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Invited Review

Inequity averse optimization in operational research

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ABSTRACT

There are many applications across a broad range of business problem domains in which equity is a concern and many well-known operational research (OR) problems such as knapsack, scheduling or assignment problems have been considered from an equity perspective. This shows that equity is both a technically interesting concept and a substantial practical concern. In this paper we review the operational research literature on inequity averse optimization. We focus on the cases where there is a tradeoff between efficiency and equity.

We discuss two equity related concerns, namely equitability and balance. Equitability concerns are distinguished from balance concerns depending on whether an underlying anonymity assumption holds. From a modeling point of view, we classify three main approaches to handle equitability concerns: the first approach is based on a Rawlsian principle. The second approach uses an explicit inequality index in the mathematical model. The third approach uses equitable aggregation functions that can represent the DM's preferences, which take into account both efficiency and equity concerns. We also discuss the two main approaches to handle balance: the first approach is based on imbalance indicators, which measure deviation from a reference balanced solution. The second approach is based on scaling the distributions such that balance concerns turn into equitability concerns in the resulting distributions and then one of the approaches to handle equitability concerns can be applied.

We briefly describe these approaches and provide a discussion of their advantages and disadvantages. We discuss future research directions focussing on decision support and robustness.

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1. Introduction

There are various real life applications where equity concerns naturally arise and it is important to address these concerns for the proposed solutions to be applicable and acceptable. As a result, there exist many articles cited in the operational research (OR) literature that consider classical problems, such as location, scheduling or knapsack problems, and extend available models so as to accommodate equity concerns. These models are used across a broad range of applications including but not limited to airflow traffic management, resource allocation, workload allocation, disaster relief, emergency service facility location and public service provision. This broad range of applications indicates that considering these classical models with an emphasis on equity is practically relevant in addition to being technically interesting.

In this paper we present a literature review on inequity aversion in operational research and a classification of the modeling approaches used to incorporate concerns about equity alongside efficiency concerns in optimization problems. The equity concept is often studied in an allocation setting, where a resource or good is allocated to a set of entities. The concern for equity involves treating a set of entities in a "fair" manner in the allocation. The allocated resource or outcome can be a certain good, a bad or be a chance of a good or bad. The entities can be for example organizations, persons or groups of individuals which are at different locations or are members of different social classes.

At this point it may be helpful to look at three small examples. Let us start with a simple example in which we have two people who are allocated some money. Consider the following two allocations to these people, who are no different in terms of claim: (100,50) and (80,70). Common sense suggests that the second allocation is more equitable than the first one. The *Pigou–Dalton principle of transfers* (PD) formalizes this intuition. The PD states that any transfer from a poorer person to a richer person, other things remaining the same, should always lead to a less equitable allocation.

PD allows us to compare allocations that have the same aggregate amount as is the case in our simple example. However, things get more complicated when we have allocations that differ in terms

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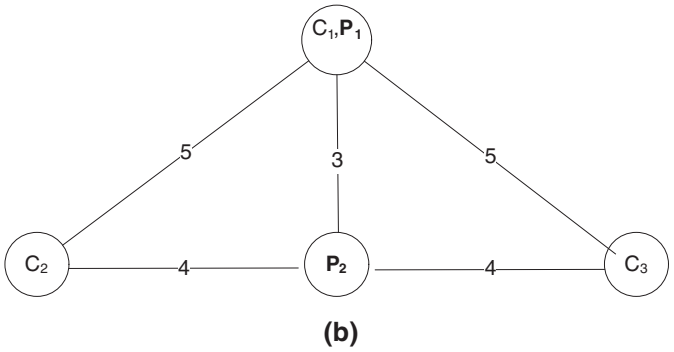

Fig. 1. Two alternative locations for an emergency service facility.

