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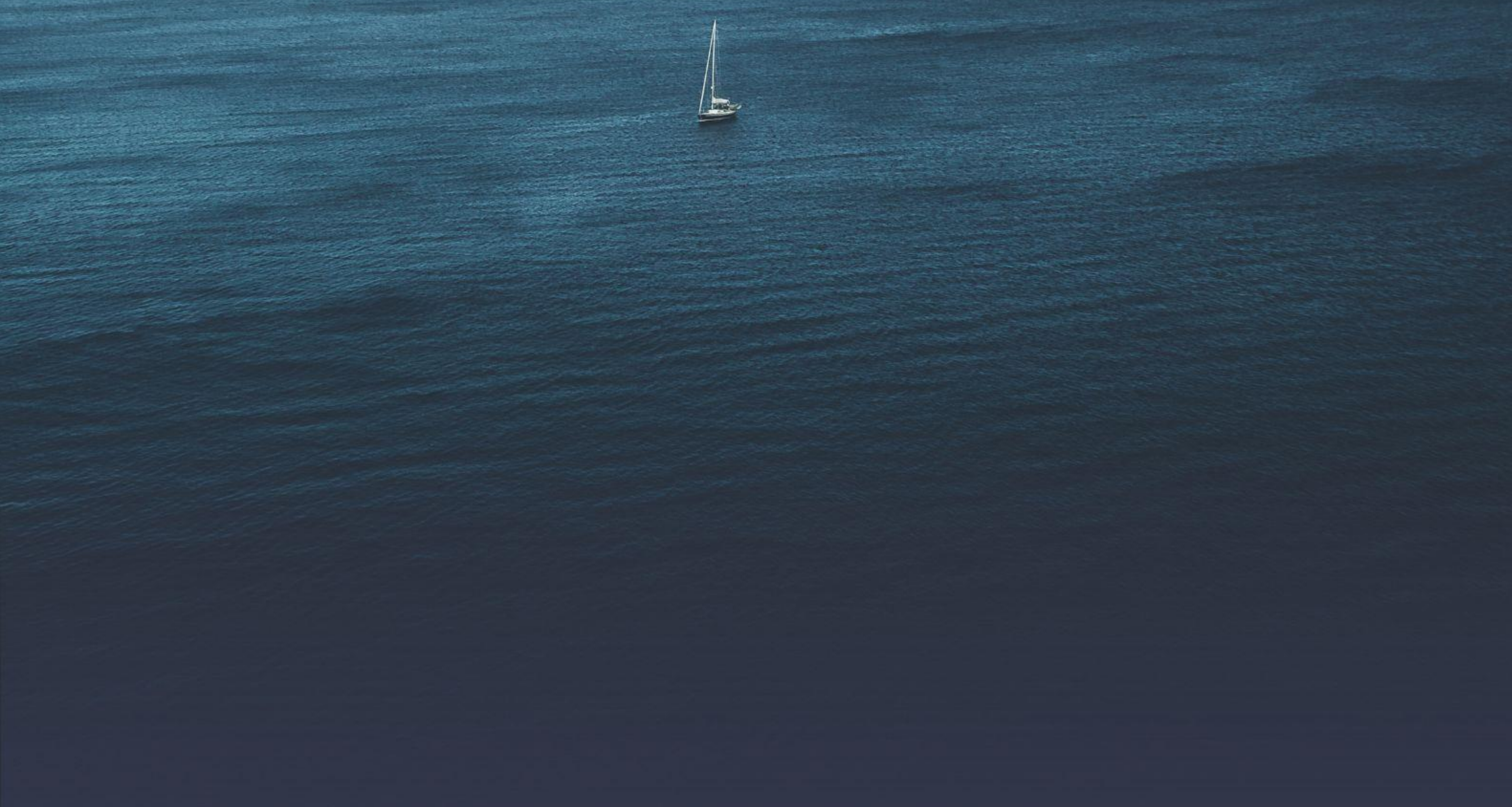

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In the memory of Professor Deng Julong (1933 - 2013),

the founder of Grey System Theory

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Evaluation of Barriers to E-commerce in Malawi using Grey Relational Analysis

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Abstract: E-commerce (electronic commerce) provides a convenient way of buying or selling products online and is a popular choice in certain segments of societies worldwide. The significance of e-commerce has been observed during the COVID-19 crisis, where customer preferences shifted from physical stores to online stores due to lockdowns and social distancing. E-commerce has been observed to be more effective in developed countries than in developing countries such as Malawi due to the difference in the resources required for the sustainability and growth of e-commerce. The current study evaluated the barriers to e-commerce in Malawi and ranked them using the Dynamic Grey Relational Analysis model. Using the primary data collected from the customers in Malawi, the study found that lack of trust in online systems and limited access to cell phones and computers and online payment methods are the most significant barriers. The study found that both human and technical (infrastructure) factors are hindering the growth of e-commerce in Malawi.

Keywords: Electronic commerce; barriers; grey model; grey relational analysis; Malawi.

1. Introduction

In 1979, British inventor Michael Aldridge introduced and pioneered what eventually came to be known as e-commerce (Greving, 2021). E-commerce is purchasing or selling goods and services over any computer network (Knight & Mann, 2017). By harnessing the power of the internet, e-commerce has changed the way organizations conduct business (Ohene-Djan, 2008). Commercial transactions in e-commerce are conducted through business-to-business (B2B), business-to-consumer (B2C), consumer-to-consumer (C2C), or consumer-to-business (C2B) (Drigas & Leliopoulos, 2018).

Over the past two decades, the widespread use of e-commerce platforms such as Amazon and eBay has fueled a massive increase in online retail. Other e-commerce platforms, such as Shopee have also emerged to fill the gap where these giants have limited access (Mesatania, 2022). The term e-commerce was coined in the 1960s with the rise of e-commerce, the buying and selling of goods through data transmission, which was made possible by the introduction of electronic data interchange (Kiran, 2020). According to the U.S. Census Bureau, e-commerce accounted for 5% of total retail sales in 2011, and by 2020, as the COVID-19 pandemic began; it has risen to more than 16% of retail sales (Lutkevich *et al.*, 2022). E-commerce is becoming a very important option for many businesses as many companies are interested in developing their online stores (Kasemsap, 2018). The significance of e-commerce first lies in consumer sovereignty; the marketing strategies of all business organizations are to a greater or lesser degree related to consumer satisfaction. Because of freedom, consumers enjoy a wide range of choices and the best services in e-commerce. Orders can be placed via the internet, and goods delivered to consumers' doorsteps, thus avoiding the inconvenience of shopping by hand. Secondly, e-commerce has introduced new markets because it is easier to penetrate and reach customers worldwide within minutes through the internet, enabling suppliers to introduce and promote new products to meet the needs of individual buyers. The third is that the employment opportunities provided by e-commerce are many, e.g., a large number of professionals are employed in the software industry (Arora & Athreye, 2002). The fourth meaning is consumer feedback on the product, seeing other buyers or seeing reviews from other customers before the final purchase (Jain *et al.*, 2021). To succeed in the current era of e-commerce, sellers need to monitor reviews and listen to what shoppers say about their products and customer service (Miva, 2020).

