only if $\underline{I} \geq \underline{J}$ and $\overline{I} \geq \overline{J}$. We also use the reverse notation $J \preccurlyeq I$ instead of $I \succcurlyeq J$.

Now, we recall the classical airport situations [6]. There is a universe of "potential" airlines, denoted by $\mathcal{I} \subseteq \mathbb{N}$ where $\mathbb{N}$ is the set of natural numbers. Let $\mathcal{N}$ be the class of non-empty and finite subsets of $\mathcal{I}$. Given $N \in \mathcal{N}$ and $i \in N$, let $c_i \in \mathbb{R}_+$ be airline i's cost, and $c = (c_i)_{i \in N}$ the costs vector. An airport problem for N is a list $c \in \mathbb{R}_+^N$. Let $\mathcal{C}^N$ be the class of all problems for N. A contributions vector for $c \in \mathcal{C}^N$ is a vector $x \in \mathbb{R}^N$. Let $X(c)$ be the set of all contributions vectors for $c \in \mathcal{C}^N$. A rule is a function defined on $_{N \in \mathcal{N}} \mathcal{C}^N$ that associates with each $N \in \mathcal{N}$ and each $c \in \mathcal{C}^N$ a vector in $X(c)$. For all $N \in \mathcal{N}$ such that $|N| = n$, let $\eta : N \to \{1, ..., n\}$ be a bijection such that $c_{\eta^{-1}(1)} \leq \cdots \leq c_{\eta^{-1}(n)}$. Thus, the airlines in N are ordered in terms of their costs. If several airlines have equal costs, the order is not unique. However, our results do not rely on any particular ordering. Our generic notation for rules is φ. For all $N \in \mathcal{N}$ and all $N' \subset N$, we define $c_{N'} = (c_i)_{i\in N'}$, $S_{N'}(c) = (S_i(c))_{i\in N'}$, and so on.

Firstly, we recall the sequential equal contributions rule.

Sequential equal contributions rule [6], φ^{SEC}: For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, and all $i \in N$,

$$\varphi_i^{SEC}(c) = \frac{c_{\eta^{-1}(1)}}{|N|} + \frac{c_{\eta^{-1}(2)} - c_{\eta^{-1}(1)}}{|N|-1} + \cdots + \frac{c_{\eta^{-1}(k)} - c_{\eta^{-1}(k-1)}}{|N|-k+1},$$

where $\eta(i) = k$.

Secondly, we recall the major and minor axioms of the airport problem. The major axioms are:

Population fairness (PF): For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, all $i \in \mathcal{I} \setminus N$, and all $j,k \in N$ such that $\min\{c_j, c_k\} \geq c_i$, we have $\varphi_j(c_{N\cup\{i\}}) - \varphi_j(c) = \varphi_k(c_{N\cup\{i\}}) - \varphi_k(c)$.

Smallest-cost consistency (SCC): For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, and all $N' \subset N$, if $x = \varphi(c)$, then $r_{N'}^x(c) \in \mathcal{C}^{N'}$ and $x_{N'} = \varphi(r_{N'}^x(c))$.

The minor axioms are:

Reasonableness (R): For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, and all $i \in N$, $0 \leq \varphi_i(c) \leq c_i$.

Efficiency (E): For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, $\sum_{i\in N}\varphi_i(c) = c^{\max}$.

Equal share lower bound (ESLB): For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, and all $i \in N$, $\varphi_i(c) \geq \frac{c_i}{|N|}$.

Cost monotonicity (CM): For all $N \in \mathcal{N}$, all $c \in \mathcal{C}^N$, all $c' \in \mathcal{C}^N$, and all $i \in N$, if $c_i' \geq c_i$ and for all $j \in N \setminus \{i\}$, $c_j' = c_j$, then for all $j \in N \setminus \{i\}$, $\varphi_j(c') \leq \varphi_j(c)$.

In [6] it is shown that the sequential equal contributions rule satisfies the properties above and they characterize the sequential equal contributions rule by using these properties. Our aim is to extend these results to the interval setting.

