

DIRECT DECOMPOSITIONS OF DUALY RESIDUATED LATTICE ORDERED MONOIDS

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Abstract

The class of dually residuated lattice ordered monoids (*DRℓ*-monoids) contains, in an appropriate signature, all ℓ -groups, Brouwerian algebras, *MV*- and *GMV*-algebras, *BL*- and pseudo *BL*-algebras, etc. In the paper we study direct products and decompositions of *DRℓ*-monoids in general and we characterize ideals of *DRℓ*-monoids which are direct factors. The results are then applicable to all above mentioned special classes of *DRℓ*-monoids.

Keywords: *DRℓ*-monoid, lattice-ordered monoid, ideal, normal ideal, polar, direct factor.

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1. Introduction

Commutative dually residuated lattice-ordered monoids (in short: *DRℓ*-monoids) were introduced and studied by K.L.N. Swamy in [20], [21], [22] as a common generalization of commutative lattice-ordered groups (*ℓ*-groups) and Brouwerian algebras. The papers [23], [24], [9]–[15], [4] and the part of the thesis [5] engaged the further research of structure properties of commutative *DRℓ*-monoids. It was shown that *MV*-algebras (see [13]) and *BL*-algebras (see [14]) which are an algebraic counterpart of the Łukasiewicz infinite valued logic and Hájek basic fuzzy logic, respectively, can be understood as special cases of commutative *DRℓ*-monoids. General *DRℓ*-monoids (i.e., not necessarily commutative), the special case of which are also all *ℓ*-groups, were introduced by Kovář in [5]. *GMV*-algebras were defined as a non-commutative generalization of *MV*-algebras in [16] and it was shown there that they are special cases of *DRℓ*-monoids. This fact was then used when studying *GMV*-algebras in [17] and [18]. Similarly, it was proved in [6] that pseudo *BL*-algebras (defined in [2] as a non-commutative generalization of *BL*-algebras) are also a special case of *DRℓ*-monoids. *DRℓ*-monoids were further studied in [8], [7] and [19].

In the paper we shall study direct products and direct decompositions of *DRℓ*-monoids. The general results are then applicable for all mentioned special cases of *DRℓ*-monoids.

2. Basic notions and notation

Definition. An algebra $M = (M; +, 0, \vee, \wedge, \rightarrow, \leftarrow)$ of signature $\langle 2, 0, 2, 2, 2, 2 \rangle$ is called a *dually residuated (non-commutative) lattice-ordered monoid* (a *DRℓ-monoid*) if

- (M1) $(M; +, 0, \vee, \wedge)$ is a lattice-ordered monoid (*ℓ-monoid*), that is, $(M; +, 0)$ is a (non-commutative) monoid, (M, \vee, \wedge) is a lattice, and for any $x, y, u, v \in M$, the following identities are satisfied:

$$u + (x \vee y) + v = (u + x + v) \vee (u + y + v),$$

$$u + (x \wedge y) + v = (u + x + v) \wedge (u + y + v);$$

- (M2) if \leq denotes the order on M induced by the lattice $(M; \vee, \wedge)$, then, for any $x, y \in M$, we have

$x \rightarrow y$ is the least element $s \in M$ such that $s + y \geq x$,

$x \leftarrow y$ is the least element $t \in M$ such that $y + t \geq x$;

(M3) M fulfils the identities

$$((x \rightarrow y) \vee 0) + y \leq x \vee y, \quad y + ((x \leftarrow y) \vee 0) \leq x \vee y,$$

$$x \rightarrow x \geq 0, \quad x \leftarrow x \geq 0.$$

Commutative $DR\ell$ -monoids (called $DR\ell$ -semigroups) were introduced by K.L.N. Swamy in [20] as a common generalization of commutative ℓ -groups and Brouwerian algebras. The present definition of a non-commutative extension of $DR\ell$ -monoids is due to [5]. Also, for basic properties of non-commutative $DR\ell$ -monoids see [5].

Let us denote by $M^+ = \{x \in M : 0 \leq x\}$ the set of all positive elements in M .

Examples.

