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INTER-RELATIONS AMONG MULTIFUNCTIONS DEFINED ON BITOPOLOGICAL SPACES

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Abstract. This paper establishes links between weakly continuous, quasicontinuous and H-almost continuous multifunctions defined on bitopological spaces with values on bitopological spaces, generalizing the results from [3], [6], [8], [12], [13] and [15].

1. Introduction

The notions of upper (lower) weakly continuous and H-upper (lower) almost continuous multifunctions were introduced in 1978 in [11] and [17]. The notion of weakly continuous function from [5] was extended in 1982 to the function defined on bitopological spaces in [2] and for multifunctions defined on bitopological spaces in [14].

In [15] are established the links between quasicontinuous, H-almost continuous and weakly continuous multifunctions between topological spaces.

There are recent researches about quasicontinuous and H-almost continuous multifunctions defined on toplogical spaces with values on bitopological spaces in [3], and defined on bitopological spaces with values on topological spaces in [6].

In this paper we will establish links between weak continuous, quasicontinuous and H-almost continuous defines on bitopological spaces with values in bitopological spaces, generalizing the results from [3], [6] and the results from [8], [12], [13] and [15].

2. Definition. Notation

Definition 1 [1]. Let (X, P, Q) be a bitopological space. We say that $A \subset X$ is (1, 2)-semi open if there exists a P-open set B such that $B \subset A \subset \mathrm{Cl}_Q(B)$.

Similarly A is (2, 1)-semi open if there exists a Q-open set B such that $B \subset A \subset \mathrm{Cl}_P(B)$.

Definition 2 [1]. Let (X, P, Q) be a bitopological space. We say that $A \subset X$ is (1, 2)-semi closed if the set $(X-A)$ is (1, 2)-semi open. Similarly A is (2, 1)-semi closed if $(X-A)$ is (2, 1)-semi open.

Definition 3 [4]. Let (X, P, Q) be a bitopological space. Then P is regular with respect to Q if for each point $x \in X$ and each P-closed set A such that $x \overline{\in} A$ there is a P-open set U and a Q-open set V disjoint from U such that $x \in U$ and $P \subset V$. (X, P, Q) is pairwise regular if P is regular with respect to Q and Q is regular with respect to P.

Definition 4 [8]. A set A of a bitopological space (X, P, Q) is called strictly (P, Q) paracompact if every cover ν of A with P-open sets has a refinement ν with P-open sets, which cover A and ν is Q locally finite. Similarly we define A to be strictly (Q, P) paracompact.

Definition 5. A multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is said to be:

a) $(2,1) - H$ upper almost continuous ($(2,1) - H$. u.a.c.) at $x_0 \in X_1$ if for each Q_2-open set G containing $F(x_0)$,

$$x_0 \in \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^+(G))).$$

b) $(2,1) - H$ lower almost continuous ($(2,1) - H$. l. a. c.) at $x_0 \in X^1$ if for each Q_2 — open set G such that $F(x_0) \cap G \neq \emptyset$,

$$x_0 \in \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^-(G))).$$

c) $(2,1) - H$. u. a. c. ($(2,1) - H$. l. a. c.) if it has this property in any point $x \in X_1$.

If F is $(2, 1)$ and $(1, 2) - H$. u. a. c. (H. l. a. c) then F is pairwise H. u. a. c. (pairwise H. l. a. c.).

Definition 6. A multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is said to be:

a) $(1, 2)$ — upper quasicontinuous ($(1,2)$ — u. q. c.) at $x_0 \in X_1$ if for each P_2 — open set V containing $F(x_0)$ there exists a $(1, 2)$ — semi open set U containing x_0 such that $F(U) \subset V$.

b) $(1, 2)$ — lower quasicontinuous ($(1,2)$ — l. q. c.) at $x_0 \in X_1$ if for each P_2 — open set V such that $F(x_0) \cap V \neq \emptyset$ there exists a $(1, 2)$ — — semi open set U containing x_0 such that $F(u) \cap V \neq \emptyset$ for every $u \in U$.

c) $(1, 2)$ — u. q. c. ($(1, 2)$ — l. q. c.) if it has this property in any point $x \in X_1$.