3. On The Interval Sequential Equal Contributions Rule

In this section we introduce the interval sequential equal contributions rule. Moreover, we take into account the airport situations where the cost of the pieces of the runway are intervals. Consider the aircraft fee problem of an airport with one runway. There is a universe of "potential" airlines, denoted by $\mathcal{I} \subseteq \mathbb{N}$ where $\mathbb{N}$ is the set of natural numbers. Let $\mathcal{N}$ be the class of non-empty and finite subsets of $\mathcal{I}$. Given $N \in \mathcal{N}$ and $i \in N$, let $T_i \in I(\mathbb{R}_+)$ be airline i's interval cost, and $T = (T_i)_{i\in N}$ the interval costs vector. An airport interval problem for N is a list $T \in I(\mathbb{R}_+^N)$. Let $\mathcal{C}^N$ be the class of all problems for N.

An interval contributions vector for $T \in \mathcal{C}^N$ is a vector $I \in I(\mathbb{R}^N)$. Let $I(T)$ be the set of all interval contributions vectors for $T \in \mathcal{C}^N$. An interval rule is a function defined on $_{N\in\mathcal{N}}\mathcal{C}^N$ that associates with each $N \in \mathcal{N}$ and each $T \in \mathcal{C}^N$ a vector in $I(T)$. For all $N \in \mathcal{N}$ such that $|N| = n$, let $\eta : N \to \{1,...,n\}$ be a bijection such that $T_{\eta^{-1}(1)} \leq \cdots \leq T_{\eta^{-1}(n)}$. Thus, the airlines in N are ordered in terms of their costs. If several airlines have equal costs, the order is not unique. However, our results do not rely on any particular ordering. Our generic notation for rules is φ. For all $N \in \mathcal{N}$ and all $N' \subset N$, we define $T_{N'} = (T_i)_{i\in N'}$, $S_{N'}(T) = (S_i(T))_{i\in N'}$, and so on. For a given airport interval situation $(N, (T_k)_{k=1,...,m})$;

Interval sequential equal contributions rule φ^{ISEC}: For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, and all $i \in N$, is given by:

$$\varphi_i^{ISEC}(T) = \frac{T_{\eta^{-1}(1)}}{|N|} + \frac{T_{\eta^{-1}(2)} - T_{\eta^{-1}(1)}}{|N|-1} + \cdots + \frac{T_{\eta^{-1}(k)} - T_{\eta^{-1}(k-1)}}{|N|-k+1}, \tag{1}$$

such that $T_{\eta^{-1}(k)} \preccurlyeq T_{\eta^{-1}(k+1)}$ where $\eta(i) = k.$

Theorem 3.1 Let $(N, (T_k)_{k=1,...,m})$ be an airport interval situation. Then the interval sequential equal contributions rule φ^{ISEC} for each player $i \in N$ is $\varphi_i^{ISEC} = [\underline{\varphi_i^{ISEC}}, \overline{\varphi_i^{ISEC}}].$

Proof. By (1) *we have for all* $i \in N$,

$$\begin{aligned}
\varphi_i^{ISEC}(T) &= \frac{T_{\eta^{-1}(1)}}{|N|} + \frac{T_{\eta^{-1}(2)} - T_{\eta^{-1}(1)}}{|N|-1} + \cdots + \frac{T_{\eta^{-1}(k)} - T_{\eta^{-1}(k-1)}}{|N|-k+1} \\
&= \frac{1}{|N|}\left[\underline{T_{\eta^{-1}(1)}}, \overline{T_{\eta^{-1}(1)}}\right] + \frac{1}{|N|-1}\left[\underline{T_{\eta^{-1}(2)} - T_{\eta^{-1}(1)}}, \overline{T_{\eta^{-1}(2)} - T_{\eta^{-1}(1)}}\right] + \\
&\cdots + \frac{1}{|N|-k+1}\left[\underline{T_{\eta^{-1}(k)} - T_{\eta^{-1}(k-1)}}, \overline{T_{\eta^{-1}(k)} - T_{\eta^{-1}(k-1)}}\right] \\
&= \begin{bmatrix} \frac{1}{|N|}\underline{T_{\eta^{-1}(1)}} + \frac{1}{|N|-1}\underline{T_{\eta^{-1}(2)} - T_{\eta^{-1}(1)}} + \cdots + \frac{1}{|N|-k+1}\underline{T_{\eta^{-1}(k)} - T_{\eta^{-1}(k-1)}}, \\ \frac{1}{|N|}\overline{T_{\eta^{-1}(1)}} + \frac{1}{|N|-1}\overline{T_{\eta^{-1}(2)} - T_{\eta^{-1}(1)}} + \frac{1}{|N|-k+1}\overline{T_{\eta^{-1}(k)} - T_{\eta^{-1}(k-1)}} \end{bmatrix} \\
&= \left[\underline{\varphi_i^{ISEC}}, \overline{\varphi_i^{ISEC}}\right].
\end{aligned}$$

Theorem 3.1 shows that one can calculate the lower bound of the interval sequential equal contributions by using the lower bounds of the interval costs; and the upper bound of the interval sequential equal contributions by using the upper bounds of the interval costs. These calculations can be done easily by using the classical sequential equal contributions rule.