- a) Let $G = (G; +, 0, -(\cdot), \vee, \wedge)$ be an ℓ -group. Set $x \rightarrow y = x - y$ and $x \leftarrow y = -y + x$ for any $x, y \in G$. Then $(G; +, 0, \vee, \wedge, \rightarrow, \leftarrow)$ is a $DR\ell$ -monoid.
- b) Let G be an ℓ -group and G^+ be its positive cone, i.e.: $G^+ = \{x \in G : 0 \leq x\}$. Set $x \rightarrow y = (x - y) \vee 0$ and $x \leftarrow y = (-y + x) \vee 0$ for any elements $x, y \in G^+$. Then $(G^+; +, 0, \vee, \wedge, \rightarrow, \leftarrow)$ is a $DR\ell$ -monoid.
- c) Let $B = (B; \vee, \wedge)$ be a Brouwerian algebra, i.e. a dually relative pseudo-complemented lattice with the largest element (that means, for any $a, b \in B$, there exists the smallest element $x \in B$ such that $b \vee x \geq a$). Let us denote by $a - b$ this relative pseudocomplement x of the element b with respect to the element a . The lattice $(B; \vee, \wedge)$ has the smallest element 0 and if we set $a + b = a \vee b$ and $a \rightarrow b = a \leftarrow b = a - b$ for every $a, b \in B$, then $(B; +, 0, \vee, \wedge, \rightarrow, \leftarrow)$ is a commutative $DR\ell$ -monoid.
- d) Let $A = (A; \oplus, \neg, \sim, 0, 1)$ be a GMV -algebra (see, e.g., [16]), i.e. a non-commutative generalization of an MV -algebra. For any $x, y \in A$, put $x \odot y = \sim(\neg x \oplus \neg y)$, $x \rightarrow y = \neg y \odot x$ and $x \leftarrow y = x \odot \sim y$. If we denote $x \vee y = x \oplus (y \odot \sim x)$ and $x \wedge y = x \odot (y \oplus \sim x)$, then $(A; \vee, \wedge)$ is a bounded distributive lattice and the algebra $(A; \oplus, 0, \vee, \wedge, \rightarrow, \leftarrow)$ is

a (bounded) $DR\ell$ -monoid. If the addition \oplus is commutative, then the negations \neg and \sim coincide, A is an MV -algebra, and the induced $DR\ell$ -monoid is commutative.

Let M be a $DR\ell$ -monoid and $x \in M$. Then the *absolute value of an element* x is $|x| = x \vee (0 \multimap x)$.

Definitions.

a) If M is a $DR\ell$ -monoid and $\emptyset \neq I \subseteq M$, then I is called an *ideal of M* if the following conditions are satisfied:

- (1) $x, y \in I \implies x + y \in I$;
- (2) $x \in I, y \in M, |y| \leq |x| \implies y \in I$.

b) An ideal I is said to be *normal* if for each $x, y \in M$ the equivalence:

$$x \multimap y \in I \iff x \leftarrow y \in I$$

is satisfied.

Remark. By [8], normal ideals are just kernels of $DR\ell$ -homomorphisms.

It is proved in [8] that the set $\mathcal{C}(M)$ of all ideals of an arbitrary $DR\ell$ -monoid M , ordered by set inclusion, is an algebraic Brouwerian lattice in which infima coincide with set intersections. Further, by Lemma 21 of [8], if I and J are normal ideals of a $DR\ell$ -monoid M , then their join $I \vee J$ in $\mathcal{C}(M)$ is the following set:

$$I \vee J = \{x \in M : |x| \leq a + b, \text{ for some } a \in I^+, b \in J^+\}.$$

Definitions.

a) Let M be a $DR\ell$ -monoid and $X \subseteq M$. Then the set

$$X^\perp = \{y \in M : |x| \wedge |y| = 0, \text{ for each } x \in X\}$$

is called the *polar of X in M* .

b) A subset $X \subseteq M$ is a *polar in M* if there exists $Y \subseteq M$ such that $X = Y^\perp$.

