

EFFICIENCY AND MULTIFUNCTIONS

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Abstract. This research paper is focused on the common concepts of the efficiency and set-valued map. After a short introduction, we propose some questions regarding the notion of efficiency and we emphasize the Pareto optimality as one of the first finite dimensional illustrative examples. We present the efficiency and the multifunctions in the infinite dimensional ordered vector spaces following also our recent results concerning the most general concept of approximate efficiency, as a natural generalization of the efficiency, with implications and applications in vector optimization and the new links between the approximate efficiency, the strong optimization - by the full nuclear cones - and Choquet's boundaries by an important coincidence result. In this way, the efficiency is strongly related to the multifunctions and Potential theory through the agency of optimization and conversely. Several pertinent references conclude this study.

1. INTRODUCTION

Throughout in our *Life, the Efficiency* was, it is and it will remain *essential* for the *Existence* and not only. Its mathematical models were unanimously accepted in various *knowledge fields*. Also, we propose it as a *New Frontier in Mathematical Physics, in the World context of priorities concerning the Alternative Energies, the Climate Exchange and the Education*. To it we dedicate our modest scientific contribution. The content of this research work is organized as follows: *Section 2* is dedicated to some useful matters on the efficiency. We briefly present in *Section 3 the Pareto Optimality* as one of the main starting points for the mathematical modeling of the *Economical Efficiency*.

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In *Section 4*, conceived as a concise Survey, we present *the most general notion of Approximate Efficiency* and its particular case of the usual *Efficiency*, with the immediate connections to Multifunctions, in *the Infinite Dimensional Ordered Vector Spaces*, completed by *the coincidence between Choquet's Boundaries and the Approximate Efficient Points Sets in Ordered Hausdorff Locally Convex Spaces*, this conclusion being based on *the first result established by us concerning such a property as this for Pareto type efficient points sets and the corresponding Choquet boundaries*. Our results represent *strong relationships between important Great Fields of Mathematics and the Human Knowledge: Vector and Strong Optimization, Set-valued Maps, the Axiomatic Theory of Potential together with its Applications and the Human Efficiency*. Finally, we indicate the selected bibliography which refers only to the papers which were used. Sections 2, 3 and a part of Section 4 are presented following [64].

2. SOME SELECTED QUESTIONS ON THE EFFICIENCY

First of all, we present a short survey on the efficiency. The current language defines the efficiency as “*the ability to produce the desired effect in dealing with any problem*”. In the actual world characterized by: *globalization which has generated efficiency gains, liberalization, individualization, informatization, informalization* ([68] and so on), the efficiency is perceived as follows: “working well, quickly and without waste”. But, our life has its Divine efficiency and the projection in the reality deals with a lot of kind of descriptions: *information efficiency, energy efficiency, eco - efficiency* (see, as recent references, [39], [45] and so on), home energy efficiency, water efficiency market enhancement programs, sports and efficiency, economic efficiency (agricultural and industrial efficiency, human efficiency in business, efficiency in financial and betting markets, efficiency in capital asset pricing models, etc.), efficiency in Mathematics (efficient algorithms in computational complexity, efficiency frontier in data envelopment analysis, statistics and so on, efficiency in multi – objective, stochastic and goal programming, efficiency in mathematical economics, etc.), efficiency in medicine, technical efficiency, etc., all of them being based on the fundamental question: “*whose valuations do we use, and how shall they be weighted ?*” [27]. Thus, the economic efficiency is characterized by the “optimal” relationships between the value of the ends (the physical outputs) and the value of the means (the physical inputs), both of them “measured” by the money. Hence, the monetary evaluations are essential for the economic efficiency which usually is associated with the sustainability defined as

“development that meets the needs of the present without compromising the ability of future generations to meet their own needs” to achieve a good society ([10], p.43). However, the goals of efficiency and sustainability might not be enough to ensure a positive social development because the economic efficiency does not include any component of it (see, for example, the distribution of goods) ([49], p.13) and the sustainability was not very clear defined [67]. In terms of the technical efficiency, a machine is considered to be useful or *“more efficient than another” when it generates “more work output per unit of energy input”*. But, it is not possible to speak about complete efficiency in any process since we have not developed yet workable procedures concerning the corresponding evaluations (see, for instance, the urban automobile traffic which engages different people from many points of view; in general, the transport systems are highly complex with different goals often conflict). In fact, in all the processes, we try to approximate the real efficiency by some kinds of fuzzy or relative efficiency in order to obtain several controls on it, taking into account its complexity. For example, one of the main purposes of the data envelopment analysis is to *“to measure”* the relative efficiency and the comparison of decision making units by the estimation of *“the distance”* between the evaluated real units and the virtual units (see, for instance, [38]). Another strong argument and a significant example in this direction is represented by *the permanent measure and the continuous supervision of the interest rate risk to obtain the optimal efficiency balance in the management of banks’ assets and liabilities* (see, for example, the pertinent asset liability management model together with the simulation analysis given in [40]). Generally speaking, from the decisional point of view, the main steps to obtain the efficiency are the following:

2.1. *Wording of the problems by the managerial staff in an adequate language for mathematicians and computer scientists because the “bilateral” dialogue is absolutely necessary to solve the programs through the agency of such as these cooperations.*

2.2. *The elaboration of the appropriate mathematical models and the corresponding numerical processings.*

2.3. *The selection , by a serious study, of the best multicriteria decisions.*

2.4. *The application of them.*

2.5. *The evaluation of the efficiency.*

We must remark that the multicriteria decision aid ([19], [68]) and the decision making under uncertainty viewed as an important area of decision making and recognized as *“ the fact that in certain situations a person does not have the information which quantitatively and qualitatively is appropriate*

to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristics”, that is, “it relates to a state of the human mind” characterized by the *“lack of complete knowledge about something”* [77] represents the real risk for the efficiency which, in our opinion, generates it. Following [77], we remember that the term of *“risk”* was initially applied for *“the situations in which the probabilities of outcomes were objectively known”*. In accordance with [21], now this concept *“means a possibility of something bad happening”* and the uncertainty *“is applied to the problems in which real alternatives with several possible outcomes exist”*. Another important matter is the efficacy defined as *“the quality of being efficacious”* in the sense of *“producing the desired effects or results”*. In our opinion, this means *to be efficient step by step*, that is, *a discrete efficiency with appropriate links between the stages*.

3. PARETO OPTIMALITY: AN ILLUSTRATIVE EXAMPLE OF FINITE DIMENSIONAL EFFICIENCY

Not even for the market economies there exists no an universal mathematical model. Pareto efficiency or Pareto optimality [51] is a central theory in economics with broad applications in game theory, engineering and the social sciences. It represents the actual finite dimensional part of the multiobjective programming in vector optimization. Thus, whenever a feasible deviation from a genuine solution S of an arbitrary multiobjective programme generates the improvement of at least one of the objectives while some other objectives degrade, any such a solution S as this is called efficient or nondominated. A system in economics and in politics is called Pareto efficient whenever “no individual can be made better off without another being made worse off” that is, a social state is economically efficient, or Pareto optimal, provided that “no person in society can become better off without anyone else becoming worse off”. This characteristic of Pareto type efficiency has been pointed out in [1] - [3], [18], [24], [51], [71] and the others. In terms of the alternative allocations this means that given a set of alternative allocations and a set of individuals, any movement from one alternative allocation to another that can make at least one individual better off, without making any other individual worse off is called a Pareto improvement or a Pareto optimization. An allocation of resources is named *Pareto efficient* or *Pareto optimal* whenever *no further Pareto improvements can be made*. If the allocation is *strictly preferred* by one person and no *other allocation would be as good for everyone*, then it is called *strongly Pareto optimal*. A *weakly Pareto optimal allocation* is one where *any feasible reallocation would be strictly preferred*

by all agents [77]. Consequently, *Pareto type efficiency* is an important approximate criterion for evaluating the economic systems and the political policies, with minimum assumptions on the interpersonal comparability. We said “approximate criterion” because it asks “the ideal” which may not reflect, for example, the workings of real economics, thanks to the following restrictive assumptions necessary for the existence of Pareto efficient outcomes: the markets exist for all possible goods, being perfectly competitive and the transaction costs are negligible. In the political policies, not every Pareto efficient outcome is regarded as desirable (see, for instance, the strategies based on the unilateral benefits). For these reasons, Pareto optimality was accepted with some or much uncertainty and controversy, but, by the Arrow’s renowned impossibility theorem given in 1951 according to which “no social preference ordering based on individual orderings only could satisfy a small set of very reasonable conditions” - the Pareto criterion being one of them, it remains “plausible and uncontroversial” [67]. Usually, the concept of efficiency replaces the notion of optimality in multiple criteria optimization because *whenever the solutions of a multiple – objectives program exist in Pareto’ sense, they cannot be improved following the ordering induced by the cone.*

4. APPROXIMATE EFFICIENCY, EFFICIENCY AND MULTIFUNCTIONS IN THE INFINITE DIMENSIONAL ORDERED VECTOR SPACES WITH RECENT CONNECTED RESULTS

Seemingly, the concept of efficiency is equivalent to the optimality, as we can see from the next abstract construction. In reality, the optimality represents a particular case of the efficiency, that is, “the best approximation” of all the efficient points. Let X be a real or complex ordered vector space, let K be the class of all convex cones defined on X and let A be an arbitrary, non-empty subset of X . Following the next considerations, we consider that the set of all efficient points of A with respect to an arbitrary $K \in \mathcal{K}$ is in the following relation with the “vectorial” minimization or maximization:

$$Eff(A) \supseteq \bigcup_{K \in \mathcal{K}} MIN_K(A) \cup \bigcup_{K \in \mathcal{K}} MAX_K(A).$$