If F is $(1, 2)$ and $(2, 1)$ — u. q. c. (l. q. c.), then F is said pairwise u. q. c. (pairwise l. q. c.).

Definition 7. [14]. A multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is said to be:

a) $(1, 2)$ — upper weakly continuous ($(1, 2)$ — u. w. c.) at $x_0 \in X_1$ if for each P_2 — open set G containing $F(x_0)$ there exists a P_1 — open set U containing x_0 such that $F(U) \subset \mathrm{Cl}_{Q_2}(G)$.

b) $(1, 2)$ — lower weakly continuous $(1, 2)$ — l. w. c.) at $x_0 \in X_1$ if for each P_2 open set G such that $F(x_0) \cap G \neq \emptyset$ there exists a P_1 — open set U containing x_0 such that $F(u) \cap \mathrm{Cl}_{Q_2}(G) \neq \emptyset$ for every $u \in U$.

c) $(1, 2)$ — u. w. c. ($((1,2)$ — l. w. c.) if it has this property in any point $x \in X_1$.

If F is $(1, 2)$ and $(2, 1)$ — u. w. c. (l. w. c.) then F is said pairwise u. w. c. (pairwise l. w. c.).

3. Properties

Lemma 1. *The following are equivalent for a multifunction* $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$:

1. F is $(1, 2)$ — u. q. c.
2. $F^+(G)$ *is* $(1, 2)$ — *semi open for every* P_2 — *open set* $G \subset X_2$.
3. $F^-(V)$ *is* $(1, 2)$ — *semi closed for every* P_2 — *closed set* $V \subset X_2$.

Proof. (1) $\Rightarrow$ (2). Let $x \in X_1$ and G be any P_2 — open set in X_2 such that $F(x_0) \subset G$. Then there is a $(1, 2)$ — semi open set U_x containing x and $F(U_x) \subset G$. Then $F^+(G) = \mathrm{U}\{U_x : x \in F^+(G)\}$. By [1, Theorem 1. 2] $F^+(G)$ is $(1, 2)$ — semi open.

(2) $\Rightarrow$ (1). Let $x \in X_1$ and G be any P_2 — open set such that $F(x_0) \subset G$. Then $x \in F^+(G)$ and $F^+(G)$ is $(1, 2)$ — semi open. Let $U = F^+(G)$ be, then $x \in U$, U is $(1, 2)$ — semi open and $F(U) \subset G$. So F is $(1, 2)$ u. q. c. at x.

(2) $\Leftrightarrow$ (3). Follows from $F^+(X_2 - G) = X_1 - F^-(G)$.

Lemma 2. *The following are equivalent for a multifunction* $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$:

1. F *is* $(1, 2)$ — *l. q. c.*
2. $F^-(G)$ *is* $(1, 2)$ — *semi open for each* P_2 — *open set* $G \subset X_2$.
3. $F^+(V)$ *is* $(1, 2)$ — *semi closed for every* P_2 — *closed set* $V \subset X_2$.

Proof. It is similar to the proof of Lemma 1.

Theorem 1. *If the multifunction* $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ *is* $(1, 2)$ — *u. q. c. and* $(2, 1)$ — *H. l. a. c., then* F *is* $(2, 1)$ — *l. w. c.*

Proof. Let $x \in X_1$ and G be any Q_2 — open set such that $F(x) \cap G \neq \emptyset$. Then $X_2 - \mathrm{Cl}_{P_2}(G)$ is a P_2 — open set and by Lemma 1, $F^+(X_2 - \mathrm{Cl}_{P_2}(G))$ is $(1, 2)$ — semi open. By [1, Theorem 1. 1] we have:

$$F^+(X_2 - \mathrm{Cl}_{P_2}(G)) \subset \mathrm{Cl}_{Q_1}(\mathrm{Int}_{P_1}(F^+(X_2 - \mathrm{Cl}_{P_2}(G)))). \text{ So}$$

$$X_1 - F^-(\mathrm{Cl}_{P_2}(G)) \subset \mathrm{Cl}_{Q_1}(\mathrm{Int}_{P_1}(X_1 - F^-(\mathrm{Cl}_{P_2}(G)))) = \mathrm{Cl}_{Q_1}(X_1 -$$

$$-\mathrm{Cl}_{P_1}(F^-(\mathrm{Cl}_{P_2}(G)))) = X_1 - \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}F^-(\mathrm{Cl}_{P_2}(G)))) \subset$$

$$\subset X_1 - \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^-(G))).$$

Thus we have

$$\mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^-(G))) \subset F^-(\mathrm{Cl}_{P_2}(G)).$$

