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SUB-ADDITIVE MEASURES OF INFORMATION IMPROVEMENT

D. S. HOODA

Additivity plays a great role in the study of information theoretic measures. However, it is very interesting to consider sub-additivity. Starting from sub-additivity for measures associated with three probability distributions of a discrete random variable and using another function of three probability distributions, it has been changed into generalized additivity. Using sum property of the functions and the generalized additivity, a functional equation and its complex solutions are obtained. In terms of the real continuous solutions of this functional equation, three sub-additive measures of information improvement have been defined and characterized. Particular cases and some simple properties including convexity of these new measures have also been studied.

1. INTRODUCTION

Let X be a random variable taking n values $x_1, x_2, \ldots, x_n$ having prediction probability distribution $Q = (q_1, q_2, \ldots, q_n)$, $\sum_{i=1}^{n} q_i \leqq 1$, $q_i > 0$ which is revised as $R = (r_1, r_2, \ldots, r_n)$, $\sum_{i=1}^{n} r_i \leqq 1, r_i > 0$ on the basis of a distribution $P = (p_1, p_2, \ldots, p_n)$, $\sum_{i=1}^{n} p_i = 1$, $p_i \geqq 0$ supposed to have been realized after some experiment, then the information theoretic measure associated with these three probability distributions P, Q and R is given by

$$I(P; Q; R) = \sum_{i=1}^{n} p_i \log_2 (r_i/q_i) . \tag{1.1}$$

The measure (1.1) is called Theil's [7] measure of information improvement and it has many applications in economics. The measure (1.1) satisfies the property of additivity which can be expressed as

$$I(P*P'; Q*Q'; R*R') = I(P; Q; R) + I(P'; Q'; R') \tag{1.2}$$

where $$P = (p_1, p_2, \ldots, p_n); \quad P' = (p'_1, p'_2, \ldots, p'_m);$$
$$P{*}P' = (p_1 p'_1, \ldots, p_1 p'_m, \ldots; p_n p'_1, \ldots, p_n p'_m) \text{ etc.}$$

Using sum property given by

$$(1.3) \qquad I(P; Q; R) = \sum_{i=1}^{n} h(p_i, q_i, r_i),$$

some generalizations of the measure (1.1) have been studied by Sharma and Soni [5] and by Taneja [6].

Sharma and Taneja [4] have studied three measures of entropy satisfying the sub-additivity

$$(1.4) \qquad H(P_1{*}P_2) \leqq H(P_1) + H(P_2)$$

and using another function G of a probability distribution such that

$$(1.5) \qquad H(P_1{*}P_2) = H(P_1)\, G(P_2) + H(P_2)\, G(P_1),$$

where $G(P_1)$ and $G(P_2)$ both take values not exceeding unity. The property (1.5) can be said as generalized additivity. The three measures of inaccuracy and relative-information associated with a pair of probability distributions and satisfying the generalized additivity

$$(1.6) \qquad H(P_1{*}P_2; Q_1{*}Q_2) = H(P_1; Q_1)\, G(P_2; Q_2) + H(P_2; Q_2)\, G(P_1; Q_1)$$

have been studied by Sharma and Gupta [3] and by Gupta [2].

In this communication, we study three sub-additive measures associated with three discrete probability distributions. Simple properties including convexity of these measures and particular cases have also been studied.

2. GENERALIZED ADDITIVITY AND FUNCTIONAL EQUATION

Let $I(P; Q; R)$ be an information theoretic measure satisfying

$$(2.1) \qquad I(P_1{*}P_2; Q_1{*}Q_2; R_1{*}R_2) \leqq I(P_1; Q_1; R_1) + I(P_2; Q_2; R_2)$$

Next let G be another function of three probability distributions satisfying

$$(2.2) \qquad I(P_1{*}P_2; Q_1{*}Q_2; R_1{*}R_2) = I(P_1; Q_1; R)\, G(P_2; Q_2; R_2) + I(P_2; Q_2; R_2)\, G(P_1; Q_1; R_1)$$

