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## TABLE OF CONTENT

### PART 1: MATHEMATICS

|  | Page |
|--|------|
| <b>STATISTICAL ANALYSIS ON THE EFFECTIVENESS OF SHORT-TERM PROGRAMS DURING COVID-19 PANDEMIC: IN THE CASE OF PROGRAM BIJAK SIFIR 2020</b><br><i>Nazihah Safie, Syerrina Zakaria, Siti Madhiah Abdul Malik, Nur Bani Ismail, Azwani Alias Ruwaidiah Idris</i> | 1    |
| <b>RADIATIVE CASSON FLUID OVER A SLIPPERY VERTICAL RIGA PLATE WITH VISCOUS DISSIPATION AND BUOYANCY EFFECTS</b><br><i>Siti Khuzaimah Soid, Khadijah Abdul Hamid, Ma Nuramalina Nasero, NurNajah Nabila Abdul Aziz</i>  | 10   |
| <b>GAUSSIAN INTEGER SOLUTIONS OF THE DIOPHANTINE EQUATION <math>x^4 + y^4 = z^3</math> FOR <math>x \neq y</math></b><br><i>Shahrina Ismail, Kamel Ariffin Mohd Atan and Diego Sejas Viscarra</i>   | 19   |
| <b>A SEMI ANALYTICAL ITERATIVE METHOD FOR SOLVING THE EMDEN-FOWLER EQUATIONS</b><br><i>Mat Salim Selamat, Mohd Najir Tokachil, Noor Aqila Burhanddin, Ika Suzieana Murad and Nur Farhana Razali</i>  | 28   |
| <b>ROTATING FLOW OF A NANOFUID PAST A NONLINEARLY SHRINKING SURFACE WITH FLUID SUCTION</b><br><i>Siti Nur Alwani Salleh, Norfifah Bachok and Nor Athirah Mohd Zin</i>  | 36   |
| <b>MODELING THE EFFECTIVENESS OF TEACHING BASIC NUMBERS THROUGH MINI TENNIS TRAINING USING MARKOV CHAIN</b><br><i>Rahela Abdul Rahim, Rahizam Abdul Rahim and Syahrul Ridhwan Morazuk</i>  | 46   |
| <b>PERFORMANCE OF MORTALITY RATES USING DEEP LEARNING APPROACH</b><br><i>Mohamad Hasif Azim and Saiful Izzuan Hussain</i>  | 53   |
| <b>UNSTEADY MHD CASSON FLUID FLOW IN A VERTICAL CYLINDER WITH POROSITY AND SLIP VELOCITY EFFECTS</b><br><i>Wan Faezah Wan Azmi, Ahmad Qushairi Mohamad, Lim Yeou Jiann and Sharidan Shafie</i>   | 60   |
| <b>DISJUNCTIVE PROGRAMMING - TABU SEARCH FOR JOB SHOP SCHEDULING PROBLEM</b><br><i>S. Z. Nordin, K.L. Wong, H.S. Pheng, H. F. S. Saipol and N.A.A. Husain</i>  | 68   |
| <b>FUZZY AHP AND ITS APPLICATION TO SUSTAINABLE ENERGY PLANNING DECISION PROBLEM</b><br><i>Liana Najib and Lazim Abdullah</i>  | 78   |
| <b>A CONSISTENCY TEST OF FUZZY ANALYTIC HIERARCHY PROCESS</b><br><i>Liana Najib and Lazim Abdullah</i>   | 89   |
| <b>FREE CONVECTION FLOW OF BRINKMAN TYPE FLUID THROUGH AN COSINE OSCILLATING PLATE</b><br><i>Siti Noramirah Ibrahim, Ahmad Qushairi Mohamad, Lim Yeou Jiann, Sharidan Shafie and Muhammad Najib Zakaria</i>  | 98   |

|  |            |
|--|------------|
| <b>RADIATION EFFECT ON MHD FERROFLUID FLOW WITH RAMPED WALL TEMPERATURE AND ARBITRARY WALL SHEAR STRESS</b>                          | <b>106</b> |
| <i>Nor Athirah Mohd Zin, Aaiza Gul, Siti Nur Alwani Salleh, Imran Ullah, Sharena Mohamad Isa, Lim Yeou Jiann and Sharidan Shafie</i> |            |