of the aggregate amount. In many situations an increase in equity results in a decrease in efficiency, which is usually measured by the total amount of the good (bad) that is allocated. As an example, consider a case where an emergency service facility is going be located. Suppose that a number of potential sites for the facility is already determined and the problem is to choose one of them. The facility will be serving different customers and it is important for the decision maker (DM) to ensure an equitable service to them. The DM evaluates how good a service is by the distance the customers have to travel to reach the facility: the shorter the distance between a customer and the facility, the better it is. One can consider choosing an alternative that minimizes the total distance that all the customers travel to the facility to evaluate how good each potential site is. However, in such a solution some of the customers may be significantly under-served. Fig. 1 shows a small example with 3 customers located at the nodes of a network (C_1, C_2 and C_3). Suppose that there are two alternative locations for the emergency service facility (P_1 and P_2, respectively). We will represent the two alternative locations using distance distributions that show the distance that each customer has to travel. The first location (P_1) results in distance distribution (0,5,5) and the second one (P_2) results in distribution (3,4,4). We see that the first alternative is more efficient in the sense that the total distance traveled is less. However, this efficiency is obtained at the expense of customers C_2 and C_3 who have to travel 5 units of distance. In the second alternative, the total distance traveled is larger but the distance traveled by the customers C_2 and C_3 is reduced. This is a typical example of the trade-off between efficiency and equity, which occurs in many real life situations. The DM's preferences would determine the better alternative in such cases: there is no "objective" way to determine which distribution is better, and reasonable people may take different views. For example the DM may argue that the first alternative is better claiming that it saves on total distance traveled, or s/he may argue that the second alternative is better as the maximum distance traveled is smaller. This review will focus on the cases where both efficiency and equity are of concern to the decision makers.

The above examples show cases where anonymity holds; that is, the identities of the entities are not important. However, as we will see in the next example, there may be situations where the entities have different characteristics and hence anonymity may not make sense. Suppose that you are the head of an academic department and you have to decide on the allocation of the next year's studentship budget to the Ph.D. students. Which of the following rules would you use as a base for your decisions?

- Allocate every student the same amount regardless of any other factor
- Allocate the budget proportional to the students' declared needs, which are measured as the shortfall from target income (students that need more get more)

Different people would give different answers to this question. The first rule respects person anonymity and hence is equitable. However, there are other sensible arguments that would favor other rules, as anonymity may be inappropriate when we have entities with different characteristics, such as different needs. These two rules involve two different dimensions of equity, "horizontal" and "vertical" equity. Horizontal equity is concerned with the extent to which entities within a class are treated similarly (Levinson, 2010); hence *giving equal amounts to the students with the same need* would satisfy concerns on horizontal equity. Vertical equity is concerned with the extent to which members of different classes are treated differently. *Giving different amounts to students with different needs* is a decision reflecting a concern for vertical equity.

As seen in this example, a reasonable equity concept might involve "unlike treatment of unlikes", such as giving different amounts to students with different needs. We call this equity concept that involves entities which are distinguished by an attribute such as need, claim or preferences *balance*.

1.1. Review methodology

The search methodology we use for this review is as follows: We used the "Web of Science" database for our search and used the keywords "equit*" (so that the words such as "equity" and "equitable" are included), "fairness" and "equality". We narrowed down the search by area (Operational Research/Management science) and we limited the search to "Journal Articles". As our focus is on current practice we surveyed the 10 years from 2003 to the time of analysis, mid way through 2013. For the "equit*" keyword, we have identified 392 articles. Screening by title, we eliminated the irrelevant ones, most of which use "equity" as a financial term, and obtained 181 articles. We further screened them by abstract. We focused on the studies that either report a modeling approach that incorporates equity concerns alongside efficiency concerns or discuss equity measures that have been used in the OR literature. We obtained 69 articles this way. For the "fairness" keyword we obtained 100 papers, which reduced to 34 after screening. As most of the articles found with the keyword "equality" use this term in its mathematical modeling sense (i.e. equality constraints in a mathematical model) only 4 articles obtained with this keyword were relevant. Scanning the references of these articles we added 27 articles to our review list.

Note that since our focus is inequity-averse optimization, we exclude the studies on non-cooperative games and filter these from the review. The articles on cooperative game theory concepts are also excluded as these concepts embody a stability rather than fairness rationale – they are solutions which can be made to "stick" rather than solutions which are attractive in an ethical sense. Moreover, we consider the approaches to problems where one has to trade equity off against efficiency and hence we do not review the solution approaches to the "fair division problem". We think there is a scope for another review for such problems. Note that if one does not have to trade equity off against efficiency, one does not have to answer the question "how much fairer is division A than division B?". It is enough to have ordinal information. In that sense, trading equity off against efficiency, brings an additional challenge to the allocation problems.

In Table 1 we report the journals that contribute to the literature with 3 or more publications. Around 14 percent of the articles were published in European Journal of Operational Research, followed by 10 percent and 8 percent in Computers and Operations Research and Operations Research, respectively. In total there were 43 journals, which shows that equity considerations arise in various settings and are discussed in publications in a variety of journals with different audiences and scopes.

The rest of the paper is as follows: Section 2 discusses the two main equity related terms, which are equitability and balance. We mention some of the applications involving equity concerns cited in

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