Let $U = \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^-(G)))$. As F is $(2, 1)$ — H. l. a. c. and G is Q_2 — open then $x \in U$. So U is Q_1 — open, $x \in U$ and $F(u) \cap \mathrm{Cl}_{P_2}(G) \neq \emptyset$. $\forall\, u \in U$, Thus F is $(2,1)$ — u. w. c. at x.

Theorem 2. *If the multifunction* $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ *is* $(1, 2)$ — *l. q. c. and* $(2, 1)$ — *H. u. a. c. then* F *is* $(2, 1)$ — *u. w. c.*

Proof. Let $x \in X_1$ and G be any Q_2 — open set such that $F(x) \subset G$. Then $(X_2 - \mathrm{Cl}_{P_2}(G))$ is P_2 — open and by Lemma 2, $F^-(X_2 - \mathrm{Cl}_{P_2}(G))$ is $(1, 2)$ — semi open. By [1, Theorem 1. 1] we have

$$F^-(X_2 - \mathrm{Cl}_{P_2}(G)) \subset \mathrm{Cl}_{Q_1}(\mathrm{Int}_{P_1}(F^-(X_2 - \mathrm{Cl}_{P_2}(G)))).$$

So

$$X_1 - F^+(\mathrm{Cl}_{P_2}(G)) \subset \mathrm{Cl}_{Q_1}(\mathrm{Int}_{P_1}(X_1 - F^+(\mathrm{Cl}_{P_2}(G)))) =$$
$$= \mathrm{Cl}_{Q_1}(X_1 - \mathrm{Cl}_{P_1}(F^+(\mathrm{Cl}_{P_2}(G)))) = X_1 - \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^+(\mathrm{Cl}_{P_2}(G)))) \subset$$
$$\subset X_1 - \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^+(G))).$$

Thus we have

$$\mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^+(G))) \subset F^+(\mathrm{Cl}_{P_2}(G)).$$

Let $U = \mathrm{Int}_{Q_1}(\mathrm{Cl}_{P_1}(F^+(G)))$. As F is $(2, 1) - H$. ua. c. and G is Q_2—open then $x \in U$. So, U is Q_1 — open, $x \in U$ and $F(U) \subset \mathrm{Cl}_{P_2}(G)$. Thus F is (2,1) — u. w. c. at x.

Corollary 1. (Popa [15]). *If the multifunction $F : (X, P) \to (Y, Q)$ is u. q. c. and H. la. a. c., then F is l. w. c.*

Corollary 2 (Popa [15]). *If the multifunction $F : (X, P) \to (Y, Q)$ is l. q. c. and H. u. a. c., then F is u. w. c.*

Theorem 3. *Suppose (X_2, P_2, Q_2) is Q_2 regular with respect to P_2 and $F(x_0)$ strictly (Q_2, P_2) paracompact, then the multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is (2, 1) u. w. c. at x_0 if and only if $F : (X_1, Q_1) \to (X_2, Q_2)$ is u. s. c.*

Proof. Suppose F is (2, 1) — u. w. c. at $x_0 \in X_1$. Let $G \subset X_2$ a Q_2—open set containing $F(x_0)$. The space (X_2, P_2, Q_2) being Q_2 regular with respect to P_2, for every $y_i \in F(x_0)$ by [16, Proposition 5. 2] there is a Q_2 — open set D_i such that $y_i \in D_i \subset \mathrm{Cl}_{P_2}(D_i) \subset G$. So, we have

$$F(x_0) \subset U\{D_i : y_i \in F(x_0)\} \subset U\{\mathrm{Cl}_{P_2}(D_i) ;\ y_i \in F(x_0)\} \subset G.$$

