

ON COMMUTATIVITY DEGREE OF CROSSED MODULES

SOMAYEH AMINI¹, SHAHRAM HEIDARIAN^{1*}, AND FARHAD KHAKSAR HAGHANI¹

ABSTRACT. In this paper, we define and study the notion of commutativity degree of finite crossed modules. We shall state some results concerning commutativity degree of crossed modules and obtain some upper and lower bounds for commutativity degree of finite crossed modules. Finally we show that, if two crossed modules are isoclinic, then they have the same commutativity degree.

1. INTRODUCTION

In 1968, Erdős and Turán [3], introduced the concept of commutativity degree of groups, when they worked on symmetric groups. Let G be a finite group, the commutativity degree of G , denoted by $d(G)$ is defined as

$$d(G) = \frac{|\{(x, y) \in G \times G : xy = yx\}|}{|G|^2}.$$

Note that $d(G) > 0$ and $d(G) = 1$ if and only if G is abelian. In 1973, Gustafson [5] obtained an upper bound for $d(G)$, when G is a non-abelian finite group. Few years later, Rusin [14] computed the value of $d(G)$, when $G' \subseteq Z(G)$ and $G' \cap Z(G)$ is trivial and classified all finite groups G for which $d(G)$ is greater than $\frac{11}{32}$. In 1995, all finite groups G , where $d(G) \geq \frac{1}{2}$ are classified, up to isoclinism, by Lescot [7]. Furthermore, Lescot [8] has also classified, up to isomorphism, all finite groups whose commutativity degrees lie in the interval $[\frac{1}{2}, 1]$. In 2006, Barry et al. [1] have shown that if G is a finite group with odd order and $d(G) \geq \frac{11}{75}$, then G is supersolvable. In addition, it had been proved that if $d(G) > \frac{1}{3}$, then G is supersolvable. In 2007, Erfanian et al. [4] studied relative commutativity degree $d(H, G)$, the probability that

Key words and phrases. Crossed module, commutativity degree, isoclinism.
2020 *Mathematics Subject Classification.* Primary: 20E34. Secondary: 20N99, 18B99.
DOI 10.46793/KgJMat2405.713A
Received: November 25, 2020.
Accepted: August 20, 2021.

elements of a given subgroup H of a finite group G commute with elements of G . In 2008, Pournaki and Sobhani [11] studied $d_g(G)$, the probability that the commutator of an arbitrarily chosen pair of elements in a finite group G equals a given element g . In 2018, Sepehrizadeh and Rismanchian [16] introduced and studied the concept of characteristic degree of a subgroup in a finite group and determined the upper and lower bounds for this probability.

A crossed module (T, G, δ) is a group homomorphism $\delta : T \rightarrow G$ together with an action of G on T satisfying certain conditions. This notion is an algebraic model for homotopy 3-types was already introduced by Whitehead [17] in 1948. In [10], [13] and [15] the concepts of isoclinism and n -isoclinism have been generalized for crossed modules (see also [6]). In 2019, Yavari and Salemkar [18] presented a generalized crossed module and investigated the category of generalized crossed modules. Also, in [2] and [12] the notions of stem cover and universal central extension have been extended for lie crossed modules.

In this paper, we generalize the concept of commutativity degree for the finite crossed modules and show that two isoclinic crossed modules have the same commutativity degree.

2. DEFINITIONS AND PRELIMINARIES ON CROSSED MODULES

In this section, we state some basic definitions, notions and elementary results.

A crossed module (T, G, δ) is a pair of groups T and G together with an action of G on T and a homomorphism $\delta : T \rightarrow G$ called the boundary map, satisfying the following axioms:

- i)* $\delta({}^g t) = g\delta(t)g^{-1}$ for all $g \in G, t \in T$;
- ii)* $\delta({}^{\delta(t)} s) = t s t^{-1}$ for all $t, s \in T$.

We will denote such a crossed module by $T \xrightarrow{\delta} G$. A crossed module (T, G, δ) is said to be finite, if the groups T and G are both finite. A crossed module (S, H, δ') is a subcrossed module of (T, G, δ) , when

- i)* S is a subgroup of T and H is a subgroup of G ;
- ii)* $\delta' = \delta|_S$, the restriction of δ to S ;
- iii)* the action of H on S is induced by the action of G on T .

