Quasi-Arithmetic Type Mean Generated by the Generalized Choquet Integral

Sebastian Wójcik
Institute of Mathematics, University of Rzeszów, Pigonia 1, 35-959 Rzeszów, Poland; swojcik@ur.edu.pl

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Abstract: It is known that the quasi-arithmetic means can be characterized in various ways, with an essential role of a symmetry property. In the expected utility theory, the quasi-arithmetic mean is called the certainty equivalent and it is applied, e.g., in a utility-based insurance contracts pricing. In this paper, we introduce and study the quasi-arithmetic type mean in a more general setting, namely with the expected value being replaced by the generalized Choquet integral. We show that a functional that is defined in this way is a mean. Furthermore, we characterize the equality, positive homogeneity, and translativity in this class of means.

Keywords: quasi-arithmetic mean; Choquet integral; positive homogeneity; translativity; certainty equivalent

MSC: 39B22; 91B30

1. Introduction

The notion of quasi-arithmetic mean, playing an important role in several branches of mathematics and its applications, was introduced in the book by Hardy, Littlewood, and Pólya [1]. Recall that, if \( I \subseteq \mathbb{R} \) is an interval and \( u : I \to \mathbb{R} \) is a strictly monotone continuous function, then the quasi-arithmetic mean \( M_u : \bigcup_{n \in \mathbb{N}} I^n \to I \), which is generated by \( u \), is given by

\[
M_u(x) = u^{-1}\left(\frac{1}{n} \sum_{i=1}^{n} u(x_i)\right)
\]

for \( x = (x_1, \ldots, x_n) \in I^n, \ n \in \mathbb{N} \).

Various axiomatic characterizations of the quasi-arithmetic mean have been independently established by de Finetti [2], Kolmogorov [3], and Nagumo [4]. For these characterizations, the symmetry property of the mean is essential. Quasi-arithmetic means have been generalized in several directions. In particular, Bajraktarević [5] introduced quasi-arithmetic means that were weighted by a weight function. Bajraktarević means were characterized by Páles [6]. A further generalization of the quasi-arithmetic means has been developed by Daróczy [7,8], who introduced deviation means.

The notion of the quasi-arithmetic mean can be considered in more general settings. In particular, if \( X : S \to \mathbb{R} \) is an \( \mathcal{F} \)-measurable essentially bounded function on a given probability space \( (S, \mathcal{F}, P) \), then the quasi-arithmetic mean of \( X \), generated by a strictly monotone continuous function \( u : \mathbb{R} \to \mathbb{R} \), is defined as follows

\[
M_{(u,P)}(X) = u^{-1}\left(\mathbb{E}_P[u(X)]\right), \quad (1)
\]

where \( \mathbb{E}_P \) denotes the expected value with respect to \( P \).

In the expected utility theory developed by von Neumann and Morgenstern [9], the quasi-arithmetic mean, as given by (1), is known as the certainty equivalent. It establishes a symmetry in preferences between a risk that is represented by \( X \) and a deterministic payoff \( M_{(u,P)}(X) \), in a
sense that a decision maker is indifferent between taking the risk $X$ and receiving $M_{(u,P)}(X)$ for sure. Quasi-arithmetic means are also applied in a utility-based insurance contracts pricing. In this setting, the quasi-arithmetic mean that is defined by (1) is called the mean-value premium. It expresses a premium principle from a client’s point of view for a risk represented by $X$.

Replacing, in (1), the probability measure $P$ by a capacity $\mu$, that is a monotone normed set function defined on measurable space $(S, \mathcal{F})$, we obtain

$$M_{(u,\mu)}(X) = u^{-1}(\mathbb{E}_\mu[u(X)]) ,$$  \hfill (2)

where $\mathbb{E}_\mu$ is the Choquet integral with respect to $\mu$ (see Section 2). It turns out that, for any $\mathcal{F}$-measurable function $X : S \rightarrow \mathbb{R}$, $\mu$-essentially bounded from below, and $\mu$-essentially bounded from above $M_{(u,\mu)}(X)$ is a well-defined mean (see Sections 2 and 3 for details). The functional $M_{(u,\mu,v)}$, as given by (2), refers to the certainty equivalent under the model of Schmeidler [10]. Some particular cases of $M_{(u,\mu)}$ have been investigated in [11]. Inspired by the results in [11], in this paper, we study the properties of the functional

$$M_{(u,\mu,v)}(X) = u^{-1}(\mathbb{E}_{\mu,v}[u(X)]) ,$$ \hfill (3)

defined on a family of all $\mathcal{F}$-measurable functions $X : S \rightarrow \mathbb{R}$, which are $v$-essentially bounded from below and $\mu$-essentially bounded from above. Here $\mathbb{E}_{\mu,v}$ stands for the generalized Choquet integral with respect to capacities $\mu$ and $v$ on $(S, \mathcal{F})$. We show that $M_{(u,\mu,v)}$ is well-defined and it is a mean, which is

$$\inf X \leq M_{(u,\mu,v)}(X) \leq \sup X .$$ \hfill (4)

Furthermore, we establish the characterizations of the equality, positive homogeneity, and translativity in the class of means defined by (3). In the whole paper $(S, \mathcal{F})$ stands for a measurable space.

2. Generalized Choquet Integral

A set function $\mu : \mathcal{F} \rightarrow [0, 1]$ is called the capacity on $(S, \mathcal{F})$ provided that it satisfies the following conditions:

1. $\mu(\emptyset) = 0$,
2. $\mu(S) = 1$, and
3. if $A, B \in \mathcal{F}$ and $A \subset B$, then $\mu(A) \leq \mu(B)$.

Obviously, every probability measure on $(S, \mathcal{F})$ is a capacity on $(S, \mathcal{F})$. Furthermore, simple calculations show that, if $\mu$ is a capacity on $(S, \mathcal{F})$, then so is the set function $\bar{\mu}$ of the form

$$\bar{\mu}(A) = 1 - \mu(S \setminus A) \text{ for } A \in \mathcal{F}. \hfill (5)$$

It is called the conjugation of $\mu$.

If $\mu$ is a capacity on $(S, \mathcal{F})$, then an $\mathcal{F}$-measurable function $X : S \rightarrow \mathbb{R}$ is called $\mu$-essentially bounded from above provided that there exists $t \in \mathbb{R}$, such that $\mu(\{s \in S : X(s) > t\}) = 0$. In such a case the $\mu$-essential supremum of $X$ is defined in the following way

$$\mu - \text{ess sup } X := \inf\{t \in \mathbb{R} : \mu(\{s \in S : X(s) > t\}) = 0\}.$$

An $\mathcal{F}$-measurable function $X : S \rightarrow \mathbb{R}$ is said to be a $\mu$-essentially bounded from below if there exists $t \in \mathbb{R}$, such that $\mu(\{s \in S : X(s) < t\}) = 0$. In that case,

$$\mu - \text{ess inf } X := \sup\{t \in \mathbb{R} : \mu(\{s \in S : X(s) < t\}) = 0\}$$

is called the $\mu$-essential infimum of $X$. 

Remark 1. Assume that \( \mu \) is a capacity on \( (S, F) \) and \( X : S \to \mathbb{R} \) is an \( F \)-measurable function. Note that:

- if \( X \) is \( \mu \)-essentially bounded from above, then \( -\infty \leq \mu - \text{ess sup } X < \infty \);
- if \( X \) is \( \mu \)-essentially bounded from below then \( -\infty < \mu - \text{ess inf } X \leq \infty \).

The following example shows that, in general, \( \mu - \text{ess sup } X \) and \( \mu - \text{ess inf } X \) need not be finite.