E-commerce is not widespread in Malawi. The country has been relatively slow to embrace the internet. E-commerce in Malawi remains low and faces some challenges. Some of these challenges include lack of trust in online systems, low levels of Internet access among the population, low rates of Internet adoption among businesses, lack of access to finance, and poor ICT skills (Malakata, 2021). These issues are cross-cutting and must be addressed in a coordinated manner (Chiphwanya, 2021). While some e-commerce applications exist in Malawi, such as online banking, business-to-business as well as business-to-consumer, e-commerce has yet to fully take off in Malawi due to the popularity of the internet. However, with the development of ICT infrastructure, more and more companies are realizing the potential of e-commerce and are increasingly included (Kumar *et al.*, 2014). The rest of this paper is structured as follows: Section 2 reviews previous literature, Section 3 gives detailed information about the data and methods, and Section 5 concludes the study.

2. Literature review

E-commerce focuses on buying goods online on a global scale. E-commerce is essentially a part of e-commerce related to financial transactions, so sharing or redesigning business processes is unnecessary (Aranda-Mena & Stewart, 2005). Developing countries are often on the receiving end of technological developments, particularly in industrialization, information technology, and military science (Lawrence & Tar, 2010). Like other developing countries, Malawi faces various challenges in adopting e-commerce. Limited infrastructure, poor access to technology, and low levels of digital literacy among potential consumers have been identified as significant barriers to adopting e-commerce in Malawi. Malawi faces various challenges in terms of infrastructure, such as inadequate road networks, limited electricity supply, and low Internet penetration. According to the World Bank (2023), only 11% of Malawi's population will have access to the internet by 2020, and this limited access is considered a significant barrier to e-commerce adoption. Limited access to reliable electricity also poses a major challenge to e-commerce in Malawi, as it affects the operation of electronic equipment required for e-commerce transactions.

In terms of access to technology, a study found that a lack of access to devices such as smartphones, computers, and laptops was a major barrier to e-commerce adoption in Malawi (Chirwa & Ngulube, 2017). This limited access to technology makes it challenging for potential consumers to access e-commerce platforms and make online purchases. The low level of digital literacy among potential consumers was also identified as a significant barrier to adopting e-commerce in Malawi. A study found that limited knowledge of e-commerce among consumers was a significant barrier to its adoption in Malawi (Mlenga & Mkandawire, 2019). Many Malawians lack knowledge of how e-commerce works, how to use online payment systems, and how to identify and mitigate online risks such as fraud.

To address these barriers, various strategies have been proposed. For instance, the Malawi government has launched initiatives aimed at improving internet connectivity and infrastructure, such as the Malawi Rural Electrification Programme (MAREP) and the Malawi National Fiber

Backbone Project (MNFBP) (Taulo *et al.*, 2015; Lishan & Tusubira, 2009). These initiatives aim to improve internet penetration rates and increase access to reliable electricity, which is expected to facilitate e-commerce adoption. In addition, efforts have been made to promote digital literacy among potential consumers. For example, the Malawi Communications Regulatory Authority (MACRA) launched an e-learning platform in 2020 to promote digital literacy and enable individuals to acquire the skills required for e-commerce transactions.

Overall, infrastructure, limited access to technology and low levels of digital literacy are significant barriers to the adoption of e-commerce in Malawi. Addressing these barriers is critical to promoting the adoption of e-commerce in Malawi, and strategies such as improving infrastructure, increasing access to technology, and promoting digital literacy can play an important role in promoting e-commerce adoption in the country. Although several studies have been conducted on barriers to e-commerce globally, in this study, we further investigated the barriers that hinder e-commerce in Malawi. However, this information is very limited. Based on the literature from different regions, a detailed list of the potential barriers has been prepared and shown in Table 1.

Table 1. Barriers and Challenges to e-Commerce

Code	Factor	Description	Source
B1	Low internet penetration	Poor infrastructure and high taxes make internet access expensive for most Malawians. Only 20.2% of the total population had access to the internet at the start of the year 2022.	Chiphwanya (2021); Kemp (2022).
B2	Limited access to electricity	As of 2021, 14.9% of people had access to electricity in Malawi	World Bank (2023)
B3	Education	Educated people are most likely to buy things online. Only 65.75% of adults (15 years and above) in Malawi can read and write.	Lawrence and Tar (2010)
B4	Lack of trust in online systems	Trust is highly significant in making financial transactions, which is critical because people fear getting scammed.	Chiphwanya (2021); Soleimanni (2022)
B5	Privacy and security	Privacy is related to the security of online transactions. Concerns about the risk of their personal information being compromised or stolen.	Udo (2001); Laurent (2021)
B6	Access to cell phones and computers	Limited availability of cell phones and computers, especially in the rural areas. Only 51.4% of the population had mobile connections at the start of the year 2022.	The current study; Kemp (2022)
B7	Payment method	This is based on customers' preferences for certain payment methods when making a purchase. 75% of people use cash payment in Malawi. In contrast, others use online payment methods.	Laurent (2021)
B8	Transportation	E-shopping will lead to the substitution of personal travel with home delivery. The road network of Malawi is poor.	Rotem-Mindali and Weltevreden (2013); Styles (2013)
B9	Urbanization	Urban people are most likely to buy things online. Only 17.70% of the country's population lives in urban areas in Malawi.	The current study
B10	Lack of support from the government	Building roads/infrastructure and promoting schools to learn required skills.	The current study
B11	Lack of knowhow among potential entrepreneurs	Most people would need guidance on how to start and maintain a business due to a lack of knowledge. 60.15% of people in Malawi are self-employed, and most are in agriculture.	Chitura *et al.* (2008)
B12	Lack of access to financing	Any market segment might lack adequate access to capital at reasonable rates to either finance or expand the business.	Malakata (2021)