The relation (2.2) can be said as generalized additivity of information improvement. Now we suppose that

$$(2.3) \qquad I(P; Q; R) = \sum_{i=1}^{n} h(p_i, q_i, r_i)$$

$$(2.4) \qquad G(P; Q; R) = \sum_{i=1}^{n} g(p_i, q_i, r_i).$$

Using (2.3) and (2.4) in (2.2) we have the functional equation

$$(2.5)\qquad \sum_{i=1}^{n}\sum_{j=1}^{m} h(p_{1i}, p_{2j}; q_{1i}q_{2j}; r_{1i}r_{2j}) = \sum_{i=1}^{n}\sum_{j=1}^{m} h(p_{1i}, q_{1i}, r_{1i}) \cdot$$

$$g(p_{2j}, q_{2j}, r_{2j}) + \sum_{i=1}^{n}\sum_{j=1}^{m} h(p_{2j}, q_{2j}, r_{2j})\, g(p_{1i}, q_{1i}, r_{1i}),$$

where

$$q_{1i}, q_{2j}, r_{1i}, r_{2j} \in (0, 1] \quad \text{and} \quad p_{1i}, p_{2j} \in [0, 1].$$

The continuous functions h and g that satisfy the functional equation (2.5) are the continuous solutions of the functional equation

$$(2.6)\qquad h(xx', yy', zz') = h(x, y, z)\, g(x', y', z') + g(x, y, z)\, h(x', y', z')$$

where

$$y, y', z, z' \in (0, 1] \quad \text{and} \quad x, x' \in [0, 1].$$

Therefore, we find the real continuous solutions of (2.6) in the following theorem:

Theorem 1. The most general complex solutions of (2.6) are given by

$$(2.7)\qquad h(x, y, z) = 0\,, \quad g(x, y, z) \ \text{arbitrary}$$

$$(2.8)\qquad h(x, y, z) = e_0(x, y, z)\, a(x, y, z); \quad g(x, y, z) = e_0(x, y, z)$$

and

$$(2.9)\qquad h(x, y, z) = \frac{1}{2k}\left[e_1(x, y, z) - e_2(x, y, z)\right];$$

$$g(x, y, z) = \tfrac{1}{2}\left[e_1(x, y, z) + e_2(x, y, z)\right],$$

where $k \neq 0$ is an arbitrary complex constant and $a(x, y, z)$, $e_j(x, y, z)$ $(j = 0, 1, 2)$ are arbitrary functions satisfying respectively

$$(2.10)\qquad a(xx', yy', zz') = a(x, y, z) + a(x', y', z')$$

and

$$(2.11)\qquad e_j(xx', yy', zz') = e_j(x, y, z)\, e_j(x', y', z') \quad (j = 0, 1, 2).$$

The proof when functions are of single variable will be found in Aczél [1], p. 205. The above result also follows on the same lines with suitable modifications.

Real Continuous Solutions of (2.6)

The real continuous solutions of (2.6) depend on solutions of the well-known in auxiliary equations (2.10) and (2.11). If we substitute the solutions of (2.10) and (2.11) in the solutions given by (2.8) and (2.9) respectively, these take the form

$$(2.12) \qquad h(x, y, z) = x^{\alpha}y^{\beta}z^{\gamma}(c_1 \log x + c_2 \log y + c_3 \log z)\,,$$
$$g(x, y, z) = x^{\alpha}y^{\beta}z^{\gamma}\,,$$

where α, β, γ, c_1, c_2, c_3 are arbitrary complex constants.

$$(2.13) \qquad h(x, y, z) = \frac{1}{2k}\,(x^{\alpha}y^{\beta}z^{\gamma} - x^{\delta}y^{\mu}z^{\nu})\,;$$
$$g(x, y, z) = \tfrac{1}{2}(x^{\alpha}y^{\beta}z^{\gamma} + x^{\delta}y^{\mu}z^{\nu})\,,$$

where α, β, γ, δ, μ, ν and k are arbitrary complex constants. Further, we see that $g(x, y, z)$ in (2.12) would be real iff α, β, γ are real and it would be continuous if α, β and γ are non-negative. It follows that corresponding $h(x, y, z)$ would be real iff c_1, c_2, c_3 are real and α, β, γ are non-negative. Thus one set of real and continuous solutions of (2.6) is given by

$$(2.14) \qquad h(x, y, z) = x^{\alpha}y^{\beta}z^{\gamma}(c_1 \log x + c_2 \log y + c_3 \log z)\,,$$
$$g(x, y, z) = x^{\alpha}y^{\beta}z^{\gamma}\,,$$

where $\alpha > 0$, $\beta \geqq 0$, $\gamma \geqq 0$ and c_1, c_2, c_3 are arbitrary real constants.