Example 1. Let \( (S, F) = (\mathbb{R}, 2^{\mathbb{R}}) \) and \( \mu : F \to [0, 1] \) be given by

\[
\mu(A) = \begin{cases} 
0 & \text{for } A \neq S, \\
1 & \text{for } A = S.
\end{cases}
\] (6)

Obviously, \( \mu \) is a capacity on \((S, F)\). Furthermore, \( X = id_{\mathbb{R}} \) is \( F \)-measurable and, for every \( t \in \mathbb{R} \), we have

\[
\mu(\{s \in \mathbb{R} : X(s) > t\}) = \mu((t, \infty)) = 0 \text{ and } \mu(\{s \in \mathbb{R} : X(s) < t\}) = \mu((-\infty, t)) = 0.
\]

Hence, \( X \) is \( \mu \)-essentially bounded, but \( \mu - \text{ess sup } X = -\infty \) and \( \mu - \text{ess inf } X = \infty \).

Lemma 1. Assume that \( \mu \) is a capacity on \((S, F)\) and \( X : S \to \mathbb{R} \) is an \( F \)-measurable function \( \mu \)-essentially bounded from above and \( \mu \)-essentially bounded from below. Then \( \mu - \text{ess inf } X \) and \( \mu - \text{ess sup } X \) are finite and

\[
\mu - \text{ess inf } X \leq \mu - \text{ess sup } X.
\] (7)

Proof. Suppose that

\[
\mu - \text{ess sup } X < \mu - \text{ess inf } X
\]

and fix \( t_1, t_2 \in \mathbb{R} \) such that

\[
\mu - \text{ess sup } X < t_1 < t_2 < \mu - \text{ess inf } X.
\]

Then

\[
1 = \mu(\{X > t_1\}) + \mu(\{X \leq t_1\}) \leq \mu(\{X > t_1\}) + \mu(\{X < t_2\}) = 0
\]

which yields a contradiction. \( \Box \)

Remark 2. Assume that \( X : S \to \mathbb{R} \) is an \( F \)-measurable function. Subsequently, for every capacity \( \mu \) on 

\( (S, F) \), we have

\[
\mu(\{X < \text{inf } X\}) = \mu(\{X > \text{sup } X\}) = \mu(\emptyset) = 0 \text{ and } \mu(\{X \leq \text{sup } X\}) = \mu(\{X \geq \text{inf } X\}) = \mu(S) = 1.
\]

Therefore:

(i) if \( X \) is bounded from below (above) then \( X \) is \( \mu \)-essentially bounded from below (above) for every capacity \( \mu \) on \((S, F)\); and,

(ii) if, for some capacity \( \mu \) on \((S, F)\), \( X \) is \( \mu \)-essentially bounded from below then

\[
\text{inf } X \leq \mu - \text{ess inf } X \leq \text{sup } X;
\] (8)

(iii) if, for some capacity \( \mu \) on \((S, F)\), \( X \) is \( \mu \)-essentially bounded from above, then

\[
\text{inf } X \leq \mu - \text{ess sup } X \leq \text{sup } X.
\] (9)

In what follows, for a given strictly increasing function \( u : \mathbb{R} \to \mathbb{R} \), we adopt the standard convention \( u(-\infty) := \lim_{x \to -\infty} u(x) \) and \( u(\infty) := \lim_{x \to \infty} u(x) \).

Lemma 2. Assume that \( \mu \) is a capacity on \((S, F)\) and \( u : \mathbb{R} \to \mathbb{R} \) is a strictly increasing continuous function.

(i) If \( X : S \to \mathbb{R} \) is an \( F \)-measurable function \( \mu \)-essentially bounded from above, then so is \( u \circ X \). Furthermore,

\[
\mu - \text{ess sup } u \circ X = u(\mu - \text{ess sup } X).
\]
(ii) If \( X : S \to \mathbb{R} \) is an \( \mathcal{F} \)-measurable function \( \mu \)-essentially bounded from below, then so is \( u \circ X \). Moreover,
\[
\mu - \text{ess inf} \ u \circ X = u(\mu - \text{ess inf} \ X).
\]

**Proof.** Let \( X : S \to \mathbb{R} \) be an \( \mathcal{F} \)-measurable function \( \mu \)-essentially bounded from above. Because \( u \) is continuous, \( u \circ X \) is \( \mathcal{F} \)-measurable. Moreover, as \( u \) is strictly increasing, we have
\[
\mu(\{u \circ X > u(t)\}) = \mu(\{X > t\}) \quad \text{for } t \in \mathbb{R}.
\]
Therefore, because \( X \) is \( \mu \)-essentially bounded from above, so is \( u \circ X \). We show that
\[
\mu - \text{ess sup} \ u \circ X \leq u(\mu - \text{ess sup} \ X). \tag{10}
\]
Suppose that \( \text{(10)} \) does not hold and fix \( t \in \mathbb{R} \), such that
\[
u(\mu - \text{ess sup} \ X) < t < \mu - \text{ess sup} \ u \circ X.
\]
Thus, \( \mu(\{u \circ X > t\}) > 0 \), hence \( t < u(\infty) \). Consequently \( t = u(s) \) for some \( s \in \mathbb{R} \) and so, we obtain
\[
\mu(\{X > s\}) = \mu(\{u \circ X > u(s)\}) = \mu(\{u \circ X > t\}) > 0.
\]
Hence, \( s \leq \mu - \text{ess sup} \ X \), that is \( t = u(s) \leq u(\mu - \text{ess sup} \ X) \), which yields a contradiction and proves \( \text{(10)} \). Now, we prove that
\[
u(\mu - \text{ess sup} \ X) \leq \mu - \text{ess sup} \ u \circ X. \tag{11}
\]
Suppose that \( \text{(11)} \) is not true and fix \( t \in \mathbb{R} \), such that
\[
u(\mu - \text{ess sup} \ u \circ X) < t < \mu - \text{ess sup} \ u \circ X.
\]
Subsequently, \( \mu(\{u \circ X > t\}) = 0 \), which implies that \( t > u(-\infty) \). Hence, \( t = u(s) \) for some \( s \in \mathbb{R} \) and we obtain
\[
\mu(\{X > s\}) = \mu(\{u \circ X > u(s)\}) = \mu(\{u \circ X > t\}) = 0,
\]
that is \( s \geq \mu - \text{ess sup} \ X \). Thus \( t = u(s) \geq u(\mu - \text{ess sup} \ X) \), which gives a contradiction and proves \( \text{(11)} \). In this way, we have proved (i). A proof of (ii) is similar. \( \square \)

If \( \mu \) is a capacity on \((S, \mathcal{F})\) and \( X : S \to \mathbb{R} \) is an \( \mathcal{F} \)-measurable function \( \mu \)-essentially bounded from above and \( \bar{\mu} \)-essentially bounded from below, then the Choquet integral of \( X \) is defined in the following way (cf. \[12\])
\[
E_{\mu}[X] := \int_{0}^{\infty} \mu(\{X > x\})dx - \int_{-\infty}^{0} \bar{\mu}(\{X < x\})dx, \tag{12}
\]
where the integrals on the right-hand side of \( \text{(12)} \) are the Riemann integrals. Note that both of the integrals on the right-hand side of \( \text{(12)} \) are finite. Several details concerning various properties of Choquet integral can be found in \[13\]. In particular, in \[13\] (Proposition 5.1), it is proved that the Choquet integral is positively homogeneous, translatable, and monotonic. Moreover, it is asymmetric, which is, for every \( \mathcal{F} \)-measurable function \( X : S \to \mathbb{R} \) \( \mu \)-essentially bounded from above and \( \bar{\mu} \)-essentially bounded from below, it holds
\[
E_{\mu}[-X] = -E_{\bar{\mu}}[X]. \tag{13}
\]
Remark 3. Note that, for all capacities \( \mu \) and \( \nu \) on \( (S, \mathcal{F}) \) and any \( \mathcal{F} \)-measurable function \( X : S \to \mathbb{R} \) \( \mu \)-essentially bounded from above and \( \nu \)-essentially bounded from below, we have
\[
E^\mu[X^+] = \int_0^\infty \mu(\{X^+ > x\}) dx = \int_0^\infty \mu(\{X > x\}) dx
\]
and
\[
E^\nu[X^-] = \int_0^\infty \nu(\{X^- > x\}) dx = \int_0^\infty \nu(\{-X > x\}) dx = \int_{-\infty}^0 \nu(\{X < x\}) dx.
\]
In particular, taking \( \nu = \bar{\mu} \), in view of (12), we obtain
\[
E^\mu[X] = E^\mu[X^+] - E^\mu[X^-].
\]