By [7], every polar in M belongs to $\mathcal{C}(M)$ and it is a polar of some ideal of M . The polar of any ideal $I \in \mathcal{C}(M)$ is its pseudocomplement in the lattice $\mathcal{C}(M)$ and therefore the set $\mathcal{P}(M)$ of all polars in M is a complete Boolean algebra with respect to set inclusion.

3. Direct products and decompositions

In this section we will study properties of direct products of *DRℓ*-monoids, in particular with respect to possibilities of introduction of inner direct products.

Lemma 1. *Let M be a *DRℓ*-monoid. Then for any $v, w \in M$ we have $v \rightarrow w = 0$ if and only if $v \leftarrow w = 0$.*

Proof. If $v \rightarrow w = 0$ and $x \in M$, then $x + v \geq w$ if and only if $x \geq 0$. Hence $w = 0 + w \geq v$. Then also $w + 0 \geq v$, thus $0 \geq v \leftarrow w$. At the same time $w \geq v$ implies $v \leftarrow w \geq 0$; therefore, $v \leftarrow w = 0$. ■

Let B and C be *DRℓ*-monoids and let $M = B \times C$ be their direct product. Denote $\tilde{B}, \tilde{C} \subseteq M$ such that

$$\tilde{B} = \{(x_1, 0) : x_1 \in B\},$$

$$\tilde{C} = \{(0, x_2) : x_2 \in C\}.$$

The following proposition seems to be well-known as a folklore:

Proposition 2. *If B and C are *DRℓ*-monoids and $M = B \times C$ then \tilde{B} and \tilde{C} are normal ideals of *DRℓ*-monoid M and it holds:*

- a) $\tilde{B} + \tilde{C} = M, \quad \tilde{B} \cap \tilde{C} = \{0\}$;
- b) $x + y = x' + y'$ implies $x = x', y = y'$ for each $x, x' \in \tilde{B}$ and $y, y' \in \tilde{C}$.

■

Proposition 3. *If $M = B \times C$, then*

$$\tilde{B} = \tilde{C}^\perp \quad \text{and} \quad \tilde{C} = \tilde{B}^\perp.$$

Proof. For any elements $x_1 \in B$ and $y_2 \in C$ it is satisfied

$$|(x_1, 0)| \wedge |(0, y_2)| \in \tilde{B} \cap \tilde{C} = \{(0, 0)\}.$$

Therefore, $\tilde{B} \subseteq \tilde{C}^\perp$ and $\tilde{C} \subseteq \tilde{B}^\perp$.

Conversely, let $(z_1, z_2) \in (\tilde{B}^\perp)^+$. Then

$$(z_1, z_2) = (z_1, 0) + (0, z_2) \quad \text{and} \quad (z_1, 0) = (z_1, 0) \wedge (z_1, z_2) = (0, 0).$$

Thus $(\tilde{B}^\perp)^+ \subseteq \tilde{C}$, therefore also $\tilde{B}^\perp \subseteq \tilde{C}$, it means $\tilde{B}^\perp = \tilde{C}$.

Analogously, $\tilde{C}^\perp \subseteq \tilde{B}$. ■

Now we will deal with possibility of introduction of an inner direct decomposition of $DR\ell$ -monoids.

At first, we will prove the following lemma.

Lemma 4. *Let M be a $DR\ell$ -monoid and let $I, J \in \mathcal{C}(M)$ be such that $I + J = M$ and $I \cap J = \{0\}$. If $a \in M$ and $a_1 \in I$, $a_2 \in J$ are such that $a = a_1 + a_2$, then $a \geq 0$ if and only if $a_1 \geq 0$ and $a_2 \geq 0$.*

Proof. Suppose $0 \leq a = a_1 + a_2$. Then $0 \rightarrow a_2 \leq (a_1 + a_2) \rightarrow a_2$. Since, by Lemma 1.1.19 of [5], it holds $(p + q) \rightarrow r \leq p + (q \rightarrow r)$ for any $p, q, r \in M$, in our case we obtain $(a_1 + a_2) \rightarrow a_2 \leq a_1 + (a_2 \rightarrow a_2) = a_1$. So $0 \rightarrow a_2 \leq a_1$. Therefore, $0 \leq (0 \rightarrow a_2) \vee 0 \leq a_1 \vee 0 \in I$. Hence $(0 \rightarrow a_2) \vee 0 \in I \cap J$, that means $(0 \rightarrow a_2) \vee 0 = 0$. Thus $0 \rightarrow a_2 \leq 0$. By Lemma 1.1.16 of [5], $p \geq q$ if and only if $q \rightarrow p \leq 0$, for any $p, q \in M$. Thus we have $a_2 \geq 0$. Similarly, $a_1 \geq 0$.