In this case, we write $(S, H, \delta') \leq (T, G, \delta)$. A subcrossed module (S, H, δ) of (T, G, δ) is a normal subcrossed module, if

- i)* H is a normal subgroup of G ;
- ii)* ${}^g s \in S$ for all $g \in G, s \in S$;
- iii)* ${}^h t t^{-1} \in S$ for all $h \in H, t \in T$.

This is denoted by $(S, H, \delta) \trianglelefteq (T, G, \delta)$.

Let (S, H, δ) be a normal subcrossed module of (T, G, δ) . Consider the triple $(\frac{T}{S}, \frac{G}{H}, \bar{\delta})$, where $\bar{\delta} : \frac{T}{S} \rightarrow \frac{G}{H}$ is induced by δ . There is the action of $\frac{G}{H}$ on $\frac{T}{S}$ given by ${}^{gH}(tS) = ({}^g t)S$. It is called the quotient crossed module of (T, G, δ) by (S, H, δ) and denoted by $\frac{(T, G, \delta)}{(S, H, \delta)}$.

Let (T, G, δ) be a crossed module. The center of (T, G, δ) is the crossed module $Z(T, G, \delta) : T^G \rightarrow St_G(T) \cap Z(G)$, where $T^G = \{t \in T : {}^g t = t \text{ for all } g \in G\}$ and $St_G(T) = \{g \in G : {}^g t = t \text{ for all } t \in T\}$. A crossed module (T, G, δ) is abelian, if $(T, G, \delta) = Z(T, G, \delta)$. In addition, the commutator subcrossed module $[(T, G, \delta), (T, G, \delta)]$ of (T, G, δ) is $[(T, G, \delta), (T, G, \delta)] : D_G(T) \rightarrow [G, G]$, where $D_G(T)$ is the subgroup generated by $\{{}^g t t^{-1} : t \in T, g \in G\}$ and $[G, G]$ is the commutator subgroup of G . A crossed module (T, G, δ) is faithful, if the action of G on T is faithful, that is $St_G(T) = 1$.

If (S, H, δ') and (R, K, δ'') are two crossed modules, then consider the triple $(S \times R, H \times K, \delta' \times \delta'')$, where $S \times R$ and $H \times K$ are direct products of groups and $\delta' \times \delta'' : S \times R \rightarrow H \times K$ is defined by $(\delta' \times \delta'')(s, r) = (\delta'(s), \delta''(r))$ for all $(s, r) \in S \times R$. There is a componentwise action of $H \times K$ on $S \times R$, induced by the actions of two crossed modules. The crossed module $(S \times R, H \times K, \delta' \times \delta'')$ is called the direct product of (S, H, δ') and (R, K, δ'') and denoted by $(S, H, \delta') \times (R, K, \delta'')$.

Let (T, G, δ) and (T', G', δ') be crossed modules. A crossed module morphism $\langle \alpha, \phi \rangle : (T, G, \delta) \rightarrow (T', G', \delta')$ is a pair of homomorphism $\alpha : T \rightarrow T', \phi : G \rightarrow G'$ such that

- i) $\delta'(\alpha(t)) = \phi(\delta(t))$ for all $t \in T$;
- ii) $\alpha({}^g t) = \phi({}^g) \alpha(t)$ for all $t \in T, g \in G$.

If $\langle \alpha, \phi \rangle : (S, H, \delta') \rightarrow (T, G, \delta)$ is a crossed module morphism such that α and ϕ are both group isomorphisms, then $\langle \alpha, \phi \rangle$ is called an isomorphism.

Lemma 2.1 ([9]). *The (T, G, δ) is abelian if and only if G is abelian and the action of the crossed module is trivial.*

Remark 2.1. Let (T, G, δ) be a crossed module. We denote $\frac{(T, G, \delta)}{Z(T, G, \delta)}$ by $\bar{T} \xrightarrow{\bar{\delta}} \bar{G}$, where $\bar{T} = \frac{T}{T^G}$ and $\bar{G} = \frac{G}{St_G(T) \cap Z(G)}$, for shortness.