Next we give the following example to illustrate the calculation of the interval sequential equal contributions rule by using Theorem 3.1.

Example 3.1 Let $(N=\{1,2,3\},(T_k)_{k=1,2,3})$ be an airport interval situation with the interval costs $T_1=[30,36]$, $T_2=[40,50]$, $T_3=[100,120]$. Then,

$$\underline{\varphi_1^{ISEC}} = \frac{\underline{T_1}}{3} = 10$$

$$\underline{\varphi_2^{ISEC}} = \frac{\underline{T_1}}{3} + \frac{\underline{T_2}-\underline{T_1}}{3-1} = 10+5 = 15$$

$$\underline{\varphi_3^{ISEC}} = \frac{\underline{T_1}}{3} + \frac{\underline{T_2}-\underline{T_1}}{3-1} + \frac{\underline{T_3}-\underline{T_2}}{3-2} = 10+5+60 = 75$$

$\underline{\varphi^{ISEC}} = (10,15,75)$ and

$$\overline{\varphi_1^{ISEC}} = \frac{\overline{T_1}}{3} = 12$$

$$\overline{\varphi_2^{ISEC}} = \frac{\overline{T_1}}{3} + \frac{\overline{T_2}-\overline{T_1}}{3-1} = 12+7 = 19$$

$$\overline{\varphi_3^{ISEC}} = \frac{\overline{T_1}}{3} + \frac{\overline{T_2}-\overline{T_1}}{3-1} + \frac{\overline{T_3}-\overline{T_2}}{3-2} = 12+7+70 = 89$$

$\overline{\varphi^{ISEC}} = (12,19,89)$ and by Theorem 3.1, $\varphi^{ISEC} = ([10,12],[15,19],[75,89])$.

4 . The Properties of The Interval Sequential Equal Contributions Rule

We define an interval allocation rule for a given airport interval situation $(N,(T_k)_{k=1,\ldots,m})$ as a map $\mathcal{F}$ associating each allocation situation $(N,(T_k)_{k=1,\ldots,m})$ to a unique rule $\mathcal{F}(N,(T_k)_{k=1,\ldots,m}) = \mathcal{F}(N,([\underline{T}_k,\overline{T}_k])_{k=1,\ldots,m}) \in \mathbb{R}^N$ with $\sum_{i\in N}\mathcal{F}_i(N,(T_k)_{k=1,\ldots,m}) = \sum_{i=1}^{m}[\underline{T}_i,\overline{T}_i] = \sum_{i=1}^{m}T_i$. In this context, we give some properties of the major and minor axioms on the airport interval problems. The major axioms are:

Interval population fairness (IPF): For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, all $i \in \mathcal{I} \setminus N$, and all $j,k \in N$ such that $\min\{T_j, T_k\} \geq T_i$, we have $\varphi_j\left(T_{N\cup\{i\}}\right) - \varphi_j(T) = \varphi_k\left(T_{N\cup\{i\}}\right) - \varphi_k(T)$.

Interval population fairness requires that upon the arrival of a new airline, the interval contributions of all airlines whose interval costs are not less than the interval cost of the new airline should be affected by equal amounts.

Interval smallest-cost consistency (ISCC): For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, all $N' \subset N$ and all $I \in I(\mathbb{R})$, if $I = \varphi(T)$, then $r^x_{N'}(T) \in \mathcal{C}^{N'}$ and $x_{N'} = \varphi\left(r^x_{N'}(T)\right)$.

Interval smallest-cost consistency requires that upon the departure of an airline with the smallest interval cost, if the problem is reevaluated from the viewpoint of the remaining airlines, then all the remaining airlines should contribute the same amounts as they did initially.

The minor axioms are:

Interval Reasonableness (IR): For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, and all $i \in N$, $[0,0] \preccurlyeq \varphi_i(T) \preccurlyeq T_i$.