Proposition 1. Assume that \( \mu \) is a capacity on \( (S, \mathcal{F}) \). Subsequently, for every \( \mathcal{F} \)-measurable function \( X : S \to \mathbb{R} \) \( \mu \)-essentially bounded from above and \( \bar{\mu} \)-essentially bounded from below, it holds
\[
\bar{\mu} - \text{ess inf } X \leq E^\mu[X] \leq \mu - \text{ess sup } X. \quad (17)
\]

Proof. Assume that \( X : S \to \mathbb{R} \) is an \( \mathcal{F} \)-measurable function \( \mu \)-essentially bounded from above and \( \bar{\mu} \)-essentially bounded from below and put \( m = \bar{\mu} - \text{ess inf } X \) and \( M = \mu - \text{ess sup } X. \) Subsequently, \( \bar{\mu}(\{X < x\}) = 0 \) for \( x \in (-\infty, m) \) and \( \mu(\{X > x\}) = 0 \) for \( x \in (M, \infty). \) Furthermore, from Corollary 1, we derive that \( m \) and \( M \) are finite and \( m \leq M. \) Therefore, the following three cases are possible:

(i) \( 0 \leq m \leq M, \)

(ii) \( m \leq M \leq 0, \)

(iii) \( m < 0 < M. \)

In the first case, using the monotonicity of \( \mu, \) for every \( x \in (-\infty, m), \) we get
\[
\mu(\{X > x\}) \geq \mu\left(\left\{ X \geq \frac{x + m}{2} \right\}\right) = 1 - \bar{\mu}\left(\left\{ X < \frac{x + m}{2} \right\}\right) = 1.
\]
Hence
\[
m = \int_0^m \mu(\{X > x\}) dx \leq \int_0^M \mu(\{X > x\}) dx \leq M.
\]
On the other hand, applying Remark 3 with \( \nu = \bar{\mu}, \) we obtain
\[
E^\mu[X] = \int_0^\infty \mu(\{X > x\}) dx - \int_0^0 \bar{\mu}(\{X < x\}) dx = \int_0^M \mu(\{X > x\}) dx.
\]
Therefore, (17) holds.

In the second case, for every \( x \in (M, \infty), \) we obtain
\[
\bar{\mu}(\{X < x\}) \geq \bar{\mu}\left(\left\{ X \leq \frac{x + M}{2} \right\}\right) = 1 - \mu\left(\left\{ X > \frac{x + M}{2} \right\}\right) = 1,
\]
that is
\[
m \leq -\int_m^0 \bar{\mu}(\{X < x\}) dx \leq -\int_m^M \bar{\mu}(\{X < x\}) dx = M.
\]
Furthermore, while taking Remark 3 with \( \nu = \bar{\mu} \) into account, we conclude that
\[
E^\mu[X] = \int_0^\infty \mu(\{X > x\}) dx - \int_0^m \bar{\mu}(\{X < x\}) dx = -\int_m^0 \bar{\mu}(\{X < x\}) dx.
\]
Hence, (17) is valid.
In the third case, while using the monotonicity of Choquet integral, in view of Remark 3, we get
\[ m \leq - \int_0^0 \mu(\{X < x\})dx = - \int_0^0 \mu(\{X < x\})dx \leq E_\mu[X] \]
\[ \leq \int_0^M \mu(\{X > x\})dx = \int_0^M \mu(\{X > x\})dx \leq M, \]
which yields the assertion. □

Now, assume that \( \mu \) and \( \nu \) are capacities on \((S, \mathcal{F})\) and \( X : S \to \mathbb{R} \) is an \( \mathcal{F} \)-measurable \( \mu \)-essentially bounded from above and \( \nu \)-essentially bounded from below function. The generalized Choquet integral of \( X \) is given by
\[ E_{\mu\nu}[X] := E_\mu[X^+] - E_\nu[X^-], \tag{18} \]
where \( X^+ \) and \( X^- \) denote the positive and negative part of \( X \), respectively, which is \( X^+ := \max\{X, 0\} \) and \( X^- := \max\{-X, 0\} \). Note that \( X^+ \) and \( X^- \) are \( \mathcal{F} \)-measurable, \( X^+ \) is \( \mu \)-essentially bounded from above and \( \mu \)-essentially bounded from below (cf. Remark 2 (i)), while \( X^- \) is \( \nu \)-essentially bounded from below \( \nu \)-essentially bounded from above. Thus, the generalized Choquet integral is well-defined by (18). Generalized Choquet integral was introduced in [14] for discrete random variables.

**Remark 4.** It follows from (16)–(18) that
\[ E_{\mu}\mu[X] = E_\mu[X] \tag{19} \]
for \( \mathcal{F} \)-measurable function \( X : S \to \mathbb{R} \) \( \mu \)-essentially bounded from above and \( \mu \)-essentially bounded from below. Hence, the Choquet integral is a particular case of the generalized Choquet integral. Another important particular case of the generalized Choquet integral is the Šipoš integral, which refers to case \( \mu = \nu \).

**Remark 5.** Because the Choquet integral is positively homogeneous and monotonic, so is the generalized Choquet integral. Moreover, in view of (13), for every capacities \( \mu \) and \( \nu \) on \((S, \mathcal{F})\) \( \mathcal{F} \)-measurable function \( X : S \to \mathbb{R} \) \( \mu \)-essentially bounded from above and \( \nu \)-essentially bounded from below, we obtain
\[ E_{\mu\nu}[-X] = -E_{\nu\mu}[X]. \tag{20} \]

**Remark 6.** Assume that \( \mu \) and \( \nu \) are capacities on \((S, \mathcal{F})\) and \( X : S \to \mathbb{R} \) is an \( \mathcal{F} \)-measurable function \( \mu \)-essentially bounded from above and \( \nu \)-essentially bounded from below. Let \( m = \nu - \text{ess inf} X \) and \( M = \mu - \text{ess sup} X \). Subsequently, \( \mu(\{X > x\}) = 0 \) for \( x \in (M, \infty) \) and \( \mu(\{X < x\}) = 0 \) for \( x \in (-\infty, m) \).