3. Research design and methodology

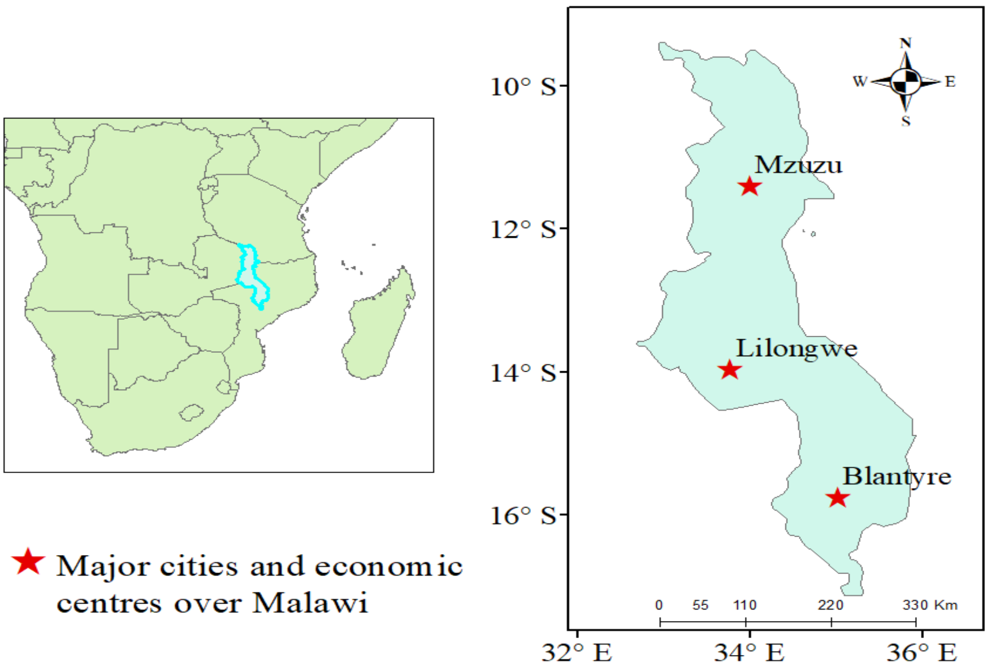
3.1 Study area

Malawi (Figure 1) is a landlocked country in Southeastern Africa with a geographical area of 118,484 square km. It shares borders with Mozambique to the east and southwest, Zambia to the west, and Tanzania to the north. Malawi's biggest economic contributors are the Agriculture industry accounting for more than one-third of the GDP. Furthermore, Malawi's economic outlook remains highly uncertain. In 2023-24, the economy will continue to suffer from high inflation and exchange rate instability (after the currency devaluation of 25% in May 2022). Malawi is one of the smaller e-commerce markets with projected revenue of $287 million by 2023. Revenue is expected to grow at a compound annual growth rate (CAGR 2023-2027) of 17%. Food and personal care is the largest market, accounting for 33.5% of Malawi's e-commerce revenue.

3.2 Data and software

The data utilized in this study was sourced through a questionnaire that was formed and distributed to several Malawians. Over Malawi, data was collected based on 12 common barriers that hinder the development of e-commerce following previous literature (as shown in Table 1). More details about the barriers which were used to construct questions for the questionnaire are summarized in Table 1.

During the study, a total of 51 Malawians responded to the questionnaire. However, the study excluded all respondents whose standard deviation (S.D.) was approaching zero from the questionnaire, signifying that they were unreliable. After excluding them, the sample size was 35 respondents and their responses were part of the analysis. The current study evaluated 12 e-commerce barriers hindering Malawi using the Dynamic Grey Relational Analysis against 35 respondents. For data visualization (drawing graphs), Origin lab software was used.



Source: the author's own construct using ArcMap GIS

Fig 1. Geographical location over Southern Africa and map of Malawi

3.3 Dynamic grey relational analysis

The Grey System Theory (GST) is an emerging methodology proposed by Julong Deng in the 1980s (Ng & Deng, 1995). Grey forecasting (Zhang *et al.*, 2023; Cudjoe *et al.*, 2023) and Grey Relational Analysis (GRA) methods are the core parts of the GST. The GRA is a measure of positive correlation that has seen numerous applications in multiple criteria decision-making (MCDM). Ivanova (2022) used the GRA to evaluate Russia's food supply chain risks during the pandemic. Kharipzhanova and Irfan (2022) used the GRA to assess Pakistan's tourism growth barriers. Esangbedo and Abifarin (2022) used the GRA to optimize parameters in material sciences. Lee *et al.* (2023) used the GRA to evaluate factors influencing consumer purchase decisions for halal products. Tsoy (2022) used the GRA to assess the expectations of Russian citizens from a potential increase in energy trade between Russia and Europe. Deng's GRA is the most influential form of the GRA and has become a significant MCDM method. However, the method has certain shortcomings. For example, the value of its distinguishing coefficient is chosen subjectively, and input data normalization is mandatory. In 2022, Javed *et al.* (2022) overcame these shortcomings by proposing the Dynamic GRA model. Later, Ouali (2022) confirmed the model's validity while studying the supplier selection problem, whereas Mahmoudi and Javed (2023) used it to validate another MCDM model. The key components of the model are discussed below.

The Grey Relational Grade (GRG) (Γ_{0k}) is:

$$\Gamma_{0k} = \sum_{j=1}^{n} w(j) \times \gamma_{0k}(j) \tag{1}$$

where, the Grey Relational Coefficient (GRC) ($\gamma_{0k}(j)$) is:

$$\gamma_{0k}(j) = \frac{\Delta_{min} + \xi(j)\Delta_{max}}{|\Delta_{0k}(j)| + \xi(j)\Delta_{max}}, k = 1,2, \dots . m \tag{2}$$

where,

$$|\Delta_{0k}(j)| = |x_0(j) - x_k(j)| \tag{3}$$

$$\Delta_{min} = min_k min_j |x_0(j) - x_k(j)| \tag{4}$$

$$\Delta_{max} = max_k max_j |x_0(j) - x_k(j)| \tag{5}$$

$$\xi(j) = \{\xi(1), \xi(2), \dots, \xi(n)\}, \xi(j) \in (0, 1] \tag{6}$$

The Dynamic GRA model was built and executed on Microsoft Excel. The method proposed by Javed *et al.* (2022) was used to estimate the values of the dynamic distinguishing coefficients.