Now $g(x, y, z)$ in (2.13) would be real only under the following sets of conditions:

(i) α, β, γ, δ, μ, ν are all real or

(ii) α, β, γ, are complex conjugate of δ, μ, ν respectively.

The continuity of $g(x, y, z)$ requires that α, β, γ, δ, μ, ν are all non-negative. When $g(x, y, z)$ in (2.13) is real, corresponding $h(x, y, z)$ is also real iff k is real. Thus one of the other two sets of real continuous solutions of (2.6) obtained from (2.13) is given by

$$(2.15) \qquad h(x, y, z) = \frac{1}{2k}\,(x^{\alpha}y^{\beta}z^{\gamma} - x^{\delta}y^{\mu}z^{\nu})\,,$$
$$g(x, y, z) = \tfrac{1}{2}(x^{\alpha}y^{\beta}z^{\gamma} + x^{\delta}y^{\mu}z^{\nu})\,,$$

where α, β, γ, δ, μ, ν (all non-negative) and k are real arbitrary constants.

For second set of solutions, let $\alpha = \alpha_1 + i\alpha_2$; $\beta = \beta_1 + i\beta_2$; $\gamma = \gamma_1 + i\gamma_2$; $\delta = \alpha_1 - i\alpha_2$; $\mu = \beta_1 - i\beta_2$; $\nu = \gamma_1 - i\gamma_2$; $k = iR$, then (2.13) gives

$$(2.16) \qquad h(x, y, z) = \frac{1}{R}\, y^{\alpha_1}y^{\beta_1}z^{\gamma_1} \sin(\alpha_2 \log x + \beta_2 \log y + \gamma_2 \log z)\,,$$
$$g(x, y, z) = x^{\alpha_1}y^{\beta_1}z^{\gamma_1} \cos(\alpha_2 \log x + \beta_2 \log y + \gamma_2 \log z)\,.$$

Taking α, β, γ, δ, μ, ν for α_1, β_1, γ_1, α_2, β_2, γ_2 respectively in (2.16), we have the third set of solutions given by

$$h(x, y, z) = \frac{1}{R} x^\alpha y^\beta z^\gamma \sin(\delta \log x + \mu \log y + \nu \log z), \tag{2.17}$$

$$g(x, y, z) = x^\alpha y^\beta z^\gamma \cos(\delta \log x + \mu \log y + \nu \log z),$$

where $\alpha(>0)$, $\beta(\geqq 0)$, $\gamma(\geqq 0)$, δ, μ, ν and R are real constants. Hence (2.14), (2.15) and (2.17) are the only three non-trivial sets of real and continuous solutions of the functional equation (2.6) for $x \in [0, 1]$ and $y, z \in (0, 1]$.

3. CHARACTERIZATION OF INFORMATION IMPROVEMENT UNDER GENERALIZED ADDITIVITY

We adopt the following definition:

Information Improvement. The measure of information improvement $I(P; Q; R)$ associated with three discrete probability distributions P, Q and R is given by

$$I(P; Q; R) = \sum_{i=1}^{n} h(p_i, q_i, r_i) \tag{3.1}$$

where $h(p, q, r)$ is a real continuous solution of (2.5) under the conditions

$$h(\tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}) = 0, \quad h(1, \tfrac{1}{2}, \tfrac{1}{2}) = 0 \quad \text{and} \quad h(1, 1, \tfrac{1}{2}) = -1. \tag{3.2}$$

Now we characterize sub-additive measures of information improvement in the next theorem which follow from Theorem 1 and sum property.