Interval reasonableness requires that each airline should contribute a non-negative interval amount, but no more than its individual interval cost.

Interval Efficiency (IE): For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, $\sum_{i\in N} \varphi_i(T) = T^{\max}$.

Interval efficiency requires that the sum of all interval contributions should be equal to the largest interval cost.

Interval Equal share lower bound (IESLB): For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, and all $i \in N$, $\varphi_i(T) \succcurlyeq \frac{T_i}{|N|}$.

Interval equal share lower bound requires that each airline should contribute at least as much as an equal division of its indivdual interval cost.

Interval Cost monotonicity (ICM): For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, all $T' \in \mathcal{C}^N$, and all $i \in N$, if $T'_i \succcurlyeq T_i$ and for all $j \in N \setminus \{i\}$, $T'_j = T_j$, then for all $j \in N \setminus \{i\}$, $\varphi_j(T') \preccurlyeq \varphi_j(T)$.

Interval cost monotonicity requires that if an airline's interval cost increases, then all other airlines should contribute at most as much as they did initially.

5 . An Axiomatic Characterization of The Interval Sequential Equal Contributions Rule

We give the axiomatic characterzations of the interval sequential equal contributions rule by using the major and the minor axioms. The first characterization is given by using IPF, IE, IESLB, ICM. The second characterization is given by using ISCC, IR, IESLB, ICM. Finally, the third characterization is given by using IBPI, IE.

The following lemma is required for the first characterization.

Lemma 5.1 For all $N \in \mathcal{N}$, all $T \in \mathcal{C}^N$, if an interval rule φ satisfies the interval efficiency, the interval equal share lower bound, and interval cost monotonicity, then

$$\varphi_{\eta^{-1}(1)}(T) = \frac{T_{\eta^{-1}(1)}}{n} = \left[\frac{\underline{T_{\eta^{-1}(1)}}}{n}, \frac{\overline{T_{\eta^{-1}(1)}}}{n}\right].$$

Proof. The proof is a straightforward generalization from the classical case and can be obtained by following the steps of Lemma 1 in [6].
Now, we give our first characterization.
Theorem 5.1 The interval sequential equal contribution rule is the only rule satisfying IE, IESLB, ICM and IPF.
Proof. It is obvious that the sequential equal contributions rule satisfies the four axioms. We only need to show the uniqueness. For uniqueness, it is clear from [6] that $\underline{\varphi_i^{ISEC}}$ and $\overline{\varphi_i^{ISEC}}$ for each $i \in N$ are the unique allocations satisfying the four properties IE, IESLB, ICM and IPF. Finally, by Theorem 2.1 we conclude that $\varphi_i^{ISEC} = [\underline{\varphi_i^{ISEC}}, \overline{\varphi_i^{ISEC}}]$ for each $i \in N$ is unique. Hence φ^{ISEC} is the unique interval allocation satisfying IE, IESLB, ICM and IPF.
Next we present our second characterization of the interval sequential equal contributions rule:
Theorem 5.2 The interval sequential equal contribution rule is the only rule satisfying IR, IESLB, ICM and ISCC.
Proof. It is obvious that the sequential equal contributions rule satisfies the four axioms. We only need to show the uniqueness. For uniqueness, it is clear from [6] that $\underline{\varphi_i^{ISEC}}$ and $\overline{\varphi_i^{ISEC}}$ for each $i \in N$ are the unique allocations satisfying the four properties IR, IESLB, ICM and ISCC. Finally, by Theorem 2.1 we conclude that $\varphi_i^{ISEC} = [\underline{\varphi_i^{ISEC}}, \overline{\varphi_i^{ISEC}}]$ for each $i \in N$ is unique. Hence φ^{ISEC} is the unique interval allocation satisfying IE, IESLB, ICM and IPF.

6 . Final Remarks

Interval uncertainty is the simplest and the most natural type of uncertainty which may influence cooperation because lower and upper bounds for future outcomes or costs of cooperation can always be estimated based on available economic data.
In this paper we consider airport situations where the costs of the pieces of the runway are given by intervals. In this context we give an axiomatic characterization of the interval sequential equal contribution rule introduced by [6].
We refer reader to [8] on several procedures specifying how a certain interval solution might be used to transform an interval allocation into a payoff vector when uncertainty regarding the value of the grand coalition is resolved. In the sequel the straightforward extension of the axiomatic characterization of the classical sequential equal contribution rule to the interval setting is advantageous.

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