4. Results and discussion

The original data is shown in Table 2. The key parameters and the dynamic distinguishing coefficients are shown in Table 3. For the sake of convenience, the fifteen potential barriers were labelled B1 to B15 (see Table 1) and the thirty-five respondents were labelled R1 to R35. Later, the current study used the Dynamic GRA for the evaluation of the barriers. The original data is shown in Table 2. The key parameters and the dynamic distinguishing coefficients are shown in Table 3. The dynamic grey relational grades and ranks of the barriers are shown in Tables 4 and 5.

Figure 2 demonstrates the dynamic grey relational grade and the ranking of the barriers. The top barriers were as follows: (lack of trust in online systems) B4, (access to cell phones and computers) B6, (payment method) B7, (lack of knowledge among potential entrepreneurs) B11 and (lack of access to financing) B12.

The first significant barrier was B4, which is the lack of trust in online systems. People are less likely to conduct e-commerce transactions when they worry about exposing their personal and

Table 2. Original data collected through the questionnaire

	B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
R1	7	4	5	6	7	7	5	7	7	3	3	7	6	4	4	4
R2	5	4	3	4	5	5	4	4	5	4	2	4	4	2	1	3
R3	7	7	6	2	7	4	6	4	2	6	4	6	7	4	4	4
R4	7	6	5	3	2	6	7	7	1	3	7	7	7	3	5	5
R5	5	1	2	1	3	1	1	2	1	3	2	1	2	5	5	4
R6	5	5	2	5	2	2	3	3	2	4	4	3	4	1	2	4
R7	7	2	2	5	7	6	3	4	6	6	4	4	5	4	5	4
R8	7	6	6	7	7	4	7	7	4	3	7	7	7	3	4	3
R9	6	4	5	5	6	3	5	3	5	5	5	5	6	2	3	3
R10	7	7	6	2	6	3	6	6	2	3	3	5	3	5	5	5
R11	6	2	6	6	6	6	6	6	6	6	3	5	5	4	4	4
R12	4	1	2	3	3	1	4	4	4	2	4	4	2	2	1	2
R13	7	7	7	7	7	7	7	7	7	5	7	5	6	3	3	3
R14	7	7	7	7	7	7	7	7	7	5	7	7	7	4	4	4
R15	7	3	6	4	6	6	6	5	7	4	4	6	6	4	6	4
R16	7	6	4	3	7	5	6	6	6	4	5	5	5	2	3	5
R17	4	4	3	4	4	3	4	4	4	4	4	4	4	1	1	1
R18	7	6	3	6	7	6	6	7	6	6	3	4	6	1	1	1
R19	7	6	7	7	7	6	7	6	5	5	6	7	6	2	5	7
R20	7	7	7	7	7	7	7	7	5	7	7	7	7	4	4	4
R21	6	6	6	4	6	1	6	6	6	4	1	6	6	1	4	6
R22	7	6	3	6	7	7	7	7	2	6	2	6	2	2	2	4
R23	7	6	5	7	6	5	7	6	2	5	5	7	5	2	5	6
R24	7	5	3	6	7	6	6	6	3	5	1	6	3	1	5	2
R25	6	6	5	5	6	3	4	5	6	4	5	5	6	2	6	5
R26	7	7	7	2	7	7	7	7	7	2	1	7	6	1	2	3
R27	7	3	3	6	7	7	7	7	7	6	5	5	5	4	4	6
R28	7	3	4	7	6	7	7	7	7	7	4	6	6	4	5	6
R29	7	7	6	5	6	7	5	6	5	7	7	6	5	5	3	4
R30	7	7	1	1	7	1	3	3	2	3	3	3	3	3	3	3
R31	7	1	2	4	5	5	5	5	5	3	7	7	7	7	7	7
R32	7	5	2	6	7	7	4	7	6	6	4	4	6	1	5	5
R33	6	5	6	6	6	6	6	6	6	6	6	6	6	3	3	3
R34	7	7	7	5	7	5	5	7	7	5	7	4	7	2	3	5
R35	7	5	2	6	7	5	7	7	7	7	7	6	7	2	3	5

financial information online. Concerns about security, privacy, and the dependability of online services might contribute to this lack of trust. Furthermore, some customers might like conventional brick-and-mortar businesses where they can see things in-person and speak with salespeople. E-commerce companies must endeavor to create a reputation for being dependable and trustworthy in order to get beyond this obstacle. They can achieve this by taking steps like using safe encryption technology, having transparent privacy rules, and offering helpful customer service.

The second most significant barrier was B6, which was cell phone and computer access. This study has observed that many Malawians do not have access to cell phones and computers. This is a major barrier to electronic commerce because electronic commerce relies heavily on the use of technology. Cell phones and computers are the primary devices used to access the internet, the backbone of electronic commerce. Without internet access, it is impossible to participate in many aspects of e-commerce, including online shopping, online banking, and online auctions. Furthermore, the use of technology such as mobile apps or digital wallets is increasingly becoming integral to electronic commerce, and not having access to these tools would severely limit an individual's ability to participate in e-commerce. Therefore, not having access to cell phones and computers can be a major obstacle for people to take advantage of the full benefits of electronic commerce.