Theorem 2. Corresponding to the real continuous solutions (2.14), (2.15) and (2.17), the three sub-additive measures of information improvement satisfying (2.2) can be only one of the following three forms:

$$I^l(P; Q; R : \alpha, \beta, \gamma) = 2^\gamma \sum_{i=1}^{n} p_i^\alpha q_i^\beta r_i^\gamma \log_2 (r_i/q_i), \tag{3.3}$$

$$\alpha > 0, \quad \beta \geqq 0, \quad \gamma \geqq 0,$$

$$I^p(P; Q; R : \alpha, \beta, \gamma, \delta) = (2^{\delta-\gamma} - 2^{\beta-\gamma})^{-1} \sum_{i=1}^{n} p_i^\alpha (q_i^\beta r_i^{\gamma-\beta} - q_i^\delta r_i^{\gamma-\delta}), \tag{3.4}$$

$$\alpha > 0, \quad \beta \geqq 0, \quad \delta \geqq 0, \quad \beta \neq \gamma, \quad \delta \neq \gamma$$

and

$$I^s(P; Q; R : \alpha, \beta, \gamma, \delta) = \frac{2^\gamma}{\sin \delta} \sum_{i=1}^{n} p_i^\alpha q_i^\beta r_i^\gamma \sin\left(\delta \log_2 \frac{r_i}{q_i}\right), \tag{3.5}$$

$$\alpha > 0, \quad \beta \geqq 0, \quad \gamma \geqq 0, \quad \delta \neq 0.$$

4. PARTICULAR CASES

(a) Taking $\alpha = 1$, $\beta = 0$, $\gamma = 0$ in (3.3), we get

$$I^{l}(P; Q; R : 1, 0, 0) = \sum_{i=1}^{n} p_i \log_2 (r_i/q_i),$$

which is Theil's [7] measure of information improvement.

(b) Taking $\beta = \gamma = \alpha - 1$ and $\delta = 0$ in (3.4), we have

$$I^{p}(P; Q; R : \alpha, \alpha - 1, \alpha - 1, 0) = (2^{1-\alpha} - 1)^{-1} \sum_{i=1}^{n} p_i^{\alpha}(q_i^{\alpha-1} - r_i^{\alpha-1})$$

which is information improvement of order α. Further we have

$$\lim_{\alpha \to 1} I^{p}(P; Q; R : \alpha, \alpha - 1, \alpha - 1, 0) = \sum_{i=1}^{n} p_i \log_2 (r_i/q_i),$$

which is Theil's [7] measure of information improvement.

(c) We see that

$$\lim_{\delta \to 0} I^{s}(P; Q; R : \alpha, \beta, \gamma, \delta) = 2^{\gamma} \sum_{i=1}^{n} p_i^{\alpha} q_i^{\beta} r_i^{\gamma} \log_2 (r_i/q_i)$$

which is (3.3).

5. PROPERTIES

Some of the common simple properties of the three subadditive measures of information improvement are enlisted below:

(a) Generalized additivity
(b) Sub-additivity
(c) Sum property
(d) Symmetry with respect to its arguments
(e) $I_n(P; Q; Q) = 0$.

Next we discuss the convexity of the sub-additive measure $I^p(P; Q; R; \alpha, \beta, \gamma, \delta)$ with respect to the probability distributions Q and R.

Theorem 3. The sub-additive measure of information improvement $I^p(P; Q; R : : \alpha, \beta, \gamma, \delta)$ is a convex $\cap$ function of the probability distribution Q whenever $\beta < 1 < < \delta$ or $\delta < 1 < \beta$.

Proof. Let us consider r probability distributions

$$Q_j(X) = \{q_j(x_1), \ldots, q_j(x_n)\}, \quad q_j(x_i) > 0, \quad \sum_{i=1}^{n} q_j(x_i) = 1,$$

$j = 1, 2, \ldots, r$ and a probability distribution

$$Q_0(X) = \{q_0(x_1), \ldots, q_0(x_n)\} \quad \text{of } X \text{ such that} \quad q_0(x_i) = \sum_{j=1}^{r} a_j\, q_j(x_i),$$

$i = 1, 2, \ldots, n$, where a_j's are non-negative numbers such that $\sum_{j=1}^{r} a_j = 1$. The probability distribution $Q_0(X)$ is a bonafide probability distribution of X since $\sum_{i=1}^{n} q_0(x_i) = \sum_{i=1}^{n} \sum_{j=1}^{r} a_j\, q_j(x_i) = 1$. Let

$$\Delta = I^p(P(X);\ Q_0(X);\ R(X) : \alpha, \beta, \gamma, \delta) - \sum_{j=1}^{r} a_j\, I^p(P(X);\ Q_j(X);\ R(X);\ \alpha, \beta, \gamma, \delta)\,.$$

Then $I^p(P; Q; R : \alpha, \beta, \gamma, \delta)$ will be a convex $\cap$ or $\cup$ function of the probability distribution Q according as $\Delta \gtrless 0$.