Therefore, making use of (14), (15) and (18), we obtain that:

(i) if \( m > 0 \) and \( M \geq 0 \) then
\[ E_{\mu\nu}[X] = \int_0^M \mu(\{X > x\})dx; \]

(ii) if \( m \leq 0 \) and \( M < 0 \) then
\[ E_{\mu\nu}[X] = -\int_0^0 \nu(\{X < x\})dx; \]

(iii) if \( m \leq 0 \leq M \) then
\[ E_{\mu\nu}[X] = \int_0^M \mu(\{X > x\})dx - \int_0^0 \nu(\{X < x\})dx; \]

(iv) if \( M < 0 < m \) then \( E_{\mu\nu}[X] = 0 \).
\textbf{Remark 7.} Assume that $\mu$ and $\nu$ are capacities on $(S, \mathcal{F})$. Subsequently, in view of Remark 6, we have
\[
\min \{ \nu - \text{ess inf} X, 0 \} \leq E_{\mu\nu}[X] \leq \max \{ \mu - \text{ess sup} X, 0 \} \tag{21}
\]
for every $\mathcal{F}$-measurable function $X : S \to \mathbb{R}$ $\mu$-essentially bounded from above and $\nu$-essentially bounded from below.

We complete with this section with the following result.

\textbf{Proposition 2.} Assume that $\mu$ and $\nu$ are the capacities on $(S, \mathcal{F})$ and $X : S \to \mathbb{R}$ is of the form
\[
X = x_1 \mathbb{1}_A + x_2 \mathbb{1}_{S \setminus A}, \tag{22}
\]
with some $A \in \mathcal{F}$ and $x_1, x_2 \in \mathbb{R}$, such that $x_1 < x_2$. Subsequently, $X$ is $\mathcal{F}$-measurable $\mu$-essentially bounded from above and $\nu$-essentially bounded from below. Furthermore,
\[
E_{\mu\nu}[X] = (1 - \mu(S\setminus A))x_1 + \mu(S\setminus A)x_2 \quad \text{whenever} \quad 0 \leq x_1, \tag{23}
\]
\[
E_{\mu\nu}[X] = \nu(A)x_1 + \mu(S\setminus A)x_2 \quad \text{whenever} \quad x_1 < 0 < x_2, \tag{24}
\]
\[
E_{\mu\nu}[X] = \nu(A)x_1 + (1 - \nu(A))x_2 \quad \text{whenever} \quad x_2 \leq 0. \tag{25}
\]

\textbf{Proof.} An $\mathcal{F}$-measurability of $X$ is obvious. Note that $\nu(\{X < x_1\}) = \nu(\emptyset) = 0$ and $\mu(\{X > x_2\}) = \mu(\emptyset) = 0$, hence $X$ is $\mu$-essentially bounded from above and $\nu$-essentially bounded from below. Furthermore, we have
\[
\mu(\{X > x\}) = \begin{cases}
1 & \text{for } x \in (-\infty, x_1), \\
\mu(S\setminus A) & \text{for } x \in [x_1, x_2), \\
0 & \text{for } x \in [x_2, \infty)
\end{cases}
\]
and
\[
\nu(\{X < x\}) = \begin{cases}
0 & \text{for } x \in (-\infty, x_1], \\
\nu(A) & \text{for } x \in (x_1, x_2], \\
1 & \text{for } x \in (x_2, \infty).
\end{cases}
\]
Therefore, while taking into account (14), (15) and (18), after a standard computation, we obtain the assertion. \qed

\section{3. Quasi-Arithmetic Type Mean Generated by the Generalized Choquet Integral}

In this section, we prove that $M_{(u, \mu, \nu)}$ defined on a family of all $\mathcal{F}$-measurable function $X : S \to \mathbb{R}$ $\nu$-essentially bounded from below and $\mu$-essentially bounded from above, as given by (3), is well-defined and it is a mean.

\textbf{Theorem 1.} Assume that $\mu$ and $\nu$ are capacities on $(S, \mathcal{F})$ and $u : \mathbb{R} \to \mathbb{R}$ be a strictly increasing continuous function. Subsequently, for every $\mathcal{F}$-measurable function $X : S \to \mathbb{R}$ $\mu$-essentially bounded from above and $\nu$-essentially bounded from below, there exists a unique $M_{(u, \mu, \nu)}(X) \in \mathbb{R}$, such that
\[
u(M_{(u, \mu, \nu)}(X)) = E_{\mu\nu}[u(X)]. \tag{26}
\]
Furthermore, $M_{(u, \mu, \nu)}$ is a mean, which is (4) holds for every $\mathcal{F}$-measurable function $X : S \to \mathbb{R}$ $\mu$-essentially bounded from above and $\nu$-essentially bounded from below.

\textbf{Proof.} Assume that $X : S \to \mathbb{R}$ is an $\mathcal{F}$-measurable function $\mu$-essentially bounded from above and $\nu$-essentially bounded from below. Subsequently, according to Lemma 2, so is $u \circ X$. Let $M = \ldots$
\(\mu - \text{ess sup} \ X\) and \(m = v - \text{ess inf} \ X\). If there exist \(s_1, s_2 \in S\), such that \((u \circ X)(s_1) < 0 < (u \circ X)(s_2)\) then, applying Lemma 2 and Corollary 7, we obtain

\[
u - \text{ess inf} X = \nu - \text{ess inf} \left(\min\{u(m), u(X(s_1))\}\right) \leq \min\{\nu - \text{ess inf} u \circ X, u(X(s_1))\} \leq \min\{\nu - \text{ess inf} u \circ X, u(0)\} \leq \max\{\mu - \text{ess sup} u \circ X, 0\} \leq \max\{\mu - \text{ess sup} u \circ X, u(X(s_2))\} \leq u(\text{sup} X).
\]

Because \(u\) is continuous, this means that (26) holds with some \(M_{(u,\mu,\nu)}(X) \in \mathbb{R}\). Furthermore, as \(u\) is strictly increasing, such an \(M_{(u,\mu,\nu)}(X)\) is unique and it satisfies (4).

Now, assume that \(u \circ X\) takes only non-positive values. Afterwards, according to Remark 2 (ii), (iii), we have \(v - \text{ess inf} u \circ X \leq 0\) and \(\mu - \text{ess sup} u \circ X \leq 0\). Hence, applying Remark 6, in view of (13), we have

\[
E_{\mu \nu}[u(X)] = -E_{\nu}[-u(X)] = E_{\nu}[u(X)].
\]

Hence, applying Proposition 1, Lemma 2, and Remark 2, we obtain

\[
u - \text{ess inf} X = \nu - \text{ess inf} \left(\max\{u(M), u(X(s_2))\}\right) \leq u(\text{sup} X).
\]

Thus, arguing as previously, we conclude that there exists a unique \(M_{(u,\mu,\nu)}(X) \in \mathbb{R}\), such that (26) holds and, moreover, (4) is valid.

If \(u \circ X\) takes only non-negative values, applying Remark 2 (ii), (iii), we have \(v - \text{ess inf} u \circ X \geq 0\) and \(\mu - \text{ess sup} u \circ X \geq 0\). Thus, making use of Remark 6, we conclude that

\[
E_{\mu \nu}[u(X)] = E_{\mu}[u(X)],
\]

hence, applying Proposition 1, Lemma 2, and Remark 2, we get

\[
u - \text{ess inf} X = \nu - \text{ess inf} \left(\max\{u(M), u(X(s_2))\}\right) \leq u(\text{sup} X).
\]

Therefore, as \(u\) is continuous and strictly increasing, we have the assertion.

\section*{Remark 8}

It follows from (26) that, for arbitrary capacities \(\mu\) and \(v\) on \((S, \mathcal{F})\) and for every continuous strictly increasing function \(u : \mathbb{R} \to \mathbb{R}\), the functional that is given by (3) is a well-defined mean on the family of all \(\mathcal{F}\)-measurable functions \(X : S \to \mathbb{R}\) \(\mu\)-essentially bounded from above and \(v\) -essentially bounded from below.

In particular, while taking (19) into account, we conclude that (2) defines a mean on a family of all \(\mathcal{F}\)-measurable functions \(X : S \to \mathbb{R}\) \(\mu\)-essentially bounded from above and \(\bar{\mu}\) -essentially bounded from below.