Table 3. The delta, and the dynamic distinguishing coefficients

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	ξ (k)
R1	3	2	1	0	0	2	0	0	4	4	0	1	3	3	3	0.43
R2	1	2	1	0	0	1	1	0	1	3	1	1	3	4	2	0.35
R3	0	1	5	0	3	1	3	5	1	3	1	0	3	3	3	0.53
R4	1	2	4	5	1	0	0	6	4	0	0	0	4	2	2	0.52
R5	4	3	4	2	4	4	3	4	2	3	4	3	0	0	1	0.68
R6	0	3	0	3	3	2	2	3	1	1	2	1	4	3	1	0.48
R7	5	5	2	0	1	4	3	1	1	3	3	2	3	2	3	0.63
R8	1	1	0	0	3	0	0	3	4	0	0	0	4	3	4	0.38
R9	2	1	1	0	3	1	3	1	1	1	1	0	4	3	3	0.42
R10	0	1	5	1	4	1	1	5	4	4	2	4	2	2	2	0.63
R11	4	0	0	0	0	0	0	0	0	3	1	1	2	2	2	0.25
R12	3	2	1	1	3	0	0	0	2	0	0	2	2	3	2	0.35
R13	0	0	0	0	0	0	0	0	2	0	2	1	4	4	4	0.28
R14	0	0	0	0	0	0	0	0	2	0	0	0	3	3	3	0.18
R15	4	1	3	1	1	1	2	0	3	3	1	1	3	1	3	0.47
R16	1	3	4	0	2	1	1	1	3	2	2	2	5	4	2	0.55
R17	0	1	0	0	1	0	0	0	0	0	0	0	3	3	3	0.18
R18	1	4	1	0	1	1	0	1	1	4	3	1	6	6	6	0.60
R19	1	0	0	0	1	0	1	2	2	1	0	1	5	2	0	0.27
R20	0	0	0	0	0	0	0	2	0	0	0	0	3	3	3	0.18
R21	0	0	2	0	5	0	0	0	2	5	0	0	5	2	0	0.35
R22	1	4	1	0	0	0	0	5	1	5	1	5	5	5	3	0.60
R23	1	2	0	1	2	0	1	5	2	2	0	2	5	2	1	0.43
R24	2	4	1	0	1	1	1	4	2	6	1	4	6	2	5	0.67
R25	0	1	1	0	3	2	1	0	2	1	1	0	4	0	1	0.28
R26	0	0	5	0	0	0	0	0	5	6	0	1	6	5	4	0.53
R27	4	4	1	0	0	0	0	0	1	2	2	2	3	3	1	0.38
R28	4	3	0	1	0	0	0	0	0	3	1	1	3	2	1	0.32
R29	0	1	2	1	0	2	1	2	0	0	1	2	2	4	3	0.35
R30	0	6	6	0	6	4	4	5	4	4	4	4	4	4	4	0.98
R31	6	5	3	2	2	2	2	2	4	0	0	0	0	0	0	0.47
R32	2	5	1	0	0	3	0	1	1	3	3	1	6	2	2	0.50
R33	1	0	0	0	0	0	0	0	0	0	0	0	3	3	3	0.17
R34	0	0	2	0	2	2	0	0	2	0	3	0	5	4	2	0.37
R35	2	5	1	0	2	0	0	0	0	0	1	0	5	4	2	0.37

The third most significant barrier was the lack of good payment method. Many Malawians find this to be a barrier as most methods are not favorable for e-commerce because they deter customers from making transactions. Customers want to be able to pay using their preferred method, whether it's a credit card or debit card, various digital wallets, such as PayPal, and they want to feel safe about the security of their payment information. Customers may decide to shop elsewhere if a website or online store does not provide a choice of payment methods or if the checkout process is difficult. A challenging payment method can potentially harm a brand's reputation and reduce consumer loyalty.

The fourth barrier from the ranking was a lack of knowledge among potential entrepreneurs. This is an important barrier to e-commerce in several ways. Firstly, Technology and Marketing: One of the prime reasons businesses fail to adopt e-commerce is a lack of knowledge about technology and marketing. E-commerce requires certain technical knowledge to set up and operate e-commerce platforms, manage payments, inventory, supply chain management, and so on.

Table 4. The dynamic grey relational coefficients

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
R1	0.46	0.57	0.72	1.00	1.00	0.57	1.00	1.00	0.39	0.39	1.00	0.72	0.46	0.46	0.46
R2	0.68	0.51	0.68	1.00	1.00	0.68	0.68	1.00	0.68	0.41	0.68	0.68	0.41	0.34	0.51
R3	1.00	0.76	0.39	1.00	0.52	0.76	0.52	0.39	0.76	0.52	0.76	1.00	0.52	0.52	0.52
R4	0.76	0.61	0.44	0.38	0.76	1.00	1.00	0.34	0.44	1.00	1.00	1.00	0.44	0.61	0.61
R5	0.51	0.58	0.51	0.67	0.51	0.51	0.58	0.51	0.67	0.58	0.51	0.58	1.00	1.00	0.80
R6	1.00	0.49	1.00	0.49	0.49	0.59	0.59	0.49	0.74	0.74	0.59	0.74	0.42	0.49	0.74
R7	0.43	0.43	0.66	1.00	0.79	0.49	0.56	0.79	0.79	0.56	0.56	0.66	0.56	0.66	0.56
R8	0.70	0.70	1.00	1.00	0.43	1.00	1.00	0.43	0.37	1.00	1.00	1.00	0.37	0.43	0.37
R9	0.56	0.71	0.71	1.00	0.45	0.71	0.45	0.71	0.71	0.71	0.71	1.00	0.38	0.45	0.45
R10	1.00	0.79	0.43	0.79	0.49	0.79	0.79	0.43	0.49	0.49	0.66	0.49	0.66	0.66	0.66
R11	0.27	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.60	0.60	0.43	0.43	0.43
R12	0.41	0.51	0.68	0.68	0.41	1.00	1.00	1.00	0.51	1.00	1.00	0.51	0.51	0.41	0.51
R13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.46	1.00	0.46	0.63	0.30	0.30	0.30
R14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.35	1.00	1.00	1.00	0.27	0.27	0.27
R15	0.41	0.74	0.48	0.74	0.74	0.74	0.58	1.00	0.48	0.48	0.74	0.74	0.48	0.74	0.48
R16	0.77	0.52	0.45	1.00	0.62	0.77	0.77	0.77	0.52	0.62	0.62	0.62	0.40	0.45	0.62
R17	1.00	0.52	1.00	1.00	0.52	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.27	0.27	0.27
R18	0.78	0.47	0.78	1.00	0.78	0.78	1.00	0.78	0.78	0.47	0.55	0.78	0.38	0.38	0.38
R19	0.62	1.00	1.00	1.00	0.62	1.00	0.62	0.44	0.44	0.62	1.00	0.62	0.24	0.44	1.00
R20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.35	1.00	1.00	1.00	1.00	0.27	0.27	0.27
R21	1.00	1.00	0.51	1.00	0.30	1.00	1.00	1.00	0.51	0.30	1.00	1.00	0.30	0.51	1.00
R22	0.78	0.47	0.78	1.00	1.00	1.00	1.00	0.42	0.78	0.42	0.78	0.42	0.42	0.42	0.55
R23	0.72	0.57	1.00	0.72	0.57	1.00	0.72	0.34	0.57	0.57	1.00	0.57	0.34	0.57	0.72
R24	0.67	0.50	0.80	1.00	0.80	0.80	0.80	0.50	0.67	0.40	0.80	0.50	0.40	0.67	0.44
R25	1.00	0.63	0.63	1.00	0.36	0.46	0.63	1.00	0.46	0.63	0.63	1.00	0.30	1.00	0.63
R26	1.00	1.00	0.39	1.00	1.00	1.00	1.00	1.00	0.39	0.35	1.00	0.76	0.35	0.39	0.44
R27	0.37	0.37	0.70	1.00	1.00	1.00	1.00	1.00	0.70	0.53	0.53	0.53	0.43	0.43	0.70
R28	0.32	0.39	1.00	0.66	1.00	1.00	1.00	1.00	1.00	0.39	0.66	0.66	0.39	0.49	0.66
R29	1.00	0.68	0.51	0.68	1.00	0.51	0.68	0.51	1.00	1.00	0.68	0.51	0.51	0.34	0.41
R30	1.00	0.50	0.50	1.00	0.50	0.60	0.60	0.54	0.60	0.60	0.60	0.60	0.60	0.60	0.60
R31	0.32	0.36	0.48	0.58	0.58	0.58	0.58	0.58	0.41	1.00	1.00	1.00	1.00	1.00	1.00
R32	0.60	0.38	0.75	1.00	1.00	0.50	1.00	0.75	0.75	0.50	0.50	0.75	0.33	0.60	0.60
R33	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.25	0.25	0.25
R34	1.00	1.00	0.52	1.00	0.52	0.52	1.00	1.00	0.52	1.00	0.42	1.00	0.31	0.35	0.52
R35	0.52	0.31	0.69	1.00	0.52	1.00	1.00	1.00	1.00	1.00	0.69	1.00	0.31	0.35	0.52