Now we have

$$(5.1)\qquad \Delta = (2^{\delta-\gamma} - 2^{\beta-\gamma})^{-1} \Big[\sum_{i=1}^{n} p^\alpha(x_i) \{q_0^\beta(x_i)\, r^{\gamma-\beta}(x_i) - q_0^\delta(x_i)\, r^{\gamma-\delta}(x_i)\} -$$

$$- \sum_{j=1}^{r} a_j \sum_{i=1}^{n} p^\alpha(x_i) \{q_j^\beta(x_i)\, r^{\gamma-\beta}(x_i) - q_j^\delta(x_i)\, r^{\gamma-\delta}(x_i)\}\Big] =$$

$$= (2^{\delta-\gamma} - 2^{\beta-\gamma})^{-1} \Big[\sum_{i=1}^{n} p^\alpha(x_i) \{(\sum_{j=1}^{r} a_j\, q_j(x_i))^\beta\, r^{\gamma-\beta}(x_i) -$$

$$- (\sum_{j=1}^{r} a_j\, q_j(x_i))^\delta\, r^{\gamma-\delta}(x_i)\} - \sum_{i=1}^{n} p^\alpha(x_i) \{ \sum_{j=1}^{r} a_j\, q_j^\beta(x_i)\, r^{\gamma-\beta}(x_i) -$$

$$- \sum_{j=1}^{r} a_j\, q_j^\delta(x_i)\, r^{\gamma-\delta}(x_i)\}\Big] =$$

$$= (2^{\delta-\gamma} - 2^{\beta-\gamma})^{-1} \sum_{i=1}^{n} p^\alpha(x_i) \Big[\{(\sum_{j=1}^{r} a_j\, q_j(x_i))^\beta - \sum_{j=1}^{r} a_j\, q_j^\beta(x_i)\}\, r^{\gamma-\beta}(x_i) -$$

$$- \{(\sum_{j=1}^{r} a_j\, q_j(x_i))^\delta - \sum_{j=1}^{r} a_j\, q_j^\delta(x_i)\}\, r^{\gamma-\delta}(x_i)\Big]\,.$$

Now by Jensen's inequality

$$(5.2)\qquad (\sum_{j=1}^{r} a_j\, q_j(x_i))^k \gtreqless \sum_{j=1}^{r} a_j\, q_j^k(x_i)\,,$$

according as $k \lesseqgtr 1$ with equality iff $q_j(x_i)$ are constants. Further we have

$$(5.3)\qquad (2^{\delta-\gamma} - 2^{\beta-\gamma})^{-1} \gtrless 0$$

according as $\beta \lesseqgtr \delta$.

By taking $\beta < 1 < \delta$ or $\delta < 1 < \beta$ it follows from (5.1), (5.2) and (5.3) that $\Delta > 0$. The result of the theorem is now obvious. □

Theorem 4. The sub-additive measure of information improvement $I^p(P; Q; R : \alpha, \beta, \gamma, \delta)$ is a convex $\cap$ function of the probability distribution R whenever $\gamma - \beta < 1 < \gamma - \delta$ or $\gamma - \delta < 1 < \gamma - \beta$.

The proof is exactly similar to that of Theorem 3.

Theorem 5. The sub-additive measures of information improvement $I^t(P; Q; R : : \alpha, \beta, \gamma)$, $I^p(P; Q; R : \alpha, \beta, \gamma, \delta)$ and $I^s(P; Q; R : \alpha, \beta, \gamma, \delta)$ are convex $\cap$ or $\cup$ functions of the probability distribution P according as $\alpha \lesseqgtr 1$.

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