## **PART 2: STATISTICS**

|   |            |
|---|------------|
| <b>A REVIEW ON INDIVIDUAL RESERVING FOR NON-LIFE INSURANCE</b>  | <b>117</b> |
| <i>Kelly Chuah Khai Shin and Ang Siew Ling</i>  |            |
| <b>STATISTICAL LEARNING OF AIR PASSENGER TRAFFIC AT THE MURTALA MUHAMMED INTERNATIONAL AIRPORT, NIGERIA</b>   | <b>123</b> |
| <i>Christopher Godwin Udomboso and Gabriel Olugbenga Ojo</i>  |            |
| <b>ANALYSIS ON SMOKING CESSATION RATE AMONG PATIENTS IN HOSPITAL SULTAN ISMAIL, JOHOR</b>   | <b>137</b> |
| <i>Siti Mariam Norrulashikin, Ruzaini Zulhusni Puslan, Nur Arina Bazilah Kamisan and Siti Rohani Mohd Nor</i>   |            |
| <b>EFFECT OF PARAMETERS ON THE COST OF MEMORY TYPE CHART</b>  | <b>146</b> |
| <i>Sakthiseswari Ganasan, You Huay Woon and Zainol Mustafa</i>  |            |
| <b>EVALUATION OF PREDICTORS FOR THE DEVELOPMENT AND PROGRESSION OF DIABETIC RETINOPATHY AMONG DIABETES MELLITUS TYPE 2 PATIENTS</b>   | <b>152</b> |
| <i>Syafawati Ab Saad, Maz Jamilah Masnan, Karniza Khalid and Safwati Ibrahim</i>  |            |
| <b>REGIONAL FREQUENCY ANALYSIS OF EXTREME PRECIPITATION IN PENINSULAR MALAYSIA</b>  | <b>160</b> |
| <i>Iszuanie Syafidza Che Ilias, Wan Zawiah Wan Zin and Abdul Aziz Jemain</i>  |            |
| <b>EXPONENTIAL MODEL FOR SIMULATION DATA VIA MULTIPLE IMPUTATION IN THE PRESENT OF PARTLY INTERVAL-CENSORED DATA</b>  | <b>173</b> |
| <i>Salman Umer and Faiz Elfaki</i>  |            |
| <b>THE FUTURE OF MALAYSIA'S AGRICULTURE SECTOR BY 2030</b>  | <b>181</b> |
| <i>Thanusha Palmira Thangarajah and Suzilah Ismail</i>  |            |
| <b>MODELLING MALAYSIAN GOLD PRICES USING BOX-JENKINS APPROACH</b>   | <b>186</b> |
| <i>Isnewati Ab Malek, Dewi Nur Farhani Radin Nor Azam, Dinie Syazwani Badrul Aidi and Nur Syafiqah Sharim</i>   |            |
| <b>WATER DEMAND PREDICTION USING MACHINE LEARNING: A REVIEW</b>   | <b>192</b> |
| <i>Norashikin Nasaruddin, Shahida Farhan Zakaria, Afida Ahmad, Ahmad Zia Ul-Saufie and Norazian Mohamaed Noor</i>   |            |
| <b>DETECTION OF DIFFERENTIAL ITEM FUNCTIONING FOR THE NINE-QUESTIONS DEPRESSION RATING SCALE FOR THAI NORTH DIALECT</b>   | <b>201</b> |
| <i>Suttipong Kawilapat, Benchlak Maneeton, Narong Maneeton, Sukon Prasitwattanaseree, Thoranin Kongsuk, Suwanna Arunpongpaisal, Jintana Leejongpermpool, Supattra Sukhawaha and Patrinee Traisathit</i> |            |

|  |            |
|--|------------|
| <b>ACCELERATED FAILURE TIME (AFT) MODEL FOR SIMULATION PARTLY INTERVAL-CENSORED DATA</b>   | <b>210</b> |
| <i>Ibrahim El Feky and Faiz Elfaki</i>   |            |
| <b>MODELING OF INFLUENCE FACTORS PERCENTAGE OF GOVERNMENTS' RICE RECIPIENT FAMILIES BASED ON THE BEST FOURIER SERIES ESTIMATOR</b> | <b>217</b> |
| <i>Chaerobby Fakhri Fauzaan Purwoko, Ayuning Dwis Cahyasari, Netha Aliffia and M. Fariz Fadillah Mardianto</i>                     |            |
| <b>CLUSTERING OF DISTRICTS AND CITIES IN INDONESIA BASED ON POVERTY INDICATORS USING THE K-MEANS METHOD</b>                        | <b>225</b> |
| <i>Khoirun Niswatin, Christopher Andreas, Putri Fardha Asa OktaviaHans and M. Fariz Fadilah Mardianto</i>                          |            |
| <b>ANALYSIS OF THE EFFECT OF HOAX NEWS DEVELOPMENT IN INDONESIA USING STRUCTURAL EQUATION MODELING-PARTIAL LEAST SQUARE</b>        | <b>233</b> |
| <i>Christopher Andreas, Sakinah Priandi, Antonio Nikolas Manuel Bonar Simamora and M. Fariz Fadillah Mardianto</i>                 |            |
| <b>A COMPARATIVE STUDY OF MOVING AVERAGE AND ARIMA MODEL IN FORECASTING GOLD PRICE</b>   | <b>241</b> |
| <i>Arif Luqman Bin Khairil Annuar, Hang See Pheng, Siti Rohani Binti Mohd Nor and Thoo Ai Chin</i>                                 |            |
| <b>CONFIDENCE INTERVAL ESTIMATION USING BOOTSTRAPPING METHODS AND MAXIMUM LIKELIHOOD ESTIMATE</b>                                  | <b>249</b> |
| <i>Siti Fairus Mokhtar, Zahayu Md Yusof and Hasimah Sapiri</i>   |            |
| <b>DISTANCE-BASED FEATURE SELECTION FOR LOW-LEVEL DATA FUSION OF SENSOR DATA</b>   | <b>256</b> |
| <i>M. J. Masnan, N. I. Maha3, A. Y. M. Shakaf, A. Zakaria, N. A. Rahim and N. Subari</i>   |            |
| <b>BANKRUPTCY MODEL OF UK PUBLIC SALES AND MAINTENANCE MOTOR VEHICLES FIRMS</b>  | <b>264</b> |
| <i>Asmahani Nayan, Amirah Hazwani Abd Rahim, Siti Shuhada Ishak, Mohd Rijal Ilias and Abd Razak Ahmad</i>                          |            |
| <b>INVESTIGATING THE EFFECT OF DIFFERENT SAMPLING METHODS ON IMBALANCED DATASETS USING BANKRUPTCY PREDICTION MODEL</b>             | <b>271</b> |
| <i>Amirah Hazwani Abdul Rahim, Nurazlina Abdul Rashid, Abd-Razak Ahmad and Norin Rahayu Shamsuddin</i>                             |            |
| <b>INVESTMENT IN MALAYSIA: FORECASTING STOCK MARKET USING TIME SERIES ANALYSIS</b>   | <b>278</b> |
| <i>Nuzlinda Abdul Rahman, Chen Yi Kit, Kevin Pang, Fauhatuz Zahroh Shaik Abdullah and Nur Sofiah Izani</i>                         |            |