Clearly, any vector optimization program (which has its origin in the usual ordered Euclidean spaces programs thanks to Pareto optimality of vector-valued real functions) includes the corresponding strong optimization program and allows to be described as one of the next optimization problems. Moreover, it is possible to replace the convex cone K by any other convenient, non-empty subset of X :

$$(P_{T,K}) : MIN_K f(T) \text{ or } (P_{T,K}) : MAX_K f(T)$$

where $K \in K$, T is a given non-empty set and $f : T \rightarrow X$ is an appropriate application. If one denotes by $S_f(T, K)$ the corresponding set of solutions, then the announced equivalence seems to be justified by the following relation:

$$\bigcup_{\emptyset \neq A \subseteq X} Eff(A) = \bigcup_{\substack{T \neq \emptyset \\ K \in K, f: T \rightarrow X}} S_f(T, K)$$

but, in reality, only the next inclusion is valid :

$$\bigcup_{\emptyset \neq A \subseteq X} Eff(A) \supseteq \bigcup_{\substack{T \neq \emptyset \\ K \in K, f: T \rightarrow X}} S_f(T, K)$$

thanks to the refinement of the notion of efficiency which can not be totally described for the moment by mathematical means, that is, the final agreement between “the dictionary’s concept of efficiency” and “the corresponding notion in mathematics” was not signed yet.

Now, let X be a non-empty set, let E be a vector space ordered by a convex, pointed cone K and let $f : X \rightarrow E$ be a function. We consider the next Vector Optimization Problem:

$$(P) \begin{cases} \min f(x) \\ x \in X \end{cases},$$

To solve it means to identify all the efficient points $x_0 \in X$ in the sense that $f(X) \cap [f(x_0) - K] = \{f(x_0)\}$. In all these cases, x_0 is an *efficient solution* and $f(x_0)$ is called a *nondominated point* of the program (P) for Multicriteria Optimization Programs in Finite Dimensional Vector Spaces. If one replaces K by $K \setminus \{0\}$ or $\text{int}(K)$, then x_0 is called strictly(weakly) efficient for X , respectively, and $f(x_0)$ is named strictly (weakly) nondominated. Consequently, whenever E is an usual ordered Euclidean space, the above concepts for x_0 means *Pareto optimal*, *strictly Pareto optimal* and *weakly Pareto optimal solution*, respectively, with the corresponding nondominated concepts for f (see, for a recent instance, [20]). So, concerning the practical vector - optimization problems, it is important to know when the set of all efficient points is non-empty, to establish its main properties (existence, domination, connectedness, compactness, density in varied topologies, etc.) and to extend the concepts together with the results to multicriteria optimization in infinite dimensional ordered vector spaces. The proper

efficiency introduced in [42] and developped in [4] – [6], [8], [9], [17], [23], [25], [26], [33], [36], [47], etc. appears as a refined case of the efficiency, that is, the set of all properly efficient solutions and the set of all positive proper efficient solutions of problem (P) are subsets of the set containing all the efficient points and the study of them has been proposed in order to eliminate some “undesirable” efficient solutions. We recall that $x_o \in X$ is a *properly efficient solution* of (P) if it is an *efficient point* and $cl[cone(f(X) + K - \{f(x_o)\})] \cap K = \{0\}$; x_o is a *positive proper efficient solution* of (P) if there exists a linear continuous functional φ on E such that $\varphi(k) > 0$ for every $k \in K$ and $\varphi[f(x_o)] \leq \varphi[f(x)]$ for all $x \in X$. This section deals with a new generalization of the efficiency, named by us the *approximate efficiency*, in ordered Hausdorff locally convex spaces. All the elements concerning the ordered topological vector spaces used here are in accordance with [52].

Let E be a vector space ordered by a convex cone K , K_1 a non-void subset of K and A a non-empty subset of E . The following definition introduces a new concept of approximate efficiency which generalizes the well known notion of Pareto efficiency.

Definition 1.[63]. We say that $a_0 \in A$ is a K_1 –Pareto (minimal) efficient point of A , in notation, $a_0 \in \text{eff}(A, K, K_1)$ (or $a_0 \in \text{MIN}_{K+K_1}(A)$) if it satisfies one of the following equivalent conditions:

- (i) $A \cap (a_0 - K - K_1) \subseteq a_0 + K + K_1$;
- (ii) $(K + K_1) \cap (a_0 - A) \subseteq -K - K_1$;

In a similar manner one defines the Pareto (maximal) efficient points by replacing $K + K_1$ with $-(K + K_1)$. Clearly,

$$A \cap (a_0 - K) \subseteq a_0 + K_1 \Rightarrow A \cap (a_0 - K - K_1) \subseteq a_0 + K + K_1 \Rightarrow \\ A \cap (a_0 - K_1) \subseteq a_0 + K,$$

which suggests other concepts for the approximate efficiency in ordered linear spaces.