Without a basic understanding of these concepts, entrepreneurs can find it challenging to launch their e-commerce platform. Entrepreneurs can be hesitant to use electronic commerce due to the perceived risk of fraudulent activities or cyber-attacks. The lack of knowledge of digital security measures can result in a reluctance to embrace e-commerce, the choice to stick to traditional business models. Thirdly, Policy and Regulations: Entrepreneurs might struggle to comply with the necessary policies, regulations, and best practices of electronic commerce. Regulations can vary by country or state. As for Malawi, keeping up with these requirements can be challenging without expert guidance. In summary, a lack of awareness or knowledge about technology, marketing, security, regulations, and compliance required for successful electronic commerce operations can be a significant stumbling block for entrepreneurs in the changing market scenario.

Lack of financial access was the fifth major obstacle. This is yet another significant hurdle to electronic commerce because it can be difficult to invest in e-commerce infrastructure like website construction, digital marketing, and online payment systems without sufficient cash. A lack of

Table 5. The dynamic grey relational grades and ranks

	GRG	Rank
B1	0.719	9
B2	0.659	11
B3	0.720	8
B4	0.897	1
B5	0.722	7
B6	0.810	3
B7	0.833	2
B8	0.746	6
B9	0.656	12
B10	0.674	10
B11	0.763	4
B12	0.762	5
B13	0.428	15
B14	0.501	14
B15	0.550	13

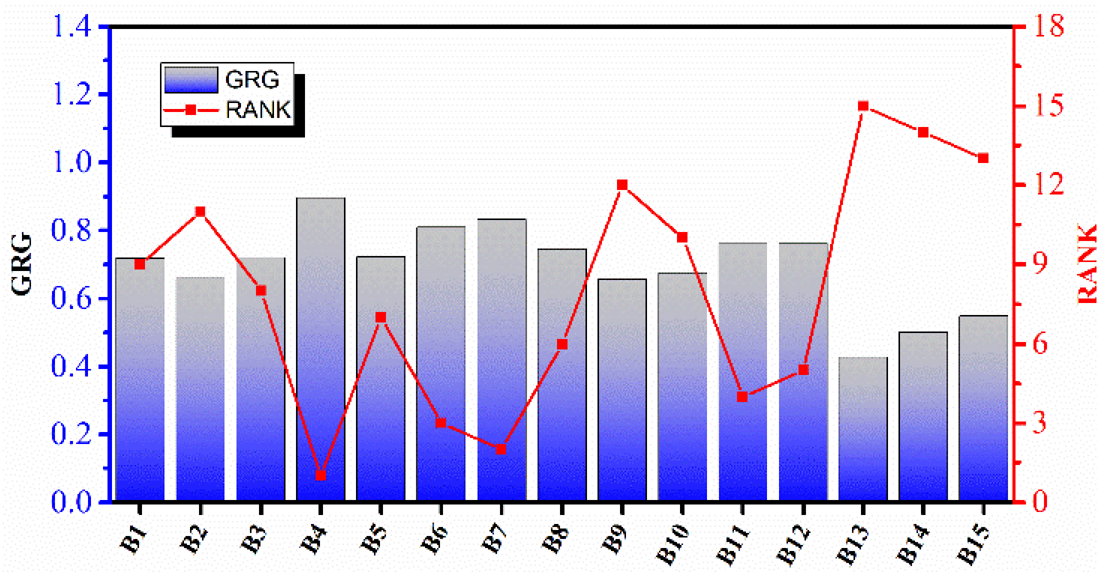


Fig 2. The dynamic grey relational grades-based ranking

funds might also make it challenging to pay for other operational expenses related to online product sales, such as product shipping and inventory purchases. Furthermore, unlike traditional brick-and-mortar businesses, e-commerce start-ups may not have a physical storefront to use as collateral for a loan or line of credit. As a result, they may be perceived as higher-risk clients to lenders, making it difficult to secure financing. Lack of funding can also restrict a company's capacity to increase its product options, enhance customer satisfaction, and take advantage of new digital marketing opportunities, stunting growth and bringing in little money. Finally, the study confirmed the suitability of the Grey Relational Analysis as demonstrated by earlier studies (e.g., Fidan, 2020; Agustin, 2022) for studying the factors influencing e-commerce.

5. Conclusion and recommendations

The current study has evaluated the barriers of electronic commerce hindering Malawi. The study used Dynamic GRA to evaluate the fifteen barriers based on the data collected from thirty-five respondents. The findings showed that Dynamic GRA is a reliable approach to assess barriers to e-commerce as it successfully ranked the barriers and helped us distinguish more important barriers from the less important ones. The most important barriers are found to be: a lack of trust in online systems, limited access to cell phones and computers, and unavailability of effective payment methods to support online transactions. Thus, human and technical factors are hindering the growth of e-commerce in Malawi.