## **PART 3: COMPUTER SCIENCE & INFORMATION TECHNOLOGY**

- ANALYSIS OF THE PASSENGERS' LOYALTY AND SATISFACTION OF AIRASIA PASSENGERS USING CLASSIFICATION** 291  
*Ee Jian Pei, Chong Pui Lin and Nabilah Filzah Mohd Radzuan*
- HARMONY SEARCH HYPER-HEURISTIC WITH DIFFERENT PITCH ADJUSTMENT OPERATOR FOR SCHEDULING PROBLEMS** 299  
*Khairul Anwar, Mohammed A.Awadallah and Mohammed Azmi Al-Betar*
- A 1D EYE TISSUE MODEL TO MIMIC RETINAL BLOOD PERFUSION DURING RETINAL IMAGING PHOTOPLETHYSMOGRAPHY (IPPG) ASSESSMENT: A DIFFUSION APPROXIMATION – FINITE ELEMENT METHOD (FEM) APPROACH** 307  
*Harnani Hassan, Sukreen Hana Herman, Zulfakri Mohamad, Sijung Hu and Vincent M. Dwyer*
- INFORMATION SECURITY CULTURE: A QUALITATIVE APPROACH ON MANAGEMENT SUPPORT** 325  
*Qamarul Nazrin Harun, Mohamad Noorman Masrek, Muhamad Ismail Pahmi and Mohamad Mustaqim Junoh*
- APPLY MACHINE LEARNING TO PREDICT CARDIOVASCULAR RISK IN RURAL CLINICS FROM MEXICO** 335  
*Misael Zambrano-de la Torre, Maximiliano Guzmán-Fernández, Claudia Sifuentes-Gallardo, Hamurabi Gamboa-Rosales, Huizilopoztli Luna-García, Ernesto Sandoval-García, Ramiro Esquivel-Felix and Héctor Durán-Muñoz*
- ASSESSING THE RELATIONSHIP BETWEEN STUDENTS' LEARNING STYLES AND MATHEMATICS CRITICAL THINKING ABILITY IN A 'CLUSTER SCHOOL'** 343  
*Salimah Ahmad, Asyura Abd Nassir, Nor Habibah Tarmuji, Khairul Firhan Yusob and Nor Azizah Yacob*
- STUDENTS' LEISURE WEEKEND ACTIVITIES DURING MOVEMENT CONTROL ORDER: UİTM PAHANG SHARING EXPERIENCE** 351  
*Syafıza Saila Samsudin, Noor Izyan Mohamad Adnan, Nik Muhammad Farhan Hakim Nik Badrul Alam, Siti Rosiah Mohamed and Nazihah Ismail*
- DYNAMICS SIMULATION APPROACH IN MODEL DEVELOPMENT OF UNSOLD NEW RESIDENTIAL HOUSING IN JOHOR** 363  
*Lok Lee Wen and Hasimah Sapiri*
- WORD PROBLEM SOLVING SKILLS AS DETERMINANT OF MATHEMATICS PERFORMANCE FOR NON-MATH MAJOR STUDENTS** 371  
*Shahida Farhan Zakaria, Norashikin Nasaruddin, Mas Aida Abd Rahim, Fazillah Bosli and Kor Liew Kee*
- ANALYSIS REVIEW ON CHALLENGES AND SOLUTIONS TO COMPUTER PROGRAMMING TEACHING AND LEARNING** 378  
*Noor Hasnita Abdul Talib and Jasmin Ilyani Ahmad*

## **PART 4: OTHERS**

- ANALYSIS OF CLAIM RATIO, RISK-BASED CAPITAL AND VALUE-ADDED INTELLECTUAL CAPITAL: A COMPARISON BETWEEN FAMILY AND GENERAL TAKAFUL OPERATORS IN MALAYSIA** 387  
*Nur Amalina Syafiqa Kamaruddin, Norizarina Ishak, Siti Raihana Hamzah, Nurfadhlina Abdul Halim and Ahmad Fadhly Nurullah Rasade*
- THE IMPACT OF GEOMAGNETIC STORMS ON THE OCCURRENCES OF EARTHQUAKES FROM 1994 TO 2017 USING THE GENERALIZED LINEAR MIXED MODELS** 396  
*N. A. Mohamed, N. H. Ismail, N. S. Majid and N. Ahmad*
- BIBLIOMETRIC ANALYSIS ON BITCOIN 2015-2020** 405  
*Nurazlina Abdul Rashid, Fazillah Bosli, Amirah Hazwani Abdul Rahim, Kartini Kasim and Fathiyah Ahmad@Ahmad Jali*
- GENDER DIFFERENCE IN EATING AND DIETARY HABITS AMONG UNIVERSITY STUDENTS** 413  
*Fazillah Bosli, Siti Fairus Mokhtar, Noor Hafizah Zainal Aznam, Juaini Jamaludin and Wan Siti Esah Che Hussain*
- MATHEMATICS ANXIETY: A BIBLIOMETRIX ANALYSIS** 420  
*Kartini Kasim, Hamidah Muhd Irpan, Noorazilah Ibrahim, Nurazlina Abdul Rashid and Anis Mardiana Ahmad*
- PREDICTION OF BIOCHEMICAL OXYGEN DEMAND IN MEXICAN SURFACE WATERS USING MACHINE LEARNING** 428  
*Maximiliano Guzmán-Fernández, Misael Zambrano-de la Torre, Claudia Sifuentes-Gallardo, Oscar Cruz-Dominguez, Carlos Bautista-Capetillo, Juan Badillo-de Loera, Efrén González Ramírez and Héctor Durán-Muñoz*

## Gaussian Integer Solutions of the Diophantine Equation $x^4 + y^4 = z^3$ for $x \neq y$

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The investigation of determining solutions for the Diophantine equation  $x^4 + y^4 = z^3$  over the Gaussian integer field, for the specific case of  $x \neq y$ , is discussed. The discussion includes various preliminary results needed to build the future resolvent theory of the Diophantine equation studied. Our findings show the existence on infinitely many solutions. Since the analytical method used is based on simple algebraic properties, it can be easily generalized to study the behavior and the conditions for existence of solutions to other Diophantine equations, allowing a deeper understanding, even when no general solution is known.