\section*{Remark 9}

Assume that \(u : \mathbb{R} \to \mathbb{R}\) is a strictly increasing continuous function. It follows from (3) and (23)–(25) that, if \(X : S \to \mathbb{R}\) is of the form (22) with some \(A \in \mathcal{F}\) and \(x, y \in \mathbb{R}\), such that \(x < y\), then

\[
M_{(u,\mu,\nu)}(X) = \begin{cases} u^{-1}((1 - \mu(S \setminus A))u(x) + \mu(S \setminus A)u(y)) & \text{if } 0 \leq u(x), \\ u^{-1}(v(A))u(x) + \mu(S \setminus A)u(y)) & \text{if } u(x) < 0 < u(y), \\ u^{-1}(v(A))u(x) + (1 - v(A))u(y)) & \text{if } u(y) \leq 0. 
\end{cases}
\]

\section*{4. Main Properties of the Mean}

In this section, we are going to investigate some of the properties of means defined by (3). From now on, we assume that \(\mu\) and \(v\) are capacities on \((S, \mathcal{F})\). By \(\mathcal{X}\), we denote a family of all \(\mathcal{F}\)-measurable function \(X : S \to \mathbb{R}\) \(\mu\)-essentially bounded from above and \(v\)-essentially bounded from
there exist $\alpha$.

Therefore, defining $f$ play an essential role in our considerations.

Subsequently, the following conditions are equivalent:

**Symmetry**

In [11], the above result is formulated for functions $f$.

**Remark 10.** In [11], the above result is formulated for functions $f : \mathbb{R} \to \mathbb{R}$. However, it remains true with the same proof for $f : I \to \mathbb{R}$.

**Theorem 2.** Assume that $u, v : \mathbb{R} \to \mathbb{R}$ are strictly increasing continuous functions and there exists a set $A \in \mathcal{F}$, such that

$$\mu(A), \nu(S \setminus A) \in (0, 1).$$

Subsequently, the following conditions are equivalent:

(i) $$M_{(\nu, \mu, u)}(X) = M_{(u, \mu, v)}(X) \quad \text{for} \quad X \in \mathcal{X}^{(2)},$$

(ii) $$M_{(\nu, \mu, u)}(X) = M_{(u, \mu, v)}(X) \quad \text{for} \quad X \in \mathcal{X},$$

(iii) there exist $\alpha \in (0, \infty)$ and $\beta \in \mathbb{R}$ such that

$$v(x) = \alpha u(x) + \beta \quad \text{for} \quad x \in \mathbb{R}$$

and

$$v = \beta \quad \text{whenever} \quad u(x)v(x) < 0 \quad \text{for some} \quad x \in \mathbb{R}.$$

**Proof.** In order to prove the implication $(i) \Rightarrow (iii)$ assume that (33) holds. The proof is based on some ideas in [11]. Suppose that

$$u(x)v(x) \geq 0 \quad \text{for} \quad x \in \mathbb{R}.$$  

Let $I^- := \{x \in \mathbb{R} : u(x) < 0 \text{ and } v(x) < 0\}$ and $I^+ := \{x \in \mathbb{R} : u(x) > 0 \text{ and } v(x) > 0\}$. Making use of (29), for every $x, y \in I^+$ with $x < y$, we obtain

$$v^-(1 - \mu(S \setminus A))v(x) + \mu(S \setminus A)v(y)) = u^-(1 - \mu(S \setminus A))u(x) + \mu(S \setminus A)u(y)),$$

and, for every $x, y \in I^-$ with $x < y$, we obtain

$$v^-(v(A)v(x) + (1 - v(A))v(y)) = u^-(v(A)u(x) + (1 - v(A))u(y)).$$

Therefore, defining $f : u(\mathbb{R}) \to \mathbb{R}$ in the following way

$$f(x) = (v \circ u^{-1})(x) \quad \text{for} \quad x \in u(\mathbb{R})$$

below. A subfamily of $\mathcal{X}$ of functions $X : S \to \mathbb{R}$ of the form (22), where $A \in \mathcal{F}$ and $x, y \in \mathbb{R}$, such that $x < y$, will be denoted by $\mathcal{X}^{(2)}$.

We begin with a characterization of the equality in this class of means. The following result will play an essential role in our considerations.

**Lemma 3.** [11] (Lemma 5.1) Let $I \subset \mathbb{R}$ be a non-degenerate interval, $f : I \to \mathbb{R}$ be a non-constant continuous function, and $\alpha, \beta \in \mathbb{R}$. If $f$ satisfies equation

$$f((1 - \alpha)x + \alpha y) = (1 - \beta)f(x) + \beta f(y) \quad \text{for} \quad x, y \in I, x < y,$$

then $\alpha = \beta$. If, moreover, $\alpha, \beta \not\in \{0, 1\}$, then there exist $a \in \mathbb{R} \setminus \{0\}$ and $b \in \mathbb{R}$, such that

$$f(x) = ax + b \quad \text{for} \quad x \in I.$$
and replacing in (38) and (39) $x$ by $u^{-1}(x)$ and $y$ by $u^{-1}(y)$, we obtain
\[
f((1 - \mu(S\setminus A))x + \mu(S\setminus A)y) = (1 - \mu(S\setminus A))f(x) + \mu(S\setminus A)f(y)
\] for $x, y \in u(I^+), x < y \quad (41)$

and
\[
f(v(A)x + (1 - v(A))y) = v(A)f(x) + (1 - v(A))f(y)
\] for $x, y \in u(I^-), x < y, \quad (42)$

respectively. Furthermore, because $u$ and $v$ are strictly increasing and continuous, so is $f$. Moreover, in view of (37), we have either $I^- = \mathbb{R}$ or $I^+ = \mathbb{R}$ or $I^- = (-\infty, z)$ and $I^+ = (z, \infty)$ for some $z \in \mathbb{R}$. If $I^+ = \mathbb{R}$, while taking into account (32) and applying Lemma 3, we conclude that there exist $\alpha \in (0, \infty)$ and $\beta \in \mathbb{R}$, such that
\[
f(x) = \alpha x + \beta \quad \text{for} \quad x \in u(\mathbb{R}). \quad (43)
\]

Hence, in view of (40), we obtain (35). If $I^- = \mathbb{R}$, the same conclusion follows from (39). In the case where $I^- = (-\infty, z)$ and $I^+ = (z, \infty)$ for some $z \in \mathbb{R}$, making use of (32) and applying Lemma 3, we obtain that there exist $\alpha^+, \alpha^- \in (0, \infty)$ and $\beta^+, \beta^- \in \mathbb{R}$, such that
\[
v(x) = \begin{cases} 
\alpha^- u(x) + \beta^- & \text{for} \quad x \in (z, \infty), \\
\alpha^+ u(x) + \beta^+ & \text{for} \quad x \in (-\infty, z)
\end{cases} \quad (44)
\]

Moreover, as $u$ and $v$ are continuous, we get $u(z) = v(z) = 0$. Hence, we have $\beta^- = \beta^+ = 0$, hence
\[
v(x) = \begin{cases} 
\alpha^- u(x) & \text{for} \quad x \in (z, \infty), \\
\alpha^+ u(x) & \text{for} \quad x \in (-\infty, z).
\end{cases} \quad (45)
\]

Additionally, note that making use of (29) and (33), for every $x \in (-\infty, z)$ and $y \in (z, \infty)$, we get
\[
v^{-1}(v(A)v(x) + \mu(S\setminus A)v(y)) = u^{-1}(v(A)u(x) + \mu(S\setminus A)u(y)).
\]