The converse implication is obvious. ■

Definitions.

- a) An element y of a $DR\ell$ -monoid M is called *singular* if $0 \rightarrow y = 0$ (or equivalently, by Lemma 1, $0 \leftarrow y = 0$).
- b) An element $x \in M$ is called *invertible* if there exists an inverse element for it in the monoid $(M; +, 0)$.

Denote by $\text{Sing}(M)$ the set of all singular elements in M and by $\text{Inv}(M)$ the set of all invertible elements in M .

Remarks. Kovář proved in [5] (see Theorem 1.2.16 and Lemma 1.2.11) that $\text{Sing}(M) \in \mathcal{C}(M)$, $\text{Sing}(M) \subseteq M^+$ and 0 is the least element in $\text{Sing}(M)$. Further, by Theorems 1.2.1 and 1.2.4 of [5], $\text{Inv}(M)$ is also an ideal of M which is, moreover, an ℓ -group. The ideals $\text{Sing}(M)$ and $\text{Inv}(M)$ play an important role in the study of structure properties of $DR\ell$ -monoids

because, by Theorem 1.3.6 of [5], each $DR\ell$ -monoid M is isomorphic to the direct product of the $DR\ell$ -monoids $\text{Sing}(M)$ and $\text{Inv}(M)$.

At the same time, extreme case can arise, because if M is an ℓ -group, then $\text{Sing}(M) = \{0\}$ and $\text{Inv}(M) = M$. If M is a Brouwerian algebra, then, conversely, $\text{Sing}(M) = M$ and $\text{Inv}(M) = \{0\}$. Consequently, the cardinality of $\text{Sing}(M)$ determines the degree of dissimilarity of properties of a given $DR\ell$ -monoid from properties of an ℓ -group.

Proposition 5. *If M is a $DR\ell$ -monoid and $a, b \in M$ are orthogonal (i.e. $|a| \wedge |b| = 0$), then $a + b = b + a$.*

Proof. a) Assume $a, b \in M^+$ and $a \wedge b = 0$. By Lemmas 1.1.5 and 1.1.9 of [5], for any $x, y, z \in M$ it holds $x \rightarrow x = 0$ and $x \rightarrow (y \wedge z) = (x \rightarrow y) \vee (x \rightarrow z)$, hence in our case we have

$$(a \rightarrow (a \wedge b)) + b = ((a \rightarrow a) \vee (a \rightarrow b)) + b = (0 \vee (a \rightarrow b)) + b = a \vee b,$$

therefore $a + b = a \vee b = b + a$, in our case.

b) Now, let a, b be arbitrary elements in M such that $|a| \wedge |b| = 0$. As mentioned in the previous remark, by Theorem 1.3.6 of [5], M is the direct product of its ideals $\text{Sing}(M)$ and $\text{Inv}(M)$. Hence there are $a', b' \in \text{Sing}(M)$ and $x_a, x_b \in \text{Inv}(M)$ such that $a = a' + x_a$, $b = b' + x_b$. By [5], $|a| = a' + |x_a|$, $|b| = b' + |x_b|$. Therefore, the assumption $|a| \wedge |b| = 0$ implies $a' \wedge b' = 0$ and $|x_a| \wedge |x_b| = 0$.