Lemma 2.2 ([10]). *Let (T, G, δ) be a crossed module. Define the maps $c_1 : \bar{T} \times \bar{G} \rightarrow D_G(T)$, where $(tT^G, g(St_G(T) \cap Z(G))) \mapsto {}^g t t^{-1}$ and $c_0 : \bar{G} \times \bar{G} \rightarrow [G, G]$, where $(g(St_G(T) \cap Z(G)), g'(St_G(T) \cap Z(G))) \mapsto [g, g']$ for all $t \in T, g, g' \in G$. Then the maps c_1 and c_0 are well-defined.*

Definition 2.1 ([15]). The crossed modules (T_1, G_1, δ_1) and (T_2, G_2, δ_2) are isoclinic, if there exist isomorphisms

$$(\eta_1, \eta_0) : (\bar{T}_1, \bar{G}_1, \bar{\delta}_1) \rightarrow (\bar{T}_2, \bar{G}_2, \bar{\delta}_2)$$

and

$$(\epsilon_1, \epsilon_0) : (D_{G_1}(T_1) \rightarrow [G_1, G_1]) \rightarrow (D_{G_2}(T_2) \rightarrow [G_2, G_2])$$

such that the diagrams

$$\begin{array}{ccc} \bar{T}_1 \times \bar{G}_1 & \xrightarrow{c_1} & D_{G_1}(T_1) \\ \downarrow \eta_1 \times \eta_0 & & \downarrow \epsilon_1 \\ \bar{T}_2 \times \bar{G}_2 & \xrightarrow{c'_1} & D_{G_1}(T_1) \end{array}$$

and

$$\begin{array}{ccc} \bar{G}_1 \times \bar{G}_1 & \xrightarrow{c_0} & [G_1, G_1] \\ \downarrow \eta_0 \times \eta_0 & & \downarrow \epsilon_0 \\ \bar{G}_2 \times \bar{G}_2 & \xrightarrow{c'_0} & [G_2, G_2] \end{array}$$

are commutative, where (c_1, c_0) and (c'_1, c'_0) are commutator maps of crossed modules (T_1, G_1, δ_1) and (T_2, G_2, δ_2) , that introduced in Lemma 2.2. The pair $((\eta_1, \eta_0), (\epsilon_1, \epsilon_0))$ will be called an isoclinism from (T_1, G_1, δ_1) to (T_2, G_2, δ_2) and this situation will be denoted by $((\eta_1, \eta_0), (\epsilon_1, \epsilon_0)) : (T_1, G_1, \delta_1) \sim (T_2, G_2, \delta_2)$.

3. COMMUTATIVITY DEGREE OF CROSSED MODULES

In the section, we generalize the notion of commutativity degree for crossed modules and state the main results of this paper.

Definition 3.1. Let (T, G, δ) be a finite crossed module. The commutativity degree $d(T, G, \delta)$ of (T, G, δ) is defined by

$$d(T, G, \delta) = \frac{|\{(x, y) \in G \times G : xy = yx, x, y \in St_G(T)\}|}{|G|^2}.$$

Let (T, G, δ) be a finite crossed module, then we set $cs(G) = \{(x, y) \in G \times G : xy = yx \text{ and } x, y \in St_G(T)\}$. Now, the commutativity degree (T, G, δ) is $d(T, G, \delta) = \frac{|cs(G)|}{|G \times G|}$. If $d(T, G, \delta)$ is abelian and the action of G on T is trivial, then $|cs(G)| = |G \times G|$ and $d(T, G, \delta) = 1$ and vice-versa. Therefore, (T, G, δ) is abelian if and only if $d(T, G, \delta) = 1$. In addition, if the action of G on T is faithful, then $d(T, G, \delta) = \frac{1}{|G|^2}$.

Proposition 3.1. Let (S, H, δ') and (R, K, δ'') be two crossed modules and $(T, G, \delta) = (S, H, \delta') \times (R, K, \delta'')$. Then $d(T, G, \delta) = d(S, H, \delta') \times d(R, K, \delta'')$.

Proof. By the definition of commutativity degree, we have

$$\begin{aligned} d(T, G, \delta) &= \frac{1}{|G|^2} |\{((h_1, k_1), (h_2, k_2)) \in G^2 : (h_1, k_1)(h_2, k_2) = (h_2, k_2)(h_1, k_1) \\ &\quad \text{and } (h_1, k_1), (h_2, k_2) \in St_G(T)\}| \\ &= \frac{1}{|G|^2} |\{((h_1, k_1), (h_2, k_2)) \in G^2 : (h_1 h_2, k_1 k_2) = (h_2 h_1, k_2 k_1) \\ &\quad \text{and } (h_1, k_1), (h_2, k_2) \in St_G(T)\}| \\ &= \left(\frac{1}{|H|^2} |\{(h_1, h_2) \in H^2 : h_1 h_2 = h_2 h_1 \text{ and } h_1, h_2 \in St_H(S)\}| \right) \end{aligned}$$

$$\begin{aligned} & \times \left(\frac{1}{|K|^2} |\{(k_1, k_2) \in K^2 : k_1 k_2 = k_2 k_1 \text{ and } k_1, k_2 \in St_K(R)\}| \right) \\ & = d(S, H, \delta') \times d(R, K, \delta''). \quad \square \end{aligned}$$