Hence, in view of (45), for every $x \in (-\infty, z)$ and $y \in (z, \infty)$, we obtain
\[
v^{-1}(v(A)\alpha^- u(x) + \mu(S\setminus A)\alpha^+ u(y)) = u^{-1}(v(A)u(x) + \mu(S\setminus A)u(y)). \quad (46)
\]

Furthermore, for every $x \in (-\infty, z)$ and $y \in (z, \infty)$ sufficiently close to $z$, we have
\[
v(A)\alpha^- u(x) + \mu(S\setminus A)\alpha^+ u(y) < 0,
\]
that is
\[
u^{-1}(v(A)\alpha^- u(x) + \mu(S\setminus A)\alpha^+ u(y)) \in (-\infty, z).
\]

Therefore, applying (45), from (46), we derive that
\[
\alpha^- v(A)u(x) + \alpha^+ \mu(S\setminus A)u(y) = \alpha^- v(A)u(x) + \alpha^+ \mu(S\setminus A)u(y)
\]
for every $x \in (-\infty, z)$ and $y \in (z, \infty)$ sufficiently close to $z$. Hence, in view of (32), we get $\alpha^+ = \alpha^-$ and, so, while taking into account (45), we obtain (35) with $\alpha := \alpha^+ = \alpha^-$ and $\beta = 0$.

Now, suppose that (37) does not hold. Subsequently, as $u$ and $v$ are continuous, there exists a non-degenerate interval $J \subseteq \mathbb{R}$, such that $u(x)v(x) < 0$ for $x \in J$. Thus, either
\[
u(x) < 0 \quad \text{for} \quad x \in J.
\]

or
\[
u(x) > 0 \quad \text{for} \quad x \in J.
\]

Therefore, either
\[
u(x) < 0 \quad \text{for} \quad x \in J
\]

or
\[
u(x) > 0 \quad \text{for} \quad x \in J.
\]
In the first case, in view of (29), we obtain
\[ v^{-1}(v(B)v(x) + (1 - v(B))v(y)) = u^{-1}((1 - \mu(S\backslash B))u(x) + \mu(S\backslash B)u(y)) \]
for every \( B \in \mathcal{F} \) and \( x, y \in J \), such that \( x < y \). Hence, replacing \( x \) by \( u^{-1}(x) \) and \( y \) by \( u^{-1}(y) \), for every \( B \in \mathcal{F} \) and \( x, y \in u(J) \) with \( x < y \), we get
\[ f((1 - \mu(S\backslash B))x + \mu(S\backslash B)y) = v(B)f(x) + (1 - v(B))f(y) \]
where \( f : u(J) \to \mathbb{R} \) is given by (40). Accordingly, as \( f \) is continuous, applying Lemma 3, we conclude that \( v(B) = 1 - \mu(S\backslash B) \) for \( B \in \mathcal{F} \), which is \( v = \bar{\mu} \). Using the similar arguments, in the second case, for every \( B \in \mathcal{F} \) and \( x, y \in J \), such that \( x < y \), we obtain
\[ f(\mu(B)x + (1 - \mu(B))y) = (1 - v(S\backslash B))f(x) + v(S\backslash B)f(y). \]
Hence, according to Lemma 3, we obtain \( \bar{\mu}(B) = 1 - v(S\backslash B) \) for \( B \in \mathcal{F} \), which again gives \( v = \bar{\mu} \).

Because \( v = \bar{\mu} \), from (29) and (33), we derive that
\[ v^{-1}((1 - \mu(S\backslash A))v(x) + \mu(S\backslash A)v(y)) = u^{-1}((1 - \mu(S\backslash A))u(x) + \mu(S\backslash A)u(y)) \]
for every \( x, y \in \mathbb{R} \), such that \( x < y \). Thus,
\[ f((1 - \mu(S\backslash B))x + \mu(S\backslash B)y) = v(B)f(x) + (1 - v(B))f(y) \]
for every \( x, y \in \mathbb{R} \) with \( x < y \), where \( f \) is given by (40). Hence, taking (32) into account and applying Lemma 3, we obtain that there exist \( \alpha \in (0, \infty) \) and \( \bar{\beta} \in \mathbb{R} \), such that (43) holds. Hence, in view of (40), we get (35). In this way, we proved the implication \((i) \Rightarrow (iii)\).

Now, we prove that \((iii) \Rightarrow (ii)\). Assume that \((iii)\) holds. Subsequently, by (35), we have
\[ v^{-1}(x) = u^{-1} \left( \frac{1}{\alpha} (x - \beta) \right) \text{ for } x \in v(\mathbb{R}). \]  

If (37) is valid, then, as we have already noted, either \( I^- = \mathbb{R} \) or \( I^+ = \mathbb{R} \) or \( I^- = (-\infty, z) \) and \( I^+ = (z, \infty) \) for some \( z \in \mathbb{R} \). In the first case, in view of (13) and (18), for every \( X \in \mathcal{X} \), we have (27) and \( E_{\mu\nu}[v(X)] = E_\nu[v(X)] \). Thus, using the fact that Choquet integral is positively homogeneous and translative, taking into account (3), (35), and (47), for every \( X \in \mathcal{X} \), we obtain
\[ M_{(\nu,\mu,v)}(X) = v^{-1}(E_{\mu\nu}[v(X)]) = v^{-1}(E_\nu[v(X)]) = u^{-1} \left( \frac{1}{\alpha} (E_\nu[\alpha u(X)] + \beta) - \beta \right) \]
\[ = u^{-1}(E_\nu[u(X)]) = u^{-1}(E_{\mu\nu}[u(X)]) = M_{(\mu,\nu,v)}(X). \]
In the second case, in view of (18), for every \( X \in \mathcal{X} \), we have (28) and \( E_{\mu\nu}[v(X)] = E_\nu[v(X)] \). Hence, arguing, as previously, we obtain (34). In the third case from the continuity of \( u \) and \( v \), we derive that \( u(z) = v(z) = 0 \). Hence, in view of (35), we get \( \beta = 0 \) and, so, as the generalized Choquet integral is positively homogeneous, making use of (47), for every \( X \in \mathcal{X} \), we obtain
\[ M_{(\nu,\mu,v)}(X) = v^{-1}(E_{\mu\nu}[v(X)]) = u^{-1} \left( \frac{1}{\alpha} E_{\mu\nu}[\alpha u(X)] \right) = u^{-1}(E_{\mu\nu}[u(X)]) = M_{(\mu,\nu,v)}(X). \]
If (37) does not hold then, according to (36), we have \( v = \bar{\beta} \). Therefore, taking (19), (35), and (47) into account, for every \( X \in \mathcal{X} \), we have obtain
\[ M_{(\nu,\mu,v)}(X) = M_{(\nu,\mu,\bar{\beta})}(X) = v^{-1}(E_{\mu\bar{\beta}}[v(X)]) = v^{-1}(E_{\mu}[v(X)]) = u^{-1} \left( \frac{1}{\alpha} (E_\mu[\alpha u(X)] + \beta) - \beta \right). \]
there exist $\alpha$ Let $u$

This proves that (iii) $\Rightarrow$ (ii).

The implication (ii) $\Rightarrow$ (i) is obvious. $\square$

Applying Theorem 2, we are going to characterize positive homogeneity and translativity in the class of means given by (3).