$F(x_0)$ being strictly (Q_2, P_2) paracompact there is a family $\{A_j : j \in J\}$ of Q_2 — open sets such that $A_j \subset D_i$ for some j and $\{A_j : j \in J\}$ is a P_2 — locally finite covering of $F(x_0)$. If I denotes the set of all admissible values of i, we have

$$F(x_0) \subset U\{A_j : j \in J\} \subset \{\mathrm{Cl}_{P_2}(D_i) : i \in I\} \subset G.$$

Let $A = U\{A_j : j \in J\}$, then $\mathrm{Cl}_{P_2}(A) = U\{\mathrm{Cl}_{P_2}(A_j) : j \in J\}$.
The multifunction F being (2, 1) — u. w. c. at x_0, A Q_2—open and $F(x_0) \subset$ $\subset A$, there is a Q_1 — open set $U \subset X_1$ containing x_0 such that $F(U) \subset$ $\subset \mathrm{Cl}_{P_2}(A) \subset G$. This shows that $F : (X_1, Q_1) \to (X_2, Q_2)$ is u. s. c. in x.
The reciprocity is obvious.

Lemma 3. *Let (X, P, Q) be a bitopological space Q regular with respect to P and $A \subset X$, then for every Q-open set D which intersects A, there exists a Q-open set D_A so that $A \cap D_A \neq \emptyset$ and $\mathrm{Cl}_P(D_A) \subset D$.*

Proof. Let $x \in A \cap D$, then $x \bar{\in} (X - D)$ and $(X - D)$ is Q-closed. Q being regular with respect to P there exists a Q-open set U and a P-open set V disjoint from U such that $x \in U$ and $(X - D) \subset V$. From $U \cap V = \emptyset$ there follows that $U \cap \mathrm{Cl}_Q(V) = \emptyset$ and thus $x \bar{\in} \mathrm{Cl}_Q(V)$. Let $D_A = X - \mathrm{Cl}_Q(V)$, then D_A is Q-open and $x \in D_A$, so $A \cap D_A \neq \emptyset$. On the other hand $\mathrm{Cl}_P(D_A) = \mathrm{Cl}_P(X - \mathrm{Cl}_Q(V)) \subset \mathrm{Cl}_P(X - V) = X - V \subset$ $\subset D$.

Theorem 4. *If (X_2, P_2, Q_2) is Q_2 — regular with respect to P_2, then the multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is (2, 1) — l. w. c. at x_0 if and only if $F : (X_1, Q_1) \to (X_2, Q_2)$ is l. s. c.*

Proof. Suppose F is (2, 1) — l. w. c. at x_0. Let $G \subset X_2$ be a Q_2-open set such that $F(x_0) \cap G \neq \emptyset$. As (X_2, P_2, Q_2) is Q_2 — regular with respect to P_2 and $F(x_0) \cap G \neq \emptyset$, there exists a Q_2 — open set D such that $D \cap F(x_0) \neq \emptyset$ and $\mathrm{Cl}_{P_2}(D) \subset G$. The multifunction F being (2, 1) — l. w. c. at x_0, D Q_2 — open and $D \cap F(x_0) \neq \emptyset$, there exists a Q_1 — open set U containing x_0 such that $F(u) \cap \mathrm{Cl}_{P_2}(D) \neq \emptyset$ for every $u \in U$, thus $F(u) \cap G \neq \emptyset$ for every $u \in U$. This shows that $F : (X_1, Q_1) \to$ $\to (X_2, Q_2)$ is l. s. c. in x_0.
The reciprocity is obvious.

Corollary 3 (Popa, [13]). *For the multifunction $F : (X, P) \to (Y, Q)$ with Y T_3 space and for which $F(x)$ is strictly paracompact set, the concept of u. w. c. multifunction in x coincides with the concept of u. s. c. multifunction.*

Corollary 4 (Popa, [12]). *For the multifunction $F : (X, P) \to (Y, Q)$, with Y T_3 space, the concept of l. w. c. multifunction in x coincides with the concept of l. s. c. multifunction in x.*

Definition 8 [8]. *Let $F : (X_1, P_1, P_2) \to (Y, Q_1, Q_2)$ be a multifunction :*

a) *F is (P_1, Q_1) — S upper almost continuous (S. u. a. c.) with respect to Q_2 at x_0 if for every Q_1-open set V containing $F(x_0)$, there exists a P_1-open set U containing x_0 such that $F(U) \subset Int_{Q_1}(Cl_{Q_2}(V))$*