Remark 1. The notion of *approximate efficiency* in the sense of the above definition is the *most general notion* of *approximate efficiency* introduced until now. We also remark that $a_0 \in \text{eff}(A, K, K_1)$ iff it is a *fixed point* for the *multifunction*

$$F : A \rightarrow A \quad \text{defined} \quad \text{by}$$

$F(t) = \{a \in A : A \cap (a - K - K_1) \subseteq t + K + K_1\}$. Consequently, for the existence of the Pareto type efficient points we can apply appropriate fixed points theorems for multifunctions (see, for instance, [12], [50], [76] and any other proper scientific papers) and we need the next usual continuity properties of multifunctions. Namely, if X and Y are two topological spaces and $f : X \rightarrow 2^Y$ is a set-valued map, then: f is *upper semicontinuous (usc)* if for any $x \in X$ and any open set $D \supseteq f(x)$ we have $D \supseteq f(x_1)$ for all x_1 in some neighbourhood $V(x)$ of x . The multifunction f is *lower semicontinuous (lsc)* if for any $x \in X$ and every open set D with $f(x) \cap D \neq \emptyset$ it follows that $f(x_1) \cap D \neq \emptyset$ for all x_1 from some neighbourhood $V(x)$ of x . The map f is *continuous* iff it is both usc and lsc. Whenever the graph of f defined by $gr(f) = \{(x, y) \in X \times Y : y \in f(x)\}$ is a *closed (open)* set of $X \times Y$ one says that f has a closed (open) graph. Any multifunction having a closed graph is also called *closed*. If $f(x)$ is a closed (compact) subset of Y for any $x \in X$, then f is a *closed-valued (compact-valued)* map. The

set-valued map f is called *compact* if $im(f) = f(X) = \bigcup_{x \in X} f(x)$ is contained

in a compact subset of Y . A topological space is *acyclic* if all of its reduced Čech homology groups over rationals vanish (see for example, the contractible spaces; in particular, the convex sets and the star-shaped sets are acyclic). The multifunction f is *acyclic* if it is usc and $f(x)$ is non-empty, compact and acyclic for all $x \in X$. The next theorem is useful to establish the existence of the (approximate) efficient points taking into account the above mentioned connection with the fixed points of multifunctions.

Theorem 1. [50]. *If A is any non-empty convex subset of an arbitrary Hausdorff separated locally convex space and $F : A \rightarrow 2^A$ a compact acyclic multifunction, then F has a fixed point, that is, there exists $a_0 \in A$ such that $a_0 \in F(a_0)$.*

Remark 2. In [47] it was proved that whenever $K_1 \subset K \setminus \{0\}$, the existence of this new type of efficient points for bounded from below sets characterizes the semi - Archimedian ordered vector spaces and the regular ordered locally convex spaces.

Remark 3. When K is pointed, that is, $K \cap (-K) = \{0\}$, then $a_0 \in \text{eff}(A, K, K_1)$ means that $A \cap (a_0 - K - K_1) = \emptyset$ or, equivalently, $(K + K_1) \cap (a_0 - A) = \emptyset$ for $0 \notin K_1$ and $A \cap (a_0 - K - K_1) = \{a_0\}$, respectively, if $0 \in K_1$. Whenever $K_1 = \{0\}$, from Definition 1 one obtains the usual concept of *efficient (Pareto minimal, optimal or admissible) point*: $a_0 \in \text{eff}(A, K)$ (or $a_0 \in \text{MIN}_K(A)$) if it fulfils (i), (ii) or any of the next equivalent properties:

$$(iii) \quad (A+K) \cap (a_0 - K) \subseteq a_0 + K;$$

$$(iv) \quad K \cap (a_0 - A - K) \subseteq -K$$

These relations show that a_0 is a *fixed point* for at least one of the following *multifunctions*:

$$F_1 : A \rightarrow A, F_1(t) = \{\alpha \in A : A \cap (\alpha - K) \subseteq t + K\},$$

$$F_2 : A \rightarrow A, F_2(t) = \{\alpha \in A : A \cap (t - K) \subseteq \alpha + K\},$$

$$F_3 : A \rightarrow A, F_3(t) = \{\alpha \in A : (A + K) \cap (\alpha - K) \subseteq t + K\},$$

$$F_4 : A \rightarrow A, F_4(t) = \{\alpha \in A : (A + K) \cap (t - K) \subseteq \alpha + K\},$$

that is, $a_0 \in F_i(a_0)$ for some $i = \overline{1, 4}$. If, in addition, K is pointed, then $a_0 \in A$ is an efficient point of A with respect to K if and only if one of the following equivalent relations holds:

$$(v) \quad A \cap (a_0 - K) = \{a_0\};$$

$$(vi) \quad A \cap (a_0 - K \setminus \{0\}) = \emptyset;$$

$$(vii) \quad K \cap (a_0 - A) = \{0\};$$

$$(viii) \quad (K \setminus \{0\}) \cap (a_0 - A) = \emptyset;$$

$$(ix) \quad (A + K) \cap (a_0 - K \setminus \{0\}) = \emptyset.$$

and we notice that $\text{eff}(A, K) = \bigcap_{\{0\} \neq K_2 \subseteq K} \text{eff}(A, K, K_2)$.