**Theorem 3.** Let $u : \mathbb{R} \to \mathbb{R}$ be a strictly increasing continuous function. Assume that there exists a set $A \in \mathcal{F}$, such that (32) holds. Subsequently, the following conditions are equivalent:

(i) $M_{(u,\mu)}(tX) = tM_{(u,\mu)}(X)$ for $X \in \mathcal{X}'(2)$, $t \in (0, \infty)$, (48)

(ii) $M_{(u,\mu)}(tX) = tM_{(u,\mu)}(X)$ for $X \in \mathcal{X}$, $t \in (0, \infty)$, (49)

(iii) there exist $\alpha, \beta, r \in (0, \infty)$ and $\delta \in \mathbb{R}$, such that

$$u(x) = \begin{cases} -\beta(-x)^r + \delta & \text{for } x \in (-\infty, 0), \\ \alpha x^r + \delta & \text{for } x \in [0, \infty) \end{cases}$$

and

$$v = \bar{u} \text{ whenever } \delta \neq 0.$$ (50)

**Proof.** Assume that (i) holds. Let, for every $t \in (0, \infty)$, $u_t : \mathbb{R} \to \mathbb{R}$, be given by

$$u_t(x) = u(tx) \text{ for } x \in \mathbb{R}. \quad (52)$$

Subsequently,

$$u_t^{-1}(x) = \frac{1}{t}u^{-1}(x) \text{ for } x \in u(\mathbb{R}), t \in (0, \infty).$$

Moreover, while using the positive homogeneity of the generalized Choquet integral, in view of (48), for every $X \in \mathcal{X}'(2)$ and $t \in (0, \infty)$, we obtain

$$M_{(u,\mu)}(X) = u_t^{-1} \left( E_{\mu'}[u_t(X)] \right) = \frac{1}{t}u^{-1} \left( E_{\mu'}[u(tX)] \right) = \frac{1}{t}M_{(u,\mu)}(tX) = M_{(u,\mu)}(X).$$

Therefore

$$M_{(u,\mu)}(X) = M_{(u,\mu)}(X) \text{ for } X \in \mathcal{X}'(2), t \in (0, \infty). \quad (53)$$

Hence, applying Theorem 2, we conclude that, for every $t \in (0, \infty)$, there exist $a(t) \in (0, \infty)$ and $b(t) \in \mathbb{R}$, such that

$$u_t(x) = a(t)u(x) + b(t) \text{ for } x \in \mathbb{R}.$$

Thus, in view of (52), we obtain

$$u(tx) = a(t)u(x) + b(t) \text{ for } x \in \mathbb{R}, t \in (0, \infty). \quad (54)$$

In particular, we have

$$u(tx) = a(t)u(x) + b(t) \text{ for } (x, t) \in (0, \infty)^2.$$

Therefore, applying [15] (Corollary 3), we obtain

$$u(x) = am(x) + \delta \text{ for } x \in (0, \infty). \quad (55)$$
where \( \alpha \in (0, \infty) \), \( \delta \in \mathbb{R} \) and \( m : (0, \infty) \to \mathbb{R} \setminus \{0\} \) is a multiplicative function, that is
\[
m(x + y) = m(x)m(y) \quad \text{for} \quad x, y \in (0, \infty).
\]
Moreover, as \( u \) is continuous and strictly increasing, in view of (55), so is \( m \). Thus, according to [16] (Theorem 13.1.6), there exists \( r \in (0, \infty) \), such that \( m(x) = x^r \) for \( x \in (0, \infty) \). Hence, making use of (55) and using the continuity of \( u \) again, we obtain
\[
u(x) = \alpha x^r + \delta \quad \text{for} \quad x \in [0, \infty).
\] (56)

Therefore, setting in (54) \( x = 0 \) and then \( x = 1 \), after a standard computation, we obtain that \( a(t) = t^r \) for \( t \in (0, \infty) \) and \( b(t) = \delta(1 - t^r) \) for \( t \in (0, \infty) \). Thus, putting in (54) \( x = -1 \), we obtain
\[
u(-t) = (u(-1) - \delta)t^r + \delta \quad \text{for} \quad t \in (0, \infty).
\]

Hence, when taking \( \beta := \delta - u(-1) \), we obtain
\[
u(x) = -\beta(-x)^r + \delta \quad \text{for} \quad x \in (-\infty, 0)
\]
which, together with (56), gives (50). Because \( u \) is strictly increasing, we also have \( \beta \in (0, \infty) \).

Assume that \( \delta \neq 0 \). Because \( u \) is a bijection on \( \mathbb{R} \), it has a unique zero, say \( x_0 \). Moreover, as \( \delta \neq 0 \), in view of (50), \( x_0 \neq 0 \). Furthermore, taking an arbitrary \( t \in (0, \infty) \setminus \{1\} \) and making use of (52), we conclude that \( \frac{x_0}{t} \) is a unique zero of \( u_t \). Thus, \( u \) and \( u_t \) have different zeroes and, so, as they are strictly increasing, we have \( u_t(x)u(x) < 0 \) for every \( x \) between these zeroes. Therefore, while taking (53) into account and applying Theorem 2, we obtain \( \nu = \bar{u} \). Consequently, (51) holds and, so, the implication (i) \( \Rightarrow \) (iii) is proven.

In order to prove the implication (iii) \( \Rightarrow \) (ii), assume that \( u \) is of the form (50) with some \( \alpha, \beta, r \in (0, \infty), \delta \in \mathbb{R} \) and (51) holds. It follows from (50) that
\[
u(tx) = t^r u(x) + \delta(1 - t^r) \quad \text{for} \quad x \in \mathbb{R}, \ t \in (0, \infty)
\] (57)
and
\[
u^{-1}(t^r x + \delta(1 - t^r)) = tu^{-1}(x) \quad \text{for} \quad x \in \mathbb{R}, \ t \in u(0, \infty).
\] (58)

Therefore, if \( \delta = 0 \), then, while using the positive homogeneity of the Choquet integral, in view of (3), for every \( X \in \mathcal{X} \) and \( t \in (0, \infty) \), we obtain
\[
M_{(u, \mu, \nu)}(tX) = u^{-1}(E_{\mu}[u(tX)]) = u^{-1}(E_{\mu}[t^r u(X)])
\]
\[
= u^{-1}(t^r E_{\mu}[u(X)]) = tu^{-1}(E_{\mu}[u(X)]) = tM_{(u, \mu, \nu)}(X)
\]
which shows that \( M_{(u, \mu, \nu)} \) is positively homogeneous.

If \( \delta \neq 0 \), then, according to (51), we have \( \nu = \bar{u} \). Hence, as the Choquet integral is positively homogeneous and translatable, in view of (19) and (57)–(58), for every \( X \in \mathcal{X} \) and \( t \in (0, \infty) \), we get
\[
M_{(u, \mu, \nu)}(tX) = M_{(u, \mu, \bar{u})}(tX) = u^{-1}(E_{\mu}[u(tX)]) = u^{-1}(E_{\mu}[u(tX)])
\]
\[
= u^{-1}(E_{\mu}[t^r u(X) + \delta(1 - t^r)]) = u^{-1}(t^r E_{\mu}[u(X)] + \delta(1 - t^r))
\]
\[
= tu^{-1}(E_{\mu}[u(X)]) = tu^{-1}(E_{\mu}[u(X)]) = tM_{(u, \mu, \nu)}(X) = tM_{(u, \mu, \nu)}(X)
\]
In this way, we have proved that (iii) \( \Rightarrow \) (ii).