Similarly we define (P_2, Q_2) — S upper almost continuity with respect to Q_1 at $x_0 \in X_1$.

b) *F is (P_1, Q_1) — S lower almost continuous (S. l. a. c.) with respect to Q_2 at x_0 if foe every Q_1-open set V with $F(x_0) \cap V \neq \emptyset$ there exists a P_1-open set U containing x_0 such that $F(u) \cap Int_{Q_1}(Cl_{Q_2}(U)) \neq \emptyset$ for every $u \in U$.*

Similarly we define (P_2, Q_2) — S lower almost continuity with respect to Q_1 at $x_0 \in X_1$.

Corollary 5. *If (X_2, P_2, Q_2) is Q_2 regular with respect to P_2, then the multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is (Q_1, Q_2) — S. l. a. c. with respect to P_2 at x_0 if and only if $F : (X_1, Q_1) \to (X_2, Q_2)$ is l. s. c. at x_0.*

Corollary 6. (Mukherjee and Ganguly, [8]). *Suppose (X_2, P_2, Q_2) is Q_2 — regular with respect to P_2 and $F(x_0)$ strictly (Q_2, P_2) paracompact, then the multifunction $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is (Q_1, Q_2) S. u. a. c. with respect to P_2 at $x_0 \in X_1$ if and only if the multifunction $F : (X_1, Q_1) \to$ $\to (X_2, Q_2)$ is u. s. c. at x_0.*

Definition 9 [9]. A single valued mapping $f : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ is said to be pairwise continuous if the induced functions $f : (X_1, P_1) \to$ $\to (X_2, P_2)$ and $f : (X_1, Q_1) \to (X_2, Q_2)$ are continuous.

Corollary 7. *Let $f : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ a single valued mapping with (X_2, P_2, Q_2) pairwise regular. Then f is weakly pairwise continuous if and only if it is pariwise continuous.*

Theorem 5. *Suppose (X_2, P_2, Q_2) is Q_2 regular with respect to P_2 and $F(x_0)$ strictly (Q_2, P_2) paracompact. If the multifunction $F : (X_1, P_1, Q_1) \to$*

$\to (X_2, P_2, Q_2)$ *is* $(1; 2)$*-l. q. c. and* $(2, 1)$*-H. u. a. c. at* x_0 *then* $F : (X_1, Q_1) \to (X_2, Q_2)$ *is s. c. s. in* x_0.

Proof. Follows from Theorems 2 and 3.

Theorem 6. *Suppose* (X_2, P_2, Q_2) *is* Q_2 *regular with respect to* P_2. *If the multifunction* $F : (X_1, P_1, Q_1) \to (X_2, P_2, Q_2)$ *is* $(1,2)$*-u.q.c. and* $(2,1)$*-H.l.a.c. at* x_0 *then* $F : (X_1, Q_1) \to (X_2, Q_2)$ *is l. s. c. at* x_0.

Proof. Follows from Theorems 1 and 4.

Corollary 8. (Ewert, [3]). *Let X be a topological space and* (Y, T_1, T_2) *be a bitopological space in which* T_2 *is regula with respect to* T_1.

a) *If a multifunction* $F : X \to (Y, T_1, T_2)$ *is* T_2*-H. l. a. c. and* T_1*-u.q.c. at* x_0*, then F is* T_2*-l. s. c. at* x_0.

b) *If for each* $x \in X$ *the set* $F(x)$ *is* T_2*-compact, F is* T_2*-H.u.a.c. and* T_1*-l.q.c. at* x_0*, then F is* T_2*-u.s.c. at* x_0.

Corollary 9. (Lipski, [6]). *Let Y be a regular topological space. If a multifunction* $F : (X, T_1, T_2) \to Y$ *with* $F(x)$ *a compact set* $\forall x \in X$, is $(1, 2)$ *u. q. c. and* $(2,1)$*-H.l.a.c., then F is* T_2*-l.s.c.*

Corollary 10. (Lipski, [6]). *Let Y be a regular topological space. If a multifunction* $F : (X, T_1, T_2) \to Y$ *is* $(1, 2)$*-l.q.c. and* $(2, 1)$*-H. u. a.c., then F is* T_2*-u. s.c*

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