**Keywords:** Diophantine equation, Gaussian integer, algebraic properties, existence, quartic

### 1. Introduction

The field of Diophantine equations is ancient, vast, and no general method exists to decide whether a given Diophantine equation has any solution or how many. Many studies were conducted in the past on solving equations in the field of Gaussian integers. For example, Szabó (2004) investigated some fourth-degree Diophantine equations in Gaussian integers, stating that for certain choices of the coefficients  $a, b, c$ , the solutions of the Diophantine equation  $ax^4 + by^4 = cz^2$  in Gaussian integers satisfy  $xy = 0$ . Apart from that, Najman (2010) showed that the equation  $x^4 \pm y^4 = iz^2$  has only trivial solutions in Gaussian integers. Then, Emory (2012) showed that nontrivial quadratic solutions exist for  $x^4 + y^4 = d^2z^4$  when either  $d = 1$  or  $d$  is a congruent number. Moreover, Izadi et al. (2015) examined solutions in the Gaussian integers for different choices of  $a, b$  and  $c$  for the Diophantine equation  $ax^4 + by^4 = cz^2$ . The same author, Izadi et al. (2018), then examined a class of fourth-power Diophantine equations of the form  $x^4 + kx^2y^2 + y^4 = z^2$  and  $ax^4 + by^4 = cz^2$  in the Gaussian integers, where  $a$  and  $b$  are prime integers. In recent years, Söderlund (2020) discovered that the only primitive non-zero integer solutions to the Fermat quartic  $34x^4 + y^4 = z^4$  are  $(x, y, z) = (\pm 2, \pm 3, \pm 5)$ . The proofs are based on a previously given complete solution to another Fermat quartic, namely  $x^4 + y^4 = 17z^4$ . Moreover, Jakimczuk (2021) investigated the equation  $x^4 - y^4 = z^s$ , and showed that if  $s$  is an odd prime, then the equation has infinitely many solutions  $(x, y, z)$  where  $x > y > 0$  and  $z > 0$ .

In this paper we carry on the investigation of determining solutions for the Diophantine equation  $x^4 + y^4 = z^3$  over the Gaussian integer field for the specific case of  $x \neq y$ , which has remained unsolved. Note that the case  $x = y$  has been solved in Ismail et al. (2021).

### 2. Results and discussion

In this section, we will use elementary algebraic methods to study the behavior of the Diophantine equation  $x^4 + y^4 = z^3$  when  $x \neq y$ . Our interest is to determine which conditions give us non-trivial solutions and which ones produce no solutions of only trivial ones. For simplicity, we will focus only on non-trivial solutions.

The ensuing discussion is supported by the following analysis. Suppose that  $(a, b, c)$  is a solution of

$$x^4 + y^4 = z^3 \tag{1}$$

such that  $a \neq b$ , and  $a, b, c \in \mathbb{Z}[i]$ . Let

$$a = r + si, \quad b = t + mi \quad \text{and} \quad c = g + hi, \tag{2}$$



where  $r, s, t, m, g, h \in \mathbb{Z}$ , and  $r \neq t$  or  $s \neq m$ . Then, replacing on (1), we have

$$(r^4 + t^4 - 6(r^2s^2 + t^2m^2) + s^4 + m^4) + 4(r^3s - rs^3 + t^3m - tm^3)i = (g^3 - 3gh^2) + (3g^3h - h^3)i,$$

which in turn implies that

$$r^4 + t^4 - 6(r^2s^2 + t^2m^2) + s^4 + m^4 = g^3 - 3gh^2, \quad (3)$$

$$4(r^3s - rs^3 + t^3m - tm^3) = 3g^2h - h^3. \quad (4)$$

Starting from (3) and (4), we will divide our study into four main cases based on possible values for  $r$  and  $s$ . Each of these cases will be subdivided into four subcases based in possible values for  $t$  and  $m$ . Finally, we will further subdivide these into four possibilities based on values for  $g$  and  $h$ .

**Case 1.** ( $r = 0, s = 0, t = 0, m \neq 0, g \neq 0, h = 0$ )

From (3) we have  $m^4 = g^3$ . (Notice that (4) is automatically satisfied under this case.) It follows that  $|m| = g^{3/4}$ , with  $m$  an integer. This implies that  $g = u^4$  for some integer  $u$ . Thus,  $|m| = |u|^3$ , or, equivalently,  $m = u^3$ . Hence,  $(m, g) = (u^3, u^4)$ . By letting  $u = \pm 1, \pm 2, \pm 3, \dots, \pm k, \dots$ , where  $k$  is an integer, we obtain infinitely many solutions for  $(m, g)$ . In turn, this leads us to infinitely many solutions for  $(a, b, c)$  of the form

$$\boxed{(a, b, c) = (0, n^3i, n^4)}.$$

**Case 2.** ( $r = 0, s = 0, t \neq 0, m \neq 0, g \neq 0, h = 0$ )

From (4), we obtain  $4(t^3m - tm^3) = 0$ , which we can rewrite as  $4tm(t^2 - m^2)$ . Since  $t, m \neq 0$ , we must have  $t^2 - m^2 = 0$ , which implies  $|t| = |m|$  or, equivalently,  $t = \pm m$ . Upon replacing on (3) we obtain

$$-4m^4 = g^3. \quad (5)$$

We can clearly see that  $g < 0$  and  $2 \mid g$ . Then, let

$$g = -2^\alpha v, \quad (6)$$

where  $v \wedge 2 = 1$ . Replacing on (5) yields  $-4m^4 = -2^{3\alpha}v^3$ , which implies

$$|m| = 2^{\frac{3\alpha-2}{4}} v^{\frac{3}{4}}. \quad (7)$$

Since  $m$  is an integer, then  $3\alpha \equiv 2 \pmod{4}$ , which is an equation whose only solutions are of the form  $\alpha = 4k + 2$  for  $k \in \mathbb{Z}$ . On the other hand, once again due to  $m$  being an integer, there must exist an integer  $u$  such that  $v = u^4$ . Then, replacing on (6), we have  $g = -2^{4k+2}u^4$ , and replacing on (7), we have  $|m| = 2^{3k+1}|u|^3$ .