Theorem 3.1. *Let (T, G, δ) be a crossed module. Then $d(T, G, \delta) \leq \frac{K(G)}{|G|}$, where $K(G)$ is the number of conjugacy classes of G .*

Proof. Let r be the number of conjugacy classes of G and $C_1, C_2, C_3, \dots, C_r$ be the conjugacy classes of G . For $i \in \{1, 2, 3, \dots, r\}$, let $x_i \in C_i$. If $y \in C_i$, then $y = x_i^g$ for some $g \in G$. Thus, $C_G(y) = C_G(x_i^g) = C_G(x_i)^g$ and $|C_G(y)| = |C_G(x_i)|$. Now

$$\begin{aligned} |G|^2 d(T, G, \delta) &= |\{(x, y) \in G \times G : xy = yx \text{ and } x, y \in St_G(T)\}| \\ &= |cs(G)| \leq \sum_{x \in G} |C_G(x)| = \sum_{i=1}^r \sum_{x \in C_i} |C_G(x)| \\ &= \sum_{i=1}^r [G : C_G(x_i)] |C_G(x_i)| = |G|r = |G|K(G). \end{aligned}$$

Therefore, $d(T, G, \delta) \leq \frac{K(G)}{|G|}$. □

Corollary 3.1. *If (T, G, δ) is a crossed module and the action of G on T is trivial, then $d(T, G, \delta) = \frac{K(G)}{|G|}$.*

Corollary 3.2. *Let (T, G, δ) be a crossed module. If the action of G on T is trivial, then $\frac{1}{|G'|} \leq d(T, G, \delta)$.*

Proof. Since $[G : G']$ count irreducible characters of degree one, $[G : G'] < K(G)$. Then $\frac{|G|}{|G||G'|} \leq \frac{K(G)}{|G|} = d(T, G, \delta)$ so $\frac{1}{|G'|} \leq d(T, G, \delta)$. □

Theorem 3.2. *Let (T, G, δ) be a crossed module. Then $d(T, G, \delta) \leq \frac{1}{4}(1 + \frac{3}{|G'|})$.*

Proof. Let l be the number of non-equivalent irreducible representation of degree 1, n_2, \dots, n_l . Consider the degree equation

$$|G| = [G : G'] + \sum_{i=[G:G']+1}^{K(G)} (n_i)^2,$$

for each $n_i \geq 2$. Hence, $|G| \geq [G : G'] + 4(K(G) - [G : G'])$. Solving for $K(G)$ yield $K(G) \leq \frac{1}{4}(|G| + 3[G : G'])$. Therefore, $d(T, G, \delta) \leq \frac{K(G)}{|G|} \leq \frac{1}{4}(1 + \frac{3}{|G'|})$. □

Theorem 3.3. *Let (T, G, δ) be a crossed module. If G is a non-abelian finite group, then $d(T, G, \delta) \leq \frac{5}{8}$.*

Proof. Consider the class equation $|G| = |Z(G)| + \sum_{i=|Z(G)|+1}^{K(G)} |[x_i]|$, where for each i , $|[x_i]| \geq 2$. So $|G| \geq |Z(G)| + 2(K(G) - |Z(G)|) \geq |Z(G) \cap St_G(T)| + 2(K(G) - |Z(G)|)$.