Moreover, $a_0 \in \text{eff}(A, K)$ iff it is a critical (equilibrium) point ([29], [30], [60], [62]) for the generalized dynamical system $\Gamma : A \rightarrow 2^A$ defined by $\Gamma(a) = A \cap (a - K)$, $a \in A$. Thus, $\text{eff}(A, K)$ describes the moments of equilibrium for Γ and the *ideal equilibria* are contained in this set. Taking $K_1 = \{\varepsilon\}$ ($\varepsilon \in K \setminus \{0\}$), it follows that $a_0 \in \text{eff}(A, K, K_1)$ iff

$A \cap (a_0 - \varepsilon - K) = \emptyset$. In all these cases, the set $\text{eff}(A, K, K_1)$ is denoted by $\varepsilon - \text{eff}(A, K)$ and it is obvious that $\text{eff}(A, K) = \bigcap_{\varepsilon \in K \setminus \{0\}} [\varepsilon - \text{eff}(A, K)]$.

Concerning existence results on the efficient points and significant properties for the efficient points sets we refer the reader to [11], [29] – [35], [43], [44], [47], [48], [54] – [62], [70], [73], [74] for a survey. The following theorem offers the first immediate connection between the strong optimization and this kind of approximate efficiency, in the environment of the ordered vector spaces.

Theorem 2. [37]. *If we denote by $S(A, K, K_1) = \{a_1 \in A : A \subseteq a_1 + K + K_1\}$ and $S(A, K, K_1) \neq \emptyset$, then $S(A, K, K_1) = \text{eff}(A, K, K_1)$.*

Remark 4. We shall denote by $S(A, K)$ the set $S(A, K, \{0\})$. If $S(A, K, K_1) \neq \emptyset$, then $K + K_1 = K$, hence $\text{eff}(A, K, K_1) = \text{eff}(A, K)$. Indeed, let $a \in S(A, K, K_1)$. Then, $a \in a + K + K_1$ which implies that $0 \in K + K_1$. Therefore,

$$K \subseteq K_1 + K + K = K_1 + K \subseteq K.$$

The above theorem shows that, for any non-empty subset of an arbitrary vector space, the set of all strong minimal elements with respect to any convex cone through the agency of every non-noid subset of it coincides with the corresponding set of the efficient points, whenever there exists at least a strong minimal element. Obviously, the result remains valid for the strong maximal elements and the corresponding efficient points, respectively.

Using this conclusion and the abstract construction given in [53] and [57] for the splines in the H-locally convex spaces introduced in [65] as separated locally convex spaces $(X, P = \{p_\alpha : \alpha \in I\})$ with any seminorm p_α ($\alpha \in I$) satisfying the parallelogram law:

$$p_\alpha^2(x + y) + p_\alpha^2(x - y) = 2[p_\alpha^2(x) + p_\alpha^2(y)] \text{ whenever } x, y \in X,$$

linear topological spaces also studied in [41], it follows that the only best simultaneous and vectorial approximation for each element in the direct sum of any (closed) linear subspace and its orthogonal, with respect to any linear (continuous) operator between two arbitrary H-locally convex spaces, is its spline function. We also note that it is possible to have $S(A, K, K_1) = \emptyset$ and $\text{eff}(A, K, K_1) = A$. Thus, for example, if one considers $X = R^n$ ($n \in N, n \geq 2$) endowed with the separated H - locally convex topology

generated by the semi - norms $p_i : X \rightarrow R_+$, $p_i(x) = |x_i|$, $\forall x = (x_i) \in X$, $i = \overline{1, n}$, $K = R_+^n$, $K_1 = \{(0, \dots, 0)\}$ and for each real number c we define

$$A_c = \left\{ (x_i) \in X : \sum_{i=1}^n x_i = c \right\}, \text{ then it is clear that } S(A_c, K, K_1) \text{ is empty and}$$

$$\text{eff}(A_c, K, K_1) = A_c.$$

At the same time, in the usual real linear space of all sequences, ordered by the convex cone $K = \{(x_n) : n \in N^*, n \geq 2, x_n \geq 0, \forall n \geq 2\}$, for

$$A = \{(x_{n\alpha}) : n \in N^*, n \geq 2, \alpha > 0\} \text{ with}$$

$$x_{n\alpha} = (n-1)^{-\alpha} - n^{-\alpha}, n \in N^*, n \geq 2, \alpha > 0 \text{ and } K_1 = \{(0, 0, \dots)\} \text{ we have}$$

$$\text{Eff}(A, K, K_1) = S(A, K, K_1) = \emptyset.$$

In all our further considerations we suppose that X is a *Hausdorff Locally Convex Space* having the topology induced by a family $P = \{p_\alpha : \alpha \in I\}$ of semi-norms, ordered by a convex cone K and its topological dual space X^* . In this framework, the next theorem contains a significant criterion for the existence of the approximate efficient points, in particular, for the usual efficient points, taking into account that the dual cone of K is defined by $K^* = \{x^* \in X^* : x^*(x) \geq 0, \forall x \in K\}$ and its attached polar cone is $K^0 = -K^*$. The cone K is called *supernormal (nuclear)* [29], [30] if for every seminorm $p_\alpha \in P$ there exists $f_\alpha \in X^*$ such that $p_\alpha(k) \leq f_\alpha(k)$ for all $k \in K$. Moreover, if $\varphi : P \rightarrow K^*$ is a function, then the convex cone $K_\varphi = \{x \in X : p_\alpha(x) \leq \varphi(p_\alpha)(x), \forall p_\alpha \in P\}$ is the *full nuclear cone* associated to K , P and φ [35]. A characterization of the supernormality by the full nuclearity is given in the next Remark 7.