Therefore, this case leads to  $(t, m, g) = (\pm 2^{3k+1}u^3, \pm 2^{3k+1}u^3, -2^{4k+2}u^4)$  and  $(t, m, g) = (\pm 2^{3k+1}u^3, \mp 2^{3k+1}u^3, -2^{4k+2}u^4)$ . In turn, this lead to

$$\boxed{(a, b, c) = (0, 2^{3k+1}u^3(1 \pm i), -2^{4k+2}u^4)},$$

for  $k, u \in \mathbb{Z}$  and  $k > 0$ .

**Case 3.** ( $r = 0, s \neq 0, t = 0, m \neq 0, g \neq 0, h = 0$ )

From (3), we obtain  $s^4 + m^4 = g^3$ . (Under these conditions, (4) is automatically satisfied.) Since  $s, m$  and  $g$  are all integers, from Theorem 1.2 and Theorem 1.3 in Ismail and Mohd Atan (2013), the triplet  $(x, y, z) = (s, m, g)$  is a solution to the equation  $x^4 + y^4 = z^3$  if and only if  $s = m = 4n^3$  and

$g = 8n^4$  (which contradicts the hypothesis that  $a \neq b$ ), or  $s = un^{3k-1}$ ,  $m = vn^{3k-1}$  and  $g = n^{4k-1}$ , where  $n = u^4 + v^4$  and for any integer  $k$ . It follows from (2) that

$$(a, b, c) = (un^{3k-1}i, vn^{3k-1}i, n^{4k-1}),$$

where  $u \neq v$ .

**Case 4.** ( $r = 0, s \neq 0, t \neq 0, m \neq 0, g \neq 0, h = 0$ )

From (3) and (4) we obtain

$$t^4 - 6t^2m^2 + m^4 + s^4 = g^3 \quad (8)$$

$$4t^3m - 4tm^3 = 0, \quad (9)$$

respectively. We can rewrite (9) as  $4tm(t^2 - m^2) = 0$ . Since  $t, m \neq 0$ , we must have  $|t| = |m|$ . Substituting in (8) yields

$$s^4 - 4m^4 = g^3. \quad (10)$$

There are two possibilities to be considered here:

(i)  $|s| = |m|$ ,

(ii)  $|s| \neq |m|$ .

Under (i) we have the following theorem, which states the form of solutions to the equation  $s^4 - 4m^4 = g^3$  when  $|s| = |m|$ .

**Theorem 1.** *The solutions to the equation  $x^4 - 4y^4 = z^3$ , when  $|x| = |y|$ , are given by  $x = s, y = m$  and  $z = g$ , where*

$$(s, m, g) = (9n^3, 9n^3, -27n^4),$$

$$(s, m, g) = (9n^3, -9n^3, -27n^4).$$

*Proof.* Let  $x = s$  and  $y = m$  such that  $s = m$ , and let  $z = g$  be a solution to  $x^4 - 4y^4 = z^3$ . We see that

$$-3m^4 = g^3. \quad (11)$$

This clearly implies that  $g \equiv 0 \pmod{3}$  and  $g$  is negative. Let  $g = -3^e u$ , where  $3 \nmid u = 1$  and  $e > 1$ . Thus, from (11) we see that

$$-3m^4 = -3^{3e} u^3,$$

from which we obtain

$$|m| = 3^{\frac{3e-1}{4}} u^{\frac{3}{4}} \quad \text{or} \quad m = \pm 3^{\frac{3e-1}{4}} u^{\frac{3}{4}}. \quad (12)$$

Since  $m$  is an integer, we must have that  $\frac{3e-1}{4}$  is an integer and there exists an integer  $v$  such that  $u = v^4$ . Thus,  $3e - 1 \equiv 0 \pmod{4}$ , which on simplifying gives  $e = 3 + 4j$  for some integer  $j$ . It follows from (12) that

$$m = \pm 3^{2+3j} v^3. \quad (13)$$

By (11) and (13), we obtain  $g^3 = -3(3^{2+3j} v^3)^4$ , which on simplifying gives  $g = -3^3(3^j v)^4$ . Let  $n = 3^j v$ . Then, we will have  $g = -27n^4$ , which from (13) gives  $m = \pm 9n^3$ . Therefore,  $s = \pm 9n^3$ . Hence, considering that  $|s| = |m|$  (or  $s = \pm m$ ), we have

$$(s, m, g) = (9n^3, 9n^3, -27n^4),$$

$$(s, m, g) = (9n^3, -9n^3, -27n^4),$$

as asserted, with  $n = 3^j v \in \mathbb{Z}$ . □

Now, remembering that  $|t| = |m|$ , we have the following solutions for the system (8)–(9) under the condition  $|s| = |m|$ :

$$\begin{aligned}(s, t, m, g) &= (9n^3, 9n^3, \pm 9n^3, -27n^4), \\ (s, t, m, g) &= (9n^3, -9n^3, \pm 9n^3, -27n^4).\end{aligned}$$

This, in turn, gives us the following solutions to our original Diophantine equation:

$$\begin{aligned}(a, b, c) &= (9n^3i, 9n^3(1 \pm i), -27n^4), \\ (a, b, c) &= (9n^3i, -9n^3(1 \pm i), -27n^4).\end{aligned}$$

Next, under (ii), we will show that (10) has no solutions when  $|s| \neq |m|$ . First, we state the following result.