By the part a), we obtain $a' + b' = b' + a'$. As $\text{Inv}(M)$ is an ℓ -group, it holds that $|x_a| \wedge |x_b| = 0$ entails $x_a + x_b = x_b + x_a$. Moreover, since M is isomorphic to the direct product of $\text{Sing}(M)$ and $\text{Inv}(M)$, elements in $\text{Sing}(M)$ commute with those in $\text{Inv}(M)$. Thus

$$\begin{aligned} a + b &= (a' + x_a) + (b' + x_b) = a' + b' + x_a + x_b = \\ &= b' + a' + x_b + x_a = (b' + x_b) + (a' + x_a) = b + a. \end{aligned}$$

■

Theorem 6. *Let M be a $DR\ell$ -monoid and $I, J \in \mathcal{C}(M)$. Let the following conditions be satisfied:*

1. $I + J = M$, $I \cap J = \{0\}$;
2. $\forall x, x' \in I, y, y' \in J; x + y = x' + y' \implies x = x', y = y'$.

If $\overline{M} = I \times J$ is the direct product of the *DRℓ*-monoids I and J , then M and \overline{M} are isomorphic.

Proof. The conditions 1 and 2 obviously yield that for every element $a \in M$ there exist unique elements $a_1 \in I$ and $a_2 \in J$ such that $a = a_1 + a_2$. Hence the mapping $f : a \mapsto (a_1, a_2)$ is a bijection of M onto \overline{M} .

Let us suppose $x \in I$ and $y \in J$. Then $|x| \in I$, $|y| \in J$ and $|x| \wedge |y| \in I \cap J = \{0\}$. It follows that x and y are orthogonal. Therefore, $x + y = y + x$ by Proposition 5. For this reason it holds for any elements $a, b \in M$

$$a + b = (a_1 + a_2) + (b_1 + b_2) = (a_1 + b_1) + (a_2 + b_2),$$

therefore

$$f(a + b) = (a_1 + b_1, a_2 + b_2) = f(a) + f(b).$$

Assume again $a = a_1 + a_2$, $b = b_1 + b_2 \in M$, $a_1, b_1 \in I$, $a_2, b_2 \in J$ and let $a \leq b$. By Lemma 1.1.14 of [5], there exists $x \in M^+$ such that $a + x = b$. Let $x = x_1 + x_2$, where $x_1 \in I$, $x_2 \in J$. By Lemma 4, it holds $x_1 \in I^+$ and $x_2 \in J^+$. From this we have $(a_1 + x_1) + (a_2 + x_2) = b_1 + b_2$, i.e. $a_1 + x_1 = b_1$, $a_2 + x_2 = b_2$, where $0 \leq x_1$, $0 \leq x_2$. As $0 \leq x_1$, it holds $a_1 \leq a_1 + x_1 = b_1$. Similarly, $a_2 \leq b_2$.

Hence, for any $a, b \in M$, $a \leq b$ if and only if $f(a) \leq f(b)$.

We have proved that f is an isomorphism of lattice-ordered monoids $(M; +, 0, \vee, \wedge)$ and $(\overline{M}; +, 0, \vee, \wedge)$. Since the values of the operations \rightarrow and \leftarrow are uniquely determined in both the *DRℓ*-monoids $M = (M; +, 0, \vee, \wedge, \rightarrow, \leftarrow)$ and $(\overline{M}; +, 0, \vee, \wedge, \rightarrow, \leftarrow)$ in the same manner by means of the operation $+$ and the order relation \leq , *DRℓ*-monoids $M = I + J$ and $\overline{M} = I \times J$ are also isomorphic. ■

Remarks.

- a) Let $\tilde{I} = \{(x, 0); x \in I\}$ and $\tilde{J} = \{(0, y); y \in J\}$. Since $I \cong \tilde{I}$ and $J \cong \tilde{J}$, the ideals I and J are (by Proposition 2 and Theorem 6) normal in M .
- b) By Theorem 6 and Proposition 3, the set of all direct factors of a *DRℓ*-monoid M is a subset of the set of all polars in M . In particular, $\text{Sing}(M)$ and $\text{Inv}(M)$ are polars in M . It holds

$$(\text{Sing}(M))^\perp = \text{Inv}(M) \quad \text{and} \quad (\text{Inv}(M))^\perp = \text{Sing}(M).$$

If M is a $DR\ell$ -monoid and $I \in \mathcal{C}(M)$, let us denote by $D(I)$ the join of ideals I and I^\perp in the lattice $\mathcal{C}(M)$.