Theorem 3. [37]. *If A is any non-empty subset of X and K_1 is every non-void subset of K , then $a_0 \in \text{eff}(A, K, K_1)$ whenever for each $p_\alpha \in P$ and $\eta \in (0, 1)$ there exists x^* in the polar cone K^0 of K such that $p_\alpha(a_0 - a) \leq x^*(a_0 - a) + \eta, \forall a \in A$.*

Remark 5. The above theorem represents an immediate extension of Proposition 1.2 in [66]. Generally, the converse of this theorem is not valid at least in partially ordered separated locally convex spaces as we can see from the example considered in Remark 4. Indeed, if one assumes the contrary in

the corresponding mathematical background then, taking $\eta = \frac{1}{4}$, it follows that for each $\lambda_0 \in [0, 1]$, there exists $c_1, c_2 \leq 0$ such that $|\lambda_0 - \lambda| \leq (c_1 - c_2)(\lambda_0 - \lambda) + \frac{1}{4}, \forall \lambda \in [0, 1]$.

Taking $\lambda_0 = \frac{1}{4}$ one obtains $|1 - 4\lambda| \leq (c_1 - c_2)(1 - 4\lambda) + 1, \forall \lambda \in [0, 1]$ which for $\lambda = 0$ implies that $c_2 \leq c_1$ and for $\lambda = \frac{1}{2}$ leads to $c_1 \leq c_2$, that is, $|1 - 4\lambda| \leq 1, \forall \lambda \in [0, 1]$, a contradiction.

Remark 6. If $a_0 \in A$ and for every $p_\alpha \in P, \eta \in (0, 1)$ there exists $x^* \in K^0$ such that $p_\alpha(a_0 - a) \leq x^*(a_0 - a) + \eta, \forall a \in A$, then $K \cap (a_0 - A) = \{0\}$ even if K is not pointed. Indeed, if $x \in K \cap (a_0 - A)$, then $a_0 - x \in A$ and for each $p_\alpha \in P$ and $\eta \in (0, 1)$ there exists $x^* \in K^0$ with $p_\alpha(x) = p_\alpha(a_0 - (a_0 - x)) \leq x^*(x) + \eta \leq \eta$. Because η is arbitrarily chosen in $(0, 1)$, we obtain $p_\alpha(x) = 0$ and since X is separated it follows that $x = 0$. If $0 \in K + K_1$, then $K + K_1 = K$ and $0 \notin K + K_1$ implies that $(K + K_1) \cap (a_0 - A) = \emptyset$. Consequently, $a_0 \in \text{eff}(A, K, K_1)$ in both cases and in this way we indicated also another proof of the theorem. The beginning and the considerations in Section 4 of [35] suggested us to consider for each function $\varphi: P \rightarrow K^* \setminus \{0\}$ the full nuclear cone $K_\varphi = \{x \in X : p_\alpha(x) \leq \varphi(p_\alpha)(x), \forall p_\alpha \in P\}$ in order to give the next generalization of Theorem 7 indicated in [35].

Theorem 4. [37]. If $0 \in K_1$ and there exists $\varphi: P \rightarrow K^* \setminus \{0\}$ with $K \subseteq K_\varphi$, then

$$\text{eff}(A, K, K_1) = \bigcup_{\substack{a \in A \\ \varphi \in P \rightarrow K^* \setminus \{0\}}} S(A \cap (a - K - K_1), K_\varphi)$$

for any non-empty subset K_1 of K .

Remark 7. If $0 \notin K_1$, then $a_0 \in \text{eff}(A, K, K_1)$ implies that $A \cap (a_0 - K - K_1) = \emptyset$. Therefore, it is not possible to have $a_0 \in S(\emptyset, K_\varphi)$. In case of $0 \in K_1$, then $\text{eff}(A, K, K_1) = \text{eff}(A, K)$ and $a_0 \in \text{eff}(A, K)$ iff $A \cap (a_0 - K) = \{a_0\}$, so in the right member of the first proved inclusion it can be selected any convex

cone, not necessary K_φ . The hypothesis $K \subseteq K_\varphi$ imposed upon the convex cone K is automatically satisfied whenever K is an *Isac's (nuclear or supernormal) cone* ([29] – [33], [35]) and it was used only to prove the inclusion

$$\text{eff}(A, K, K_1) \subseteq \bigcup_{\substack{a \in A \\ \varphi: P \rightarrow K^* \setminus \{0\}}} S(A \cap (a - K - K_1), K_\varphi).$$