**Lemma 1.** *Let  $u$  and  $v$  be integers such that  $u \wedge v = 1$ , and let  $(u^2 - 2v^2) \wedge (u^2 + 2v^2) = d$ . We have that if  $u$  is odd, then  $d = 1$ ; if  $u$  is even, then  $d = 2$ .*

*Proof.* Let  $(u^2 - 2v^2) \wedge (u^2 + 2v^2) = d$ . Then, there exist  $s$  and  $t$  such that

$$u^2 - 2v^2 = ds \quad \text{and} \quad u^2 + 2v^2 = dt.$$

Suppose first that  $u$  is odd. Then,  $d$  is odd since both  $u^2 - 2v^2$  and  $u^2 + 2v^2$  are odd. Also,

$$2u^2 = d(s + t) \quad \text{and} \quad 4v^2 = d(t - s).$$

Since  $d \wedge 2 = 1$ , we must have that  $d \mid u^2$  and  $d \mid v^2$ . We conclude that  $d = 1$  since  $u \wedge v = 1$ .

Suppose next that  $u$  is even. Let  $u = 2^e w$ , where  $e$  is a positive integer and  $2 \wedge w = 1$ . Then,

$$u^2 - 2v^2 = (2^e w)^2 - 2v^2 \quad \text{and} \quad u^2 + 2v^2 = (2^e w)^2 + 2v^2,$$

from which we see that

$$u^2 - 2v^2 = 2(2^{2e-1}w^2 - v^2) \quad \text{and} \quad u^2 + 2v^2 = 2(2^{2e-1}w^2 + v^2).$$

Now, since  $u \wedge v = 1$ , it follows that  $v$  is odd and  $w \wedge v = 1$ , and by a similar method as above, it can be proved that

$$(2^{2e-1}w^2 - v^2) \wedge (2^{2e-1}w^2 + v^2) = 1.$$

Thus, we can clearly see that

$$(u^2 - 2v^2) \wedge (u^2 + 2v^2) = 2(2^{2e-1}w^2 - v^2) \wedge 2(2^{2e-1}w^2 + v^2) = 2.$$

Therefore,  $(u^2 - 2v^2) \wedge (u^2 + 2v^2) = 1$  when  $u$  is odd, and  $(u^2 - 2v^2) \wedge (u^2 + 2v^2) = 2$  when  $u$  is even, as asserted.  $\square$

We now have the following lemma which states the nonexistence of solutions for (10) under certain particular conditions.

**Lemma 2.** *There are no integer solutions to  $x^4 - 4y^4 = z^3$  such that  $x \wedge y = 1$ ,  $x$  is odd, and  $y \neq 0$ .*

*Proof.* Suppose there exist integers  $u$ ,  $v$  and  $g$  such that  $u^4 - 4v^4 = g^3$ , with  $u \wedge v = 1$ ,  $u$  odd, and  $v \neq 0$ . Then,

$$(u^2 - 2v^2)(u^2 + 2v^2) = g^3.$$

Since  $u$  is odd, by Lemma 1 we have  $(u^2 - 2v^2) \wedge (u^2 + 2v^2) = 1$ , so  $(u^2 + 2v^2)$  and  $(u^2 - 2v^2)$  are coprime factors of  $g^3$ . Let  $g = ab$ , such that  $u^2 + 2v^2 = a^3$  and  $u^2 - 2v^2 = b^3$ . Then  $a \wedge b = 1$ . We can readily see that

$$a^3 + b^3 = 2u^2, \quad (14)$$

$$a^3 - b^3 = 4v^2. \quad (15)$$

From Cohen (2002), given that  $a \wedge b = 1$ , equation (14) has only two disjoint parameterized solutions where  $u$  is odd, according to the following cases (up to exchange of  $u$  and  $v$ ).

- (a) For  $s, t \in \mathbb{Z}$  such that  $s \wedge t = 1$ ,  $s$  is odd and  $s \not\equiv t \pmod{3}$ ,

$$\begin{cases} a = (s^2 + 2t^2)(5s^2 + 8ts + 2t^2), \\ b = -(s^2 + 4ts - 2t^2)(3s^2 + 4ts + 2t^2), \\ u = \pm(s^2 - 2ts - 2t^2)(7s^4 + 20ts^3 + 24t^2s^2 + 8t^3s + 4t^4). \end{cases}$$

By replacing in (15), we have

$$v^2 = 2s(19s^4 - 4s^3t + 8st^3 + 4t^4)(s^4 + 4s^3t + 16s^2t^2 + 24st^3 + 12t^4)(s^2 + st + t^2)(s + 2t). \quad (16)$$

Since  $v$  is an integer, at least one of the parameterized factors in (15) must be even. We can readily see that  $s^2 + st + t^2$  must be even, since the remaining factors are odd. Upon rewriting  $s^2 + st + t^2 = s^2 + t(s + t)$ , we can see that  $s$  and  $t(s + t)$  have the same parity. Thus,  $t(s + t)$  should be odd, implying that  $t$  and  $t + s$  are odd. However, this is not possible since  $t + s$  would then be the sum of two odd numbers, making it even. This is a contradiction, so this case has no solutions.

- (b) For  $s, t \in \mathbb{Z}$  such that  $s \wedge t = 1$ ,  $s \not\equiv t \pmod{2}$  and  $3 \nmid t$ ,

$$\begin{cases} a = (3s^2 - 2ts + t^2)(3s^2 + 6ts + t^2), \\ b = (3s^2 - 6ts + t^2)(3s^2 + 2ts + t^2), \\ u = \pm(3s^2 - t^2)(9s^4 + 18t^2s^2 + t^4). \end{cases}$$

By replacing in (15), we have

$$v^2 = 2st(81s^4 - 6s^2t^2 + t^4)(3s^4 - 2s^2t^2 + 3t^4)(3s^2 + t^2). \quad (17)$$

First, we will prove that all the parameterized factors of (17) are pairwise coprime. Indeed, we know that  $s \wedge t = 1$ , and it is evident that  $s$  does not divide any other parameterized factors, nor does  $t$ . Then, we only need to prove that the parenthesized factors are pairwise coprime. As an example, we will prove the second equality; the other two have similar proofs.