Based on the findings, the study makes five recommendations: (1) there is a need to create transparent privacy policies that will be carefully adhered to, employ secure payment gateways and encryption techniques, and include customer evaluations and ratings to foster trust and offer customers guarantees and warranties. (2) There is a need to improve the access to cell phones and computers. By offering offline services like phone ordering, cash on delivery, and SMS notification; partnering with regional businesses or organizations that can act as access point providers; and delivering online services that can be accessed using low-tech devices like feature phones, efforts should be made to improve e-commerce. (3) A good payment system should be introduced. Providing a variety of payment options that satisfy the needs of diverse clients, collaborating with trustworthy and well-known payment gateways, creating a safe and intuitive payment platform, and offering a cash-on-delivery service is important to overcome barriers to e-commerce. (4) Training should be provided to potential entrepreneurs. Creating workshops and training programs to educate aspiring business owners, collaborating with regional institutions or groups that may assist with training and providing mentorship and coaching programs can greatly facilitate the development of an online infrastructure needed to improve e-commerce. (5) Improving access to financing is crucial. By offering crowdfunding services, collaborating with banks, financial institutions, or venture capitalists who can provide funding, creating partnerships with government agencies or organizations that offer financing for small businesses, and creating microfinance programs specifically for e-commerce businesses the currently dire situation of e-commerce in Malawi can be improved. Finally, lessons should be learned from other developing countries like China, the largest e-commerce market globally, where the widespread use of online payment methods (e.g., Alipay and WeChat Pay) and the presence of a competitive e-commerce infrastructure (e.g., Taobao, JD.com, and Pinduoduo) have made the life of online customers much easier and thus played an indispensable role in the growth of e-commerce in the country.

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Posterior Variance Test: *Ex ante* Evaluation of Grey Forecasting model

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Abstract: Scholars frequently use *ex post* evaluation metrics such as the Mean Absolute Percentage Error (MAPE) to estimate the forecast accuracy. However, *ex ante* metrics are essential to know whether a given forecasting model is suitable for a given variable irrespective of the outcome of *ex post* evaluations. The *ex ante* measures help us ensure that the forecast is accurate, not by chance. The current study presents the Posterior Variance Test (PVT), which can serve as an *ex ante* measure of grey forecast accuracy. The study forecasted the methane emissions from Australia and India using a grey forecasting model and found that even though the MAPE generated "accurate forecasts" for both cases, the PVT invalidated the model's suitability for one of the two cases. The data visualization also corroborated the outcome of the PVT.

Keywords: Posterior error test; grey forecast; forecast accuracy; forecast error; methane emission.

1. Introduction

Ex ante and *ex post* are Latin words for *before* and *after* a particular event, respectively. According to the Collins English Dictionary, *ex ante* is something "based on what is expected to happen," while *ex post* is something "based on analysis of past performance" (Collins, 2023a; 2023b). Thus, *ex ante* means we look at future events based on possible predictions, while *ex post* means we look at results and events after they have occurred. The terminologies are particularly well-known in economics, planning, and forecasting literature (Steiger, 2018; Clements, 2014; Boardman *et al.*, 1994). In the forecasting context, *ex ante* measure of forecast accuracy implies testing the qualification of a forecasting model/technique before it is used to produce a simulation of a future event. *Ex post* measure of forecast accuracy implies testing the accuracy of that simulation (output of a forecasting model).

If a forecasting model fails to pass *ex ante* evaluation, its forecasting is deemed unscientific (and thus, unreliable) even if it did not fail *ex post* evaluation. Many "good" things may happen in real-life by "chance" (Rastrigin, 1984). A forecasting model can produce a "good" forecast by chance, and one would find *ex post* evaluation confirming the forecast accuracy. But there is no guarantee that the same model would produce a "good" forecast for another similar event. A forecast that happens to be accurate by chance is not scientific but an accurate guess. A forecasting model that is generally valid for all types of events is non-existent, as no single forecasting model can consistently outperform all other methods (Liu *et al.*, 2022). Nevertheless, a forecasting model that is generally valid for a particular type of event (e.g., forecasting project costs or duration) must be guided by theory, even though a theory (e.g., S-curve) is not exactly applicable to all types of problems (see, e.g., Al-Rasheed & Soliman, 2022). However, a theory can help the mathematical modellers develop more realistic models by allowing them to understand and incorporate general characteristics of a particular type of event (a set of similar events).

If one looks at the forecasting literature (see, e.g., Boamah, 2021; Ahmed *et al.*, 2020; Kırbaş *et al.*, 2020), including the grey forecasting literature (see, e.g., Cudjoe *et al.*, 2023; Singh *et al.*, 2022), one finds that most scholars have performed *ex post* evaluations. *Ex ante* evaluations are generally taken for granted. One reason can be that it is easier to compare multiple forecasting models (such as done by Khan and Osińska (2023), Wei and Xie (2022), and others) on *ex post* measures. *Ex ante* measures for different models can be different because of different parameters and guiding principles (and properties). Also, if necessary and sufficient conditions of a model are not known (Chen & Huang, 2013), constructing an *ex ante* measure is not easy. Deng Julong, the founder of the grey forecasting methodology, proposed the earliest known technique for *ex ante* evaluation of grey forecasting models (Javed & Cudjoe, 2022). Till today no better alternative has been proposed by the grey forecasters revealing the lack of interest in the *ex ante* evaluations. The current study aims to highlight the significance of this technique, the Posterior Variance Test (PVT), for grey forecasting. The PVT is a useful technique. By using it, data analysts can easily classify the forecasting models into qualified (valid) and unqualified (invalid) ones. Instead of applying a grey forecasting model first and then finding it unsuitable for a particular problem, the PVT helps them identify the unqualified models beforehand.

The rest of the study is organized as follows. The second section introduces grey forecasting, its one model, and an error metric. The third section presents the PVT. In the fourth section, the PVT is applied to two cases, and its performance is evaluated. In the fifth section, the study is concluded.