Moreover, K is an Isac's cone if and only if there exists $\varphi : P \rightarrow K^* \setminus \{0\}$ such that $K \subseteq K_\varphi$. Indeed, Lemma 5 of [35] ensures the necessity of the above inclusion condition. Conversely, since for every seminorm $p_\alpha \in P$ there exists $\varphi(p_\alpha) \in K^* \setminus \{0\}$ and for any $x \in K \subseteq K_\varphi$ it follows that $p_\alpha(x) \leq \varphi(p_\alpha)(x)$, we conclude the nuclearity of K . When K is an arbitrary pointed convex cone, A is a non-empty subset of X and $a_0 \in \text{eff}(A, K)$, then, by virtue of (v) in Remark 3, we have $A \cap (a_0 - K) = \{a_0\}$, that is, $A \cap (a_0 - K) - a_0 = \{0\} \subset K_\varphi$. Hence, $a_0 \in S(A \cap (a_0 - K), K_\varphi)$ for every mapping $\varphi : P \rightarrow K^* \setminus \{0\}$ and the next corollary is valid.

Corollary 4.1. *For every non-empty subset A of any Hausdorff locally convex space ordered by an arbitrary, pointed convex cone K with its dual cone K^* we have*

$$\text{eff}(A, K) = \bigcup_{\substack{a \in A \\ \varphi: P \rightarrow K^* \setminus \{0\}}} S(A \cap (a - K), K_\varphi)$$

Remark 8. The hypothesis of Theorem 3 together with Lemma 3 of [35] involves K to be pointed. Consequently, $0 \in K_1$ iff $0 \in K + K_1$. If $a_0 \in S(A \cap (a - K - K_1), K_\varphi)$ for some $\varphi : P \rightarrow K^*$ and $a \in A$ with $a_0 = a - k - k_1$, $k \in K$, $k_1 \in K_1$, then $K \cap (a_0 - A) = \{0\}$ because $A \cap (a - K - K_1) \subseteq a_0 + K_\varphi$ in any such a case as this. Indeed, let $x \in K \cap (a_0 - A)$ be an arbitrary element. Then, $a_0 - x \in A$ and $a_0 - x = a - k - k_1 - x \in a - K - K_1$. Therefore, $a_0 - x \in a_0 + K_\varphi$, that is, $x \in K_\varphi$. For every $p_\alpha \in P$ we have $p_\alpha(-x) \leq \varphi(p_\alpha)(-x) = -\varphi(p_\alpha)(x) \leq 0$. Since p_α was arbitrary chosen in P and X is a Hausdorff locally convex space, it follows that $x = 0$.

Remark 9. Clearly, the announced theorem represents a significant result concerning the possibilities of scalarization for the study of some Pareto efficiency programs in separated locally convex spaces, as we can see also in

the final comments of [35] for the particular cases of Hausdorff locally convex spaces ordered by closed, pointed and normal cones.

Remark 10. As an open problem, it is interesting to replace K_1 with any non-empty subset of an ordered linear space X , under proper hypotheses.

Remark 11. It is well known that the Choquet boundary represents a basic concept in the axiomatic theory of potential and its applications and the efficiency is a fundamental notion in vector optimization. The main aim of the last part in this section is to indicate the recent generalization of our coincidence result established in [11] between the set of all Pareto type minimum points of any non-empty, compact set in an ordered Hausdorff locally convex space and the Choquet boundary of the same set with respect to the convex cone of all real, increasing and continuous functions defined on the set, using our new concept of approximate efficiency. Following this line, firstly the Choquet boundary concept is revised in an original manner.

Let us consider an arbitrary Hausdorff locally space (E, τ) , where τ denotes its topology and let K be any closed, convex, pointed cone in E . The usual order relation \leq_K associated with K is defined by $x \leq_K y$ ($x, y \in E$) if there exists $k \in K$ with $y = x + k$. Clearly, this order relation on E is closed, that is, the set G_K given by $G_K = \{(x, y) \in E \times E : x \leq_K y\}$ is a closed subset of $E \times E$ endowed with the induced product topology. If S is any convex cone satisfying the properties:

- a) $\forall x \in X, \exists s \in S, s > 0$ and $s(x) < +\infty$;
- b) S linearly separates $X_1 = \{x \in X : \exists s \in S \text{ with } s(x) < 0\}$, that is, for every $x, y \in X_1, x \neq y$, there exists $s, t \in S$ with real values in x and y such that $s(x)t(y) \neq s(y)t(x)$, then, on the set $M_+(X)$ of all positive Radon measures defined on X , one associates the following natural pre-order relation: if $\mu, \nu \in M_+(X)$, then $\mu \leq_S \nu$ means that $\mu(s) \leq \nu(s)$ for all $s \in S$.