Let  $d = (81s^4 - 6s^2t^2 + t^4) \wedge (3s^2 + t^2)$ , and suppose  $d \neq 1$ . Then, there exist integers  $\alpha$  and  $\beta$  such that

$$81s^4 - 6s^2t^2 + t^4 = d\alpha, \quad (18)$$

$$3s^2 + t^2 = d\beta. \quad (19)$$

Let us notice that (19) and the hypotheses impose certain restrictions on  $d$ . Indeed, we must have  $2 \nmid d$ , because the left-hand-side of the equation is odd; also,  $3 \nmid d$  because  $3 \nmid t$ ; finally,  $d \nmid t^2$  because otherwise we would have  $d \mid s^2$ , which contradicts that  $s \wedge t = 1$ .

By multiplying (19) by  $-27s^2$  and adding (18), we have

$$t^2(t^2 - 33s^2) = d(\alpha - 27s^2\beta).$$

From this, we must have  $d \mid (t^2 - 33s^2)$ . Then, there exists an integer  $\gamma$  such that  $t^2 - 33s^4 = d\gamma$ . From this and (19), we have  $36s^2 = d(\beta - \gamma)$ , which leads to a contradiction in light of the restrictions imposed by (19). Thus, we must have  $d = 1$  in this case.

Therefore, the parameterized factors on (17) are pairwise coprime. We must conclude that all those factors are squares, except for the one that is even, i.e,  $s$  or  $t$ . In particular, we must have that

$$3s^4 - 2s^2t^2 + 3t^4 = r^2 \tag{20}$$

for some integer  $r$ . Since  $s \not\equiv t \pmod{2}$ , there exists an integer  $k$  such that  $s - t = 2k + 1$  or, equivalently,  $s = 2k + t + 1$ . By replacing on (20), we obtain

$$\begin{aligned} r^2 = & 48k^4 + 96k^3t + 64k^2t^2 + 16kt^3 + 4t^4 + 96k^3 + 144k^2t + 64kt^2 \\ & + 8t^3 + 72k^2 + 72kt + 16t^2 + 24k + 12t + 3. \end{aligned}$$

We can readily see that the left-hand-side of this equation has the form  $4n + 3$ , for some integer  $n$ , i.e.,  $4n + 3 = r^2$ . However,  $r^2 \not\equiv 3 \pmod{4}$  for all  $r \in \mathbb{Z}$ , which leads to a contradiction, so this case has no solutions.

Therefore, we conclude that there are no integer solutions to  $x^4 - 4y^4 = z^3$  with  $x \wedge y = 1$ ,  $x$  odd, and  $y \neq 0$ . □

We now prove the following result, which states the nonexistence of solutions to (10) when  $x \wedge y = 1$  and  $x$  is even. Notice that these conditions automatically imply that  $y \neq 0$ . Thus, this result is “complementary” to the previous lemma in the sense that we are considering exactly the same hypothesis, except for the fact that  $x$  is now even.

**Lemma 3.** *There are no integer solutions to  $x^4 - 4y^4 = z^3$  with  $x \wedge y = 1$  and  $x$  even.*

*Proof.* Suppose  $x = u$ ,  $y = v$  and  $z = g$  satisfy the equation  $x^4 - 4y^4 = z^3$ , with  $u \wedge v = 1$  and  $u$  an even integer. By lemma 1, we have

$$(u^2 - 2v^2) \wedge (u^2 + 2v^2) = 2.$$

Therefore, we must have

$$\left(\frac{u^2 - 2v^2}{2}\right) \wedge \left(\frac{u^2 + 2v^2}{2}\right) = 1.$$

Let  $u = 2^e w$ , with  $e \geq 1$  and  $2 \wedge w = 1$ . Then,

$$(2^e w)^4 - 4v^4 = g^3,$$

from which

$$((2^e w)^2 + 2v^2) ((2^e w)^2 - 2v^2) = g^3.$$

That is,

$$4(2^{2e-1}w^2 + v^2)(2^{e-1}w^2 - v^2) = g^3. \tag{21}$$

It can be clearly seen that  $g$  is even. Hence, let

$$g = 2^f p_1^{e_1} p_2^{e_2} \dots p_k^{e_k}.$$

be the prime power decomposition of  $g$ , where  $2 \wedge p_i = 1$  for  $i = 1, 2, \dots, k$ , and  $f > 0$ . Dividing both sides of (21) by 4 we obtain

$$(2^{2e-1}w^2 + v^2)(2^{e-1}w^2 - v^2) = 2^{3f-2} p_1^{3e_1} p_2^{3e_2} \dots p_k^{3e_k}. \tag{22}$$

Since  $f > 0$ , then  $3f - 2 \geq 1$ . Hence, the integer on the right-hand-side of (22) is even. Clearly, since  $v$  is odd, both factors on the left-hand-side of (22) are odd, and thus the integer of the right-hand-side should also be odd. Therefore, we have a contradiction. We conclude that there are no integer solutions  $x = u$ ,  $y = v$  and  $z = g$  to the equation  $x^4 - 4y^4 = z^3$  such that  $u \wedge v = 1$  and  $u$  is even. □

The following result shows the nonexistence of solutions to (10) such that  $s$  and  $m$  are coprime.

**Lemma 4.** *There exist no integer solutions to the equation  $x^4 - 4y^4 = z^3$  with  $x \wedge y = 1$  and  $y \neq 0$ .*

*Proof.* Direct consequence of Lemma 2 and Lemma 3.  $\square$

Finally, we have the following theorem which states the nonexistence of solutions when  $|x| \neq |y|$ , i.e., the main result for (ii).