Proposition 7. *If M is a $DR\ell$ -monoid, $I \in \mathcal{C}(M)$ and I is a direct factor of $DR\ell$ -monoid $D(I)$, then $I + I^\perp \in \mathcal{C}(D(I))$ and $I + I^\perp = D(I) = I \vee I^\perp$ (in the sense of $\mathcal{C}(M)$).*

Proof. Since I and I^\perp are normal ideals of $D(I)$, by Lemma 21 of [8], it holds that

$$I \vee I^\perp = \{x \in D(I); |x| \leq a + b, \text{ where } a \in I, b \in I^\perp\}.$$

in $\mathcal{C}(D(I))$ (consequently, also in $\mathcal{C}(M)$).

By Proposition 5, $a + b = b + a = a \vee b$. By Theorem 1.1.23 of [5], the underlying lattice $(M; \vee, \wedge)$ is distributive, therefore the lattice $(D(I)^+; \vee, \wedge)$ is also distributive. For this reason, from the inequality $|x| \leq a + b$, where $a \in I^+$ and $b \in (I^\perp)^+$, it follows the existence of elements $0 \leq a_1 \leq a$, $0 \leq b_1 \leq b$ in $D(I)$ such that $|x| = a_1 \vee b_1 = a_1 + b_1$. At the same time $a_1 \in I$, $b_1 \in I^\perp$ and hence $I \vee I^\perp = I + I^\perp$. ■

Corollary 8. *If M is a $DR\ell$ -monoid and $I \in \mathcal{C}(M)$, then $DR\ell$ -monoids $I + I^\perp$ and $I \times I^\perp$ are isomorphic if and only if $x + y = x' + y'$ implies $x = x'$ and $y = y'$, for any $x, x' \in I$ and $y, y' \in I^\perp$.* ■

By Proposition 15 of [8], for any ideal I of a $DR\ell$ -monoid M (and hence also for each polar in M) it holds that its polar I^\perp is the pseudocomplement of I in $\mathcal{C}(M)$. We can specify this result for the direct factors of M .

Proposition 9. *If an ideal I of a $DR\ell$ -monoid M is a direct factor in M , then the polar I^\perp is the complement of I in the lattice $\mathcal{C}(M)$.* ■

Now we can prove the following proposition:

Proposition 10. *If M is an arbitrary $DR\ell$ -monoid, then ideals I of M , for which there exists an ideal $J \in \mathcal{C}(M)$ such that I and J satisfy condition 1 from Theorem 6, form a Boolean lattice. This lattice is a sublattice of $\mathcal{C}(M)$.*

Proof. Let I and J satisfy the given assumptions. Then from distributivity of the lattice $\mathcal{C}(M)$ we obtain

$$(I \vee J) \cap (I^\perp \cap J^\perp) = (I \cap I^\perp \cap J^\perp) \vee (J \cap I^\perp \cap J^\perp) = \{0\},$$

$$(I \vee J) \vee (I^\perp \cap J^\perp) = (I \vee J \vee I^\perp) \cap (I \vee J \vee J^\perp) = M,$$

hence $I \vee J$ and $I^\perp \cap J^\perp$ satisfy condition 1.

The remaining part of the assertion follows from Proposition 9. \blacksquare

Let us consider the following condition of uniqueness of decomposition for $DR\ell$ -monoids M :

$$(UD) \quad \begin{array}{l} \text{If } I, J \in \mathcal{C}(M), I \cap J = \{0\}, x, x' \in I, y, y' \in J \\ \text{and } x + y = x' + y', \text{ then } x = x' \text{ and } y = y'. \end{array}$$

Theorem 11. *If $DR\ell$ -monoid M satisfies condition (UD), then the direct factors in M form a Boolean sublattice of the lattice $\mathcal{C}(M)$.*

Proof. If condition (UD) holds in M , then $I \in \mathcal{C}(M)$ is a direct factor if and only if I and $J = I^\perp$ satisfy condition 1. Therefore, the theorem follows from Proposition 10. \blacksquare

Remark. If G is an ℓ -group, then $DR\ell$ -monoids G and G^+ satisfy condition (UD). Hence their direct factors form a Boolean lattice.

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