Since G is not abelian, $\frac{G}{Z(G)}$ is not cyclic. Then $|\frac{G}{Z(G)}| \geq 4$, hence

$$\left| \frac{G}{Z(G) \cap St_G(T)} \right| \geq \left| \frac{G}{Z(G)} \right| \geq 4$$

and $|Z(G) \cap St_G(T)| \leq \frac{|G|}{4}$. Therefore, $K(G) \leq \frac{1}{2} \left(|G| + \frac{|G|}{4} \right) = \frac{5|G|}{8}$. Then $d(T, G, \delta) \leq \frac{K(G)}{|G|} \leq \frac{5}{8}$. \square

Theorem 3.4. *Let (T, G, δ) be a crossed module. If G be a nonabelian p -group, then $d(T, G, \delta) \leq \frac{p^2+p-1}{p^3}$.*

Proof. Let p be the prime number, $|G| = p^n$ and $|Z(G)| = p^m$. If $|G/Z(G)| = 1$ or $|G/Z(G)| = p$, then $G/Z(G)$ is cyclic and G will be abelian. Thus, $m \leq n - 2$ and we have

$$\begin{aligned} |G|^2 d(T, G, \delta) &\leq |G| K(G) \\ &= \sum_{x \in G} |C_G(x)| \\ &= \sum_{x \in Z(G)} |C_G(x)| + \sum_{x \in G \setminus Z(G)} |C_G(x)| \\ &\leq p^{m+n} + p^{n-1}(p^n - p^m) \\ &= p^{m+n} + p^{n-1}(|G| - |Z(G)|) \\ &\leq p^{2n-3}(p^2 + p - 1). \end{aligned}$$

Hence, $d(T, G, \delta) \leq \frac{p^2 + p - 1}{p^3}$. \square

The following corollary obtains from previous theorem.

Corollary 3.3. *Let (T, G, δ) be a crossed module and the action of G on T is trivial. If p is a prime number and G is non-abelian with $|G| = p^3$, then $d(T, G, \delta) = \frac{p^2+p-1}{p^3}$.*

Proof. Let $|G| = p^3$. By Corollary 3.1 and Theorem 3.4,

$$\begin{aligned} p^6 d(T, G, \delta) &= |G|^2 d(T, G, \delta) \\ &= |G| K(G) \\ &= \sum_{x \in G} |C_G(x)| \\ &= \sum_{x \in Z(G)} |C_G(x)| + \sum_{x \in G \setminus Z(G)} |C_G(x)| \\ &= p^4 + p^2(|G| - |Z(G)|) \\ &= p^3(p^2 + p - 1). \end{aligned}$$

Hence, $d(T, G, \delta) = \frac{p^2+p-1}{p^3}$. \square

Proposition 3.2. *Let (T, G, δ) be a crossed module and the action of G on T be trivial. If $|\frac{G}{Z(G)}| = p^k$, then $d(T, G, \delta) \geq \frac{p^{k-1} + p^{k-1}}{p^{2k-1}}$.*

Proof. Let $|\frac{G}{Z(G)}| = p^k$ and $x \in G$ such that $x \notin Z(G)$. Then, since $x \in C_G(x)$ and $x \notin Z(G)$, we have $C_G(x) \subsetneq G$. Also $Z(G) \subsetneq C_G(x)$. Thus $|Z(G)| < |C_G(x)| < |G|$ and then $p|Z(G)| \leq |C_G(x)| \leq p^{k-1}|Z(G)|$, where $|C_G(x)|$ dividing $|G|$. So $||x|| = |G : C_G(x)|$ and $p^{k-1} \geq ||x|| \geq p$. From the class equation we have $|G| = |Z(G)| + \sum_{x \in G} ||x|| \leq |Z(G)| + p^{k-1}(K(G) - |Z(G)|) \leq |Z(G)| + p^{k-1}(K(G) - |Z(G) \cap St_G(T)|)$, therefore

$$K(G) \geq \frac{|G| + (p^{k-1})|Z(G) \cap St_G(T)| - |Z(G)|}{p^{k-1}}.$$

Now solving for $d(T, G, \delta)$ and Corollary 3.1 yield $d(T, G, \delta) \geq \frac{p^k + p^{k-1} - 1}{p^{2k-1}}$. □

Example 3.1. Let $D_{pq} = \langle a, b : a^p = b^q = e, bab^{-1} = a^r \rangle$ such that p is prime, $q|p-1$ and r has order $q \pmod p$. This type of group is called a generalized dihedral group. Conjugacy classes type are $[e]$, $[a^u]$ and $[b^w]$ so that no classes are 1, $\frac{p-1}{q}$ and $q-1$, respectively and $Z(D_{pq}) = \{e\}$. Consider the map $i : D_{pq} \rightarrow D_{pq}$. If the action of D_{pq} on D_{pq} is conjugacy, then $St_{D_{pq}}(D_{pq}) = Z(D_{pq})$ and $d(D_{pq}, D_{pq}, i) = \frac{|Z(D_{pq})|^2}{|D_{pq}|^2} = \frac{1}{(pq)^2}$. If the action of D_{pq} on D_{pq} is trivial, then

$$d(D_{pq}, D_{pq}, i) = \frac{K(D_{pq})}{|D_{pq}|} = \frac{1 + \frac{p-1}{q} + q - 1}{pq} = \frac{q^2 + p - 1}{pq^2}.$$

If the action of D_{pq} on D_{pq} is faithful, then $d(D_{pq}, D_{pq}, i) = \frac{1}{|D_{pq}|^2} = \frac{1}{(pq)^2}$.