Let S_1 be the convex cone of all lower semicontinuous and bounded from below real functions s on X having the next property: if $x \in X$ and $\mu \leq_S \varepsilon_x$, where $\varepsilon_x(f) = f(x)$ for every real continuous function f on X denotes the Dirac measure, implies that $\mu(s) \leq s(x)$. Any non-empty subset $T \subseteq X$ will be called S -boundary if, whenever $s \in S_1$ and its restriction on T denoted by $s|_T$ is positive, it follows that $s \geq 0$. The smallest, closed S -boundary is usually called *the Silov boundary of X with respect to S* . A closed set $A \subseteq X$ is called S -absorbent if $x \in A$ and $\mu \leq_S \varepsilon_x$ implies that $\mu(X \setminus A) = 0$. The set

$\partial_S X = \{x \in X_1 : \{x\} \text{ is } S\text{-absorbent}\}$ is named *the Choquet boundary of X with respect to S* and clearly its closure coincides with *the Silov boundary* of X with respect to S . The trace on $\partial_S X$ of the topology on X in which the closed sets coincide with X or with any of the S -absorbent subsets of X contained in X_1 is usually called *the Choquet topology of $\partial_S X$* .

Definition 2. A real function $f : X \rightarrow R$ is called $(K + K_1)$ -increasing if $f(x_1) \geq f(x_2)$ whenever $x_1, x_2 \in X$ and $x_1 \in x_2 + K_1 + K$.

It is obvious that every real increasing function defined on any linear space ordered by an arbitrary convex cone K is $K + K_1$ -increasing, for each non-empty subset K_1 of K .

Now, we present the coincidence of the approximate efficient points sets and the Choquet boundaries, which generalizes the main results given in [11] and [60], respectively, and can not be obtained as a consequence of the Axiomatic Potential Theory.

Theorem 5. [63]. If A is any non-void, compact subset of X and

(i) K is an arbitrary, closed, convex, pointed cone in X ;

(ii) K_1 is a non-empty subset of K such that $K + K_1$ is closed with respect to the Hausdorff separated locally convex topology on X .

Then, $\text{eff}(A, K, K_1)$ coincides with the Choquet boundary of A with respect to the convex cone S_1 of all $K + K_1$ -increasing real continuous functions on A . Consequently, the set $\text{eff}(A, K, K_1)$ endowed with the corresponding trace topology is a Baire space and, if (A, τ_A) is metrizable, then $\text{eff}(A, K, K_1)$ is a G_δ -subset of X .

Corollary 5.1.

(i)

$\text{eff}(A, K, K_1) = \{a \in A : f(a) = \sup\{f(a') : a' \in A \cap (a - K - K_1)\} \text{ for all } f \in C(A)\}$;

(ii) $\text{eff}(A, K, K_1)$ and $\text{eff}(A, K, K_1) \cap \{a \in A : s(a) \leq 0\}$ ($s \in S$) are compact sets with

respect to Choquet's topology;

(iii) $\text{eff}(A, K, K_1)$ is a compact subset of A .

Corollary 5.2. Under the hypotheses of the above theorem we proved that

$\text{eff}(A, K, K_1) = \{a \in A : f(a) = \bar{f}(a), \forall f \in C(A)\} = \partial_{S_1} A = \{a \in A : a \in F(a)\}$

where $F : A \rightarrow A$ is the multifunction defined by

$$F(t) = \{a \in A : A \cap (a - K - K_1) \subseteq t + K + K_1\}, \forall t \in A.$$

Remark 12.

In general, $\text{eff}(A, K, K_1)$ coincides with the Choquet boundary of A only with respect to the convex cone of all real, continuous and $K + K_1$ -increasing functions on A . Thus, for example, if A is a non-empty, compact and convex subset of X , then the Choquet boundary of A with respect to the convex cone of all real, continuous and concave functions on A coincides with the set of all extreme points for A . But, it is easy to see that, even in finite dimensional cases, an extreme point for a compact convex set is not necessary an efficient point and conversely.

Remark 13.

As we have already specified before Theorem 1, there exists more general conditions than compactness imposed upon a non-empty set A in a separated locally convex space ordered by a convex cone K ensuring that $\text{eff}(A, K) \neq \emptyset$. Perhaps our coincidence result suggests a natural extension of the Choquet boundary at least in these cases. Anyhow, Theorem 4 represents an important link between vector optimization and potential theory and a new way for the study of the properties of efficient points sets and the Choquet boundaries. Indeed, one of the main question in potential theory is to find the Choquet boundaries.

This fact is relatively easy for particular cases but, in general, it is an unsolved problem. Since in a lot of cases the efficient points sets contain dense subsets which can be identified by adequate optimization methods, it is possible to determine the corresponding Choquet boundaries in all these situations. In this direction of study, an important role is attributed to the density properties of the efficient points sets with respect to varied topologies. Consequently, our coincidence result has its practical consequences at first for the axiomatic theory of potential and its applications. At the same time, by the above coincidence result, the Choquet boundaries offer important properties for the efficient points sets.

In this way, the above coincidence result establishes a strong relationship between the approximate (in particular, strong) solutions for vector optimization programs in separated, ordered topological vector spaces and Choquet's boundaries of non-empty compact sets.

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