**Theorem 2.** *The equation  $x^4 - 4y^4 = z^3$  has no integer solutions with  $|x| \neq |y| \neq 0$ .*

*Proof.* We will prove by contradiction. Suppose there exists a solution  $x = s$ ,  $y = m$  and  $z = g$  to this equation, with  $|x| \neq |y| \neq 0$ . We then have  $s^4 - 4m^4 = g^3$  with  $s \neq m$ . Let  $d = s \wedge m$ ,  $u = \frac{s}{d}$  and  $v = \frac{m}{d}$ . Then  $u \wedge v = 1$  and  $v \neq 0$ . Since  $d \mid s$  and  $d \mid m$ , we have  $d^4 \mid g^3$ . That is,

$$u^4 - 4v^4 = \frac{g^3}{d^4}, \quad (23)$$

where  $\frac{g^3}{d^4}$  is an integer. Let  $w = \frac{g^3}{d^4}$ . Then,  $wd^4 = g^3$ , and thus  $g = w^{\frac{1}{3}}d^{\frac{4}{3}}$ . Since  $g$  is an integer, there exist  $h$  and  $k$  such that  $w = h^3$  and  $d = k^3$ . Replacing in (23), we have  $u^4 - 4v^4 = h^3$ . Thus,  $(u, v, h)$  is a solution to the equation  $x^4 - 4y^4 = z^3$  with  $u \wedge v = 1$ . This contradicts Lemma 4.

Therefore, we conclude there are no integer solutions  $x = s$ ,  $y = m$  and  $z = g$  to the equation  $x^4 - 4y^4 = z^3$  with  $|s| \neq |m|$ .  $\square$

**Corollary 1.** *The equation  $x^4 - 4y^4 = z^3$  has integer solutions with  $|x| \neq |y|$  if and only if  $y = 0$ . In that case,  $x = n^3$  and  $y = n^4$  for  $n \in \mathbb{Z}$ .*

*Proof.* Notice that, given the assertion of the previous theorem, it is enough to prove that there exist solutions when  $y = 0$ . Indeed, suppose  $y = 0$ . Then,  $x^4 = z^3$ , which implies

$$x = z^{\frac{3}{4}}. \quad (24)$$

Since  $x$  is an integer, there exists an integer  $n$  such that  $z = n^4$ . Replacing in (24), we have  $x = n^3$ .  $\square$

*Remark 1.* Although the previous corollary shows there exist solutions for (10) with  $|s| \neq |m|$ , we do not need to consider them under the context of the case we are currently studying (i.e., **Case 2.4.3**), because one of the corresponding conditions is  $m \neq 0$ .

## 2.1 Symmetrical cases

The cases we have studied in the previous discussion were carefully chosen as representatives of a simple algebraic analysis that can be performed on any Diophantine equation. There exist other cases that we have left out, whose solutions can be readily found by exploiting symmetries in their equations. In order to avoid redundancy, we have left out these case until now. Here, we present a small summary of the results that are obtained when the symmetric equations are exploited, and we further apply our method to solve them. Table 1 shows the results of this procedure.

## 3. Conclusions

In this work, we have studied the algebraic properties of the Diophantine equation  $x^4 + y^4 = z^4$  in Gaussian integers, for  $x \neq y$ . Our main focus has been on studying some of the conditions that give rise to non-trivial solutions, and study their particular forms. Our findings show the existence on infinitely many solutions.

Since the analytical method we used in this study is based on simple algebraic properties, it can be easily generalized to study the behavior and the conditions for existence of solutions to other Diophantine equations, allowing a deeper understanding, even when no general solution is known.

Future work on this subject will be focused on obtaining a general solution to the equation.

Table 1: Solutions to cases considering symmetrical cases.

| Conditions   | Symmetrical to | Solutions $(a, b, c)$   |
|--|----------------|---|
| $r = 0, s = 0, t \neq 0, m = 0, g \neq 0, h = 0$       | Case 1         | $(0, n^3, n^4)$   |
| $r = 0, s \neq 0, t = 0, m = 0, g \neq 0, h = 0$       | Case 1         | $(n^3i, 0, n^4)$  |
| $r \neq 0, s = 0, t = 0, m = 0, g \neq 0, h = 0$       | Case 1         | $(n^3, 0, n^4)$   |
| $r \neq 0, s \neq 0, t = 0, m = 0, g \neq 0, h = 0$    | Case 2         | $(2^{3k+1}u^3(1 \pm i), 0, -2^{4k+2}u^4)$                             |
| $r = 0, s \neq 0, t \neq 0, m = 0, g \neq 0, h = 0$    | Case 3         | $(4n^3i, 4n^3, 8n^4)$<br>$(un^{3k-1}i, vn^{3k-1}, n^{4k-1})$          |
| $r \neq 0, s = 0, t = 0, m \neq 0, g \neq 0, h = 0$    | Case 3         | $(4n^3, 4n^3i, 8n^4)$<br>$(un^{3k-1}, vn^{3k-1}i, n^{4k-1})$          |
| $r \neq 0, s = 0, t \neq 0, m = 0, g \neq 0, h = 0$    | Case 3         | $(un^{3k-1}, vn^{3k-1}, n^{4k-1})$                                    |
| $r \neq 0, s = 0, t \neq 0, m \neq 0, g \neq 0, h = 0$ | Case 4         | $(9n^3, 9n^3(1 \pm i), -27n^4)$<br>$(9n^3, -9n^3(1 \pm i), -27n^4)$   |
| $r \neq 0, s \neq 0, t = 0, m \neq 0, g \neq 0, h = 0$ | Case 4         | $(9n^3(1 \pm i), 9n^3i, -27n^4)$<br>$(-9n^3(1 \pm i), 9n^3i, -27n^4)$ |
| $r \neq 0, s \neq 0, t \neq 0, m = 0, g \neq 0, h = 0$ | Case 4         | $(9n^3(1 \pm i), 9n^3, -27n^4)$<br>$(-9n^3(1 \pm i), 9n^3, -27n^4)$   |

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