Lemma 3.1. *Let (T_1, G_1, δ_1) and (T_2, G_2, δ_2) be two crossed modules and $\varphi = \langle \alpha, \beta \rangle : (T_1, G_1, \delta_1) \rightarrow (T_2, G_2, \delta_2)$ be an isomorphism. Then φ induced isomorphisms*

$$\varphi_1 : \frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \rightarrow \frac{G_2}{St_{G_2}(T_2) \cap Z(G_2)},$$

where

$$\varphi_1(g_1(St_{G_1}(T_1) \cap Z(G_1))) = \beta(g_1)(St_{G_2}(T_2) \cap Z(G_2)),$$

$\varphi_2 : \frac{T_1}{T_1^{G_1}} \rightarrow \frac{T_2}{T_2^{G_2}}$, where $\varphi_2(t_1 T_1^{G_1}) = \alpha(t_1) T_2^{G_2}$, $\varphi_3 : [G_1, G_1] \rightarrow [G_2, G_2]$, where $\varphi_3[g_1, g_1] = [g_2, g_2]$ or $\varphi_3(g_1) = \beta(g_1)$, $\varphi_4 : D_{G_1}(T_1) \rightarrow D_{G_2}(T_2)$, where $\varphi_4(g_1 t_1 t_1^{-1}) = \beta^{(g_1)} \alpha(t_1) \alpha(t_1^{-1})$. In addition the following diagrams commute:

$$\begin{array}{ccc} \bar{G}_1 \times \bar{G}_1 & \xrightarrow{\varphi_1 \times \varphi_1} & \bar{G}_2 \times \bar{G}_2 \\ \downarrow c_0 & & \downarrow c'_0 \\ G'_1 & \xrightarrow{\varphi_3} & G'_2 \end{array}$$

and

$$\begin{array}{ccc} \bar{T}_1 \times \bar{G}_1 & \xrightarrow{\varphi_2 \times \varphi_1} & \bar{T}_2 \times \bar{G}_2 \\ \downarrow c_1 & & \downarrow c'_1 \\ D_{G_1}(T_1) & \xrightarrow{\varphi_4} & D_{G_1}(T_1). \end{array}$$

Proof. Let $(g_1, g'_1) \in G_1 \times G_1$. Then $c'_0(\varphi_1 \times \varphi_1)(\bar{g}_1, \bar{g}'_1) = c'_0(\varphi_1(\bar{g}_1), \varphi_1(\bar{g}'_1)) = c'_0(\beta(\bar{g}_1), \beta(\bar{g}'_1)) = [\beta(g_1), \beta(g'_1)] = \beta[g_1, g'_1] = \varphi_3[g_1, g'_1] = \varphi_3 c_0(\bar{g}_1, \bar{g}'_1)$. Now, let $(\bar{t}_1, \bar{g}_1) \in \bar{T}_1 \times \bar{G}_1$. Then

$$\begin{aligned} c'_1(\varphi_2 \times \varphi_1)(\bar{t}_1, \bar{g}_1) &= c'_1(\varphi_2(\bar{t}_1), \varphi_1(\bar{g}_1)) \\ &= c'_1(\alpha(t_1)T_2^{G_2}, \beta(g_1)(St_{G_2}(T_2) \cap Z(G_2))) \\ &= \beta(g_1)\alpha(t_1)\alpha(t_1)^{-1} = \varphi_4(g_1 t_1 t_1^{-1}) \\ &= \varphi_4 c_1(\bar{t}_1, \bar{g}_1). \end{aligned} \quad \square$$

Theorem 3.5. *Let $(T_1, G_1, \delta_1), (T_2, G_2, \delta_2)$ be two isoclinic finite crossed modules. Then $d(T_1, G_1, \delta_1) = d(T_2, G_2, \delta_2)$.*