The implication (ii) \( \Rightarrow \) (i) is obvious. \( \square \)
Theorem 4. Let $I \subseteq \mathbb{R}$ be a non-degenerate interval and let $u : \mathbb{R} \to \mathbb{R}$ be a strictly increasing continuous function. Assume that there exists a set $A \in \mathcal{F}$, such that (32) holds. Subsequently, the following conditions are equivalent:

(i) 
$$M_u(X + t) = M_u(X) + t \quad \text{for } X \in \mathcal{X}^{(2)}, \ t \in I, \quad (59)$$

(ii) 
$$M_u(X + t) = M_u(X) + t \quad \text{for } X \in \mathcal{X}, \ t \in I, \quad (60)$$

(iii) one of the subsequent possibilities holds:

(a) $\nu = \bar{\mu}$ and there exist $\alpha \in (0, \infty), \beta \in \mathbb{R}$ such that

\[ u(x) = ax + \beta \quad \text{for } x \in \mathbb{R}, \quad (61) \]

(b) there exist $a, \beta, r \in \mathbb{R}$ with $ar > 0$, such that

\[ u(x) = ae^{rx} + \beta \quad \text{for } x \in \mathbb{R} \]

and

\[ \nu = \bar{\mu} \quad \text{whenever } a\beta < 0. \quad (63) \]

Proof. Assume that (i) holds. For every $t \in I$ define a function $u_t : \mathbb{R} \to \mathbb{R}$ in the following way

\[ u_t(x) = u(x + t) \quad \text{for } x \in \mathbb{R}. \quad (64) \]

Subsequently, for every $t \in I$ $u_t$ is strictly increasing and continuous. Moreover, we have

\[ u_t^{-1}(x) = u^{-1}(x) - t \quad \text{for } x \in u(\mathbb{R}). \]

Thus, taking (59) into account, for every $X \in \mathcal{X}^{(2)}$ and $t \in I$, we obtain

\[ M_{(u_t, \mu, \nu)}(X) = u_t^{-1}\left(E_{\mu, \nu}[u_t(X)]\right) = u^{-1}\left(E_{\mu, \nu}[u(X + t)]\right) - t = M_{(u, \mu, \nu)}(X + t) - t = M_{(u, \mu, \nu)}(X). \]

Hence,

\[ M_{(u, \mu, \nu)}(X) = M_{(u_t, \mu, \nu)}(X) \quad \text{for } X \in \mathcal{X}^{(2)}, \ t \in I. \quad (65) \]

Therefore, according to Theorem 2, for every $t \in I$, there exist $a(t) \in (0, \infty)$ and $\beta(t) \in \mathbb{R}$, such that

\[ u_t(x) = a(t)u(x) + \beta(t) \quad \text{for } x \in \mathbb{R} \]

which, in view of (64), gives

\[ u(x + t) = a(t)u(x) + \beta(t) \quad \text{for } x \in \mathbb{R}, \ t \in I. \]

Thus, applying [17] (Theorem 2), we conclude that either (61) holds with some $\alpha \in (0, \infty)$ and $\beta \in \mathbb{R}$, or (62) is valid with some $a, \beta, r \in \mathbb{R}$, such that $ar > 0$.

If $u$ is of the form (61) or it is of the form (62) with $a\beta < 0$ then it has a unique zero, say $x_0$. Hence, taking a $t \in I \setminus \{0\}$, we obtain that $x_0 - t$ is a unique zero of $u_t$. Therefore, as $u$ and $u_t$ are strictly increasing, we have $u_t(x)u(x) < 0$ for every $x$ belonging to the interval with endpoints $x_0$ and $x_0 - t$. Thus, taking (65) into account and applying Theorem 2, we obtain $\nu = \bar{\mu}$, which proves the implication $(i) \Rightarrow (iii)$. 
Now, we prove that \((iii) \Rightarrow (ii)\). Assume that \((iii)\) holds. In the case of \((a)\), we have
\[ u^{-1}(x) = \frac{1}{\alpha}(x - \beta) \quad \text{for} \quad x \in \mathbb{R}. \]

Hence, as the Choquet integral is positively homogeneous and translative, taking into account (3) and (19), for every \(X \in \mathcal{X}\), we obtain
\[ M_{(u,\mu,\nu)}(X) = M_{(u,\mu,\bar{\nu})}(X) = u^{-1}\left(E_{\mu}[u(X)]\right) = \frac{1}{\alpha}(E_{\mu}[\alpha X + \beta] - \beta) = E_{\mu}[X]. \]

Therefore, again using the translativity of the Choquet integral, we obtain (60).

In the case of \((b)\), we get
\[ u^{-1}(x) = \frac{1}{r} \ln \left(\frac{x - \beta}{\alpha}\right) \quad \text{for} \quad x \in u(\mathbb{R}). \quad (66) \]

If \(\alpha \beta < 0\), then \(\nu = \bar{\mu}\) and, so, as the Choquet integral is positively homogeneous an translative, making use of (3), (19) and (66), for every \(X \in \mathcal{X}\), we obtain
\[ M_{(u,\mu,\nu)}(X) = M_{(u,\mu,\bar{\nu})}(X) = u^{-1}\left(E_{\mu}[u(X)]\right) = \frac{1}{r} \ln \left(\frac{E_{\mu}[\alpha e^{\alpha X} + \beta] - \beta}{\alpha}\right) = \frac{1}{r} \ln \left(E_{\mu}[e^{\alpha X}]\right). \]

Thus, while using the positive homogeneity of the Choquet integral, for every \(X \in \mathcal{X}\) and \(t \in I\), we obtain
\[
M_{(u,\mu,\nu)}(X + t) = \frac{1}{r} \ln \left(E_{\mu}[e^{\alpha (X + t)}]\right) = \frac{1}{r} \ln \left(E_{\mu}[e^{rt e^{\alpha X}}]\right) = \frac{1}{r} \ln \left(e^{rt} E_{\mu}[e^{\alpha X}]\right)
\]
\[
= \frac{1}{r} \left(rt + \ln \left(E_{\mu}[e^{\alpha X}]\right)\right) = \frac{1}{r} \ln \left(E_{\mu}[e^{\alpha X}]\right) + t = M_{(u,\mu,\nu)}(X) + t,
\]
that is (60) holds. If \(\alpha \beta \geq 0\) then either \(u(\mathbb{R}) \subset (0, \infty)\) or \(u(\mathbb{R}) \subset (-\infty, 0)\). In the first case, by (18), we have (28). Hence, for every \(X \in \mathcal{X}\), we obtain
\[ M_{(u,\mu,\nu)}(X) = u^{-1}\left(E_{\mu}[u(X)]\right) = \frac{1}{r} \ln \left(\frac{E_{\mu}[\alpha e^{\alpha X} + \beta] - \beta}{\alpha}\right) = \frac{1}{r} \ln \left(E_{\mu}[e^{\alpha X}]\right). \]

Thus, as we have already noted, (60) holds. In the latter case, according to (18), we have (27). Therefore, in a similar way, we get
\[ M_{(u,\mu,\nu)}(X) = \frac{1}{r} \ln \left(E_{\mu}[e^{\alpha X}]\right) \quad \text{for} \quad X \in \mathcal{X}, \]
which implies (60). In this way we have proved that \((iii) \Rightarrow (ii)\).

The implication \((ii) \Rightarrow (i)\) is obvious. \(\square\)

Remark 11. Applying Remark 8, from Theorems 2–4, one can easily deduce the characterizations of the equality, positive homogeneity, and translativity for the functional that is defined by (2). Furthermore, Theorems 2–4 generalize the results in [11] (Theorems 3.1–3.3).

5. Conclusions

We have introduced a new class of quasi-arithmetic type means generated by the generalized Choquet Integral. Our approach is motivated by recent applications of this type of means in the theory of decision making under risk and in the theory of insurance premium principles. Using the methods of functional equations, we established characterizations of some important properties in the
considered class of means. It is remarkable that the aforementioned characterizations are expressed not only in terms of the relations between functions generating means, but they involve also the properties of capacities under consideration.

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