Proof. Consider the following relation:

$$\begin{aligned} \frac{|G_1|^2 d(T_1, G_1, \delta_1)}{|St_{G_1}(T_1) \cap Z(G_1)|^2} &= \frac{|G_1|^2}{|St_{G_1}(T_1) \cap Z(G_1)|^2} \\ &\quad \times \frac{|\{(x, y) \in G_1 \times G_1 : xy = yx \text{ and } x, y \in St_{G_1}(T_1)\}|}{|G_1|^2} \\ &= \left| \frac{1}{|St_{G_1}(T_1) \cap Z(G_1)|} \right|^2 \\ &\quad \times |\{(x, y) \in G_1 \times G_1 : xy = yx \text{ and } x, y \in St_{G_1}(T_1)\}| \\ &= \left| \frac{1}{|St_{G_1}(T_1) \cap Z(G_1)|} \right|^2 \\ &\quad \times |\{(x, y) \in G_1 \times G_1 : [x, y] = 1 \text{ and } x, y \in St_{G_1}(T_1)\}| \\ &= \left| \frac{1}{|St_{G_1}(T_1) \cap Z(G_1)|} \right|^2 |\{(x, y) \in G_1 \times G_1 : x, y \in St_{G_1}(T_1) \\ &\quad \text{and } c_0(x(St_{G_1}(T_1) \cap Z(G_1)), y(St_{G_1}(T_1) \cap Z(G_1))) = 1\}| \\ &= \left| \left\{ (\alpha, \beta) \in \left(\frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \right)^2 : c_0(\alpha, \beta) = 1 \right\} \right| \\ &= \left| \left\{ (\alpha, \beta) \in \left(\frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \right)^2 : \varphi_3 c_0(\alpha, \beta) = 1 \right\} \right| \\ &= \left| \left\{ (\alpha, \beta) \in \left(\frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \right)^2 : c'_0(\varphi_1, \varphi_1)(\alpha, \beta) = 1 \right\} \right| \end{aligned}$$

$$\begin{aligned}
&= \left| \left\{ (\alpha, \beta) \in \left(\frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \right)^2 : c'_0(\varphi_1(\alpha), \varphi_1(\beta)) = 1 \right\} \right| \\
&= \left| \left\{ (\gamma, \sigma) \in \left(\frac{G_2}{St_{G_2}(T_2) \cap Z(G_2)} \right)^2 : c'_0(\gamma, \sigma) = 1 \right\} \right|.
\end{aligned}$$

By the above reasoning applied to (T_2, G_2, δ_2) in place of (T_1, G_1, δ_1) , this expression equals to $\left| \frac{G_2}{St_{G_2}(T_2) \cap Z(G_2)} \right|^2 d(T_2, G_2, \delta_2)$. That is $\left| \frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \right|^2 d(T_1, G_1, \delta_1) = \left| \frac{G_2}{St_{G_2}(T_2) \cap Z(G_2)} \right|^2 d(T_2, G_2, \delta_2)$. But $\frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)}$ and $\frac{G_2}{St_{G_2}(T_2) \cap Z(G_2)}$ are isomorphic, hence $\left| \frac{G_1}{St_{G_1}(T_1) \cap Z(G_1)} \right| = \left| \frac{G_2}{St_{G_2}(T_2) \cap Z(G_2)} \right|$. Now the equality $d(T_1, G_1, \delta_1) = d(T_2, G_2, \delta_2)$ follows. \square

Corollary 3.4. *Let (T_2, G_2, δ_2) be a subcrossed module of crossed module (T_1, G_1, δ_1) and $(T_1, G_1, \delta_1) = (T_2, G_2, \delta_2)Z(T_1, G_1, \delta_1)$, where $T_1 = G_2T_1^{G_1}$ and $G_1 = G_2(St_{G_1}(T_1) \cap Z(G_1))$. Then $d(T_1, G_1, \delta_1) = d(T_2, G_2, \delta_2)$.*

Proof. By Proposition 4 of [10], (T_1, G_1, δ_1) and (T_2, G_2, δ_2) are isoclinic, therefore $d(T_1, G_1, \delta_1) = d(T_2, G_2, \delta_2)$. \square

4. CONCLUSION

In this paper, we extended the concept of commutativity degree in group theory to finite crossed modules and derived some properties of this new concept. All our previous results show that the notion of commutativity degree, which was introduced in this paper, can be used to classify finite crossed modules. It is clear that this study which started here, can be successfully extended to calculating commutativity degree of some specific crossed modules. This will surely be the subject of further research.

Acknowledgements. The authors thank to the referee for his/her careful reading and their excellent suggestions.

REFERENCES

- [1] F. Barry, D. MacHale and Á. Ní Shé, *Some supersolvability conditions for finite groups*, Math. Proc. R. Ir. Acad. **106A**(2) (2006), 163–177.
- [2] B. Edalatzaheh, *Universal central extensions of lie crossed modules over a fixed lie algebra*, Appl. Categ. Structures **27** (2019), 111–123. <https://doi.org/10.1007/s10485-018-9545-z>
- [3] P. Erdős and P. Turán, *On some problems of a statistical group-theory IV*, Acta Math. Hungar. **19** (1968), 413–435.
- [4] A. Erfanian, R. Rezaei and P. Lescot, *On the relative commutativity degree of a subgroup of a finite group*, Comm. Algebra **35**(12) (2007), 4183–4197. <https://doi.org/10.1080/00927870701545044>
- [5] W. H. Gustafson, *What is the probability that two group elements commute?* Amer. Math. Monthly **80** (1973), 1031–1034. <https://doi.org/10.2307/2318778>

- [6] P. Hall, *The classification of prime-power groups*, J. Reine Angew. Math. **182** (1940), 130–141. <https://doi.org/10.1515/crll.1940.182.130>
- [7] P. Lescot, *Central extensions and commutativity degree*, Comm. Algebra **29**(10) (2001), 4451–4460. <https://doi.org/10.1081/agn-100106768>
- [8] P. Lescot, *Isoclinism classes and commutativity degrees of finite groups*, J. Algebra **177**(3) (1995), 847–869. <https://doi.org/10.1006/jabr.1995.1331>
- [9] K. J. Norrie, *Crossed modules and analogues of group theorems*, PhD thesis, King's College, University of London, 1987.
- [10] A. Odabas, E. Ö. Uslu and E. Ilgaz, *Isoclinism of crossed modules*, J. Symbolic Comput. **74** (2016), 408–424. <https://doi.org/10.1016/j.jsc.2015.08.006>
- [11] M. R. Pournaki and R. Sobhani, *Probability that the commutator of two group elements is equal to a given element*, J. Pure Appl. Algebra **212**(4) (2008), 727–734. <https://doi.org/10.1016/j.jpaa.2007.06.013>
- [12] H. Ravnbod and A. R. Salemkar, *On stem covers and the universal central extensions of lie crossed modules*, Comm. Algebra **47**(7) (2019), 2855–2869. <https://doi.org/10.1080/00927872.2018.1541461>
- [13] H. Ravanbod, A. R. Salemkar and S. Talebtash, *Characterizing n -isoclinic classes of crossed modules*, Glasg. Math. J. **61** (2019), 637–656. <https://doi.org/10.1017/S0017089518000411>
- [14] D. J. Rusin, *What is the probability that two elements of a finite group commute?* Pacific J. Math. **82**(1) (1979), 237–247.
- [15] A. R. Salemkar, H. Mohammadzadeh and S. Shahrokhi, *Isoclinism of crossed modules*, Asian-Eur. J. Math. **9**(3) (2016), Article ID 1650091. <https://doi.org/10.1142/S1793557116500911>
- [16] Z. Sepehrizadeh and M. R. Rismanchian, *On the characteristic degree of finite groups*, J. Algebr. Syst. **6**(1) (2018), 71–80. <https://dx.doi.org/10.22044/jas.2018.6328.1316>
- [17] J. H. C. Whithead, *On operators in relative homotopy groups*, Ann. of Math. **49** (1948), 610–640. <https://doi.org/10.2307/1969048>
- [18] M. Yavari and A. Salemkar, *The category of generalized crossed modules*, Categ. Gen. Algebr. Struct. Appl. **10**(1) (2019), 157–171. <http://dx.doi.org/10.29252/cgasa.10.1.157>

¹DEPARTMENT OF MATHEMATICS,
 SHAHREKORD BRANCH, ISLAMIC AZAD UNIVERSITY,
 SHAHREKORD, IRAN

*CORRESPONDING AUTHOR

Email address: amini1360sa@gmail.com

Email address: heidarianshm@gmail.com

Email address: haghani1351@yahoo.com