2. Grey forecasting

In 1982, Deng Julong proposed the Grey System Theory (GST), further refined by his pupil Liu Sifeng and others in succeeding decades. It is a practice-oriented research-intensive mathematical discipline (like operations research, artificial intelligence, etc.) that aims to solve complex problems and aid quantitative decision-making through a continuously evolving toolbox of intelligent mathematical models. However, unlike the Taguchi methods, it does not end at "Deng's methods" and can be extended with new information and developments, for instance, by updating older methods (e.g., the Dynamic Grey Relational Analysis is the generalized form of Deng's Grey Relational Analysis method), introducing new methods (e.g., the Grey Ordinal Priority Approach to multiple criteria decision analysis), and introducing new research directions (e.g., the concept of bidirectional grey relational analysis was introduced to the GST by Deng's successors). In his correspondence with Liu Sifeng, Lotfi A. Zadeh (the founder of Fuzzy Set Theory) noted the GST as "an important approach to uncertainty."[1]

Among the significant contributions of the GST is the methodology of grey forecasting, proposed by Deng (1984). Grey forecasting is a data-driven time series forecasting methodology that aims to discover the law governing the development of time series by transforming the original data's unobvious trend into a growth trend using the cumulative sum operator (Xie, 2022). In its simplest form, a grey forecasting model is a "grey differential equation," which is an organic (inseparable) integration of differential equation and regression model (Guo & Guo, 2009). It represents an essential contribution of the GST to differential equations (mathematics), regression (statistics), and forecasting. Since its introduction, grey forecasting has provided solutions to many real-world problems. For instance, a 1994 study reported its success in obtaining good representations of both temperature and precipitation for Cold Lake, Alberta, Canada (Bass *et al.*, 1996). In 2014, a grey forecasting model was used to forecast the traffic volume at the Qinhuangdao Port, China (Bin, 2014). In 2017, it was shown that with a small sample size and multiple failure

[1] The copy of the email by Zadeh to Liu can be obtained from the author at a reasonable request.

modes, a grey forecasting model outperformed the Crow/AMSAA reliability growth model in predicting system reliability growth parameters (Talafuse & Pohl, 2017). In 2023, Italian scholars performed the first diffusion analysis of ISO/IEC 27001 using the grey forecasting models (Podrecca & Sartor, 2023). Several grey forecasting models have been proposed to date. Most of them share some common characteristics. Based on these common characteristics, one can record the key steps of a grey forecasting model as:

1. Data collection (and preparation, if data is not in the appropriate form),
   a. The data sets must be positive and equidistant in classical models and their modern variants.
2. Data pre-processing through a cumulative sum operator (or its variants),
3. The grey differential equation (and its discrete approximation as a regression-like equation)
   a. Usually, these equations contain a set of parameters whose values are yet to be estimated.
4. A procedure to estimate the values of the aforementioned unknown parameters (such as through the Ordinary Least Square method),
5. Reverse data accumulation (unprocessing),
   a. It is usually done through a difference equation.
6. The solution to the differential equation.
7. Simulation (forecasting)

These are the procedures generally present in every grey forecasting model though some models have extra, and sometimes very complicated, procedures. Probably because of computational complexity, many grey forecasting models have not seen any application after being proposed, and only a few models have seen several applications. The next section presents a representative grey forecasting model to which the PVT will be applied later.

2.1 EGM (1, 1, α, θ)

EGM $(1, 1, \alpha, \theta)$ represents the even form of a grey model with a first-order differential equation containing one variable and weighted background value involving conformable fractional accumulation. It was proposed by Javed *et al.* (2020), and has seen several interesting applications (see, e.g., Tulkinov, 2023; Podrecca & Sartor, 2023; Singh *et al.*, 2022). Let the set of actual data is

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \dots x^{(0)}(n)\right), x^{(0)}(k) \geq 0, n \geq 4 \tag{1}$$

And the set of conformable fractional accumulated data of $X^{(0)}$ is

$$X^{(\alpha)} = \left(x^{(\alpha)}(1), x^{(\alpha)}(2), \dots x^{(\alpha)}(n)\right) \tag{2}$$

where, $x^{(\alpha)}(k) = \sum_{i=1}^{k}\left(\frac{x^{(0)}(i)}{i^{1-\alpha}}\right), k = 1,2, \dots, n$ and $\alpha \in (0,1]$. The adjacent neighbor average set of $X^{(1)}$ will be

$$Z^{(1)} = \left(z^{(1)}(1), z^{(1)}(2), \dots z^{(1)}(n)\right) \tag{3}$$

where the background value $z^{(1)}(k) = \theta. x^{(\alpha)}(k) + (1-\theta). x^{(\alpha)}(k-1)$ and $\theta \in [0,1]$.

The even form of GM (1, 1), a first-order, single-variable grey forecasting model with parameters a and b, is a continuous-time grey differential equation defined as

$$\frac{dx^{(1)}(k)}{dk} + ax^{(1)}(k) = b, k \geq 1 \tag{4}$$

Its discrete approximation is a linear regression-like equation given by

$$x^{(0)}(k) + az^{(1)}(k) = b \tag{5}$$

Or,

$$x^{(0)}(k) = -az^{(1)}(k) + b \tag{6}$$

The parameters a and b can be estimated through the Ordinary Least Square method, i.e.,

$$[a, b]^T = [B^T B]^{-1} B^T Y \tag{7}$$

where,

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix} \text{ and } Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}$$

The time response function of the grey forecasting model is expressed as

$$\hat{x}^{(\alpha)}(k) = \left(x^{(0)}(1) - \frac{b}{a}\right) e^{-a(k-1)} + \frac{b}{a} \text{ , } k = 1,2, \dots, n \tag{8}$$

The inverse conformable fractional accumulation, which is needed to extract the simulation of the actual data set $\hat{x}^{(0)}(k)$ from the simulation of the accumulated data set $\hat{x}^{(\alpha)}(k)$, is executed through the following approximate regressive reduction formula.

$$\hat{x}^{(0)}(k) = k^{1-\alpha}\left(\hat{x}^{(\alpha)}(k) - \hat{x}^{(\alpha)}(k-1)\right), \qquad k = 1,2, \dots, n;\ \hat{x}^{(0)}(0) = 0 \tag{9}$$

This procedure of data unprocessing is unique to grey forecasting models. The time-response function of $X^{(0)}$, which is an exponential function of time, is given by

$$\hat{x}^{(0)}(k) = k^{1-\alpha}(1 - e^{a})\left(x^{(0)}(1) - \frac{b}{a}\right) e^{-a(k-1)} \text{ , } k = 1,2, \dots, n \tag{10}$$

whereas, $\hat{x}^{(0)}(1) = x^{(\alpha)}(1) = x^{(0)}(1)$. For the complete detail on the even grey model, its parameters, and properties, Liu *et al.* (2022) can be referred to, and for complete information on conformable fractional accumulation, Ma *et al.* (2020) should be consulted.

EGM (1, 1, α, θ) is a generalized form of the classical model EGM (1, 1). When $\alpha = 1$ and $\theta = 0.5$, the EGM (1, 1, α, θ) reduces to the classical even grey forecasting model EGM (1, 1), which is available in Liu *et al.* (2022). The advantage of EGM (1, 1, α, θ) lies in its ability to adjust the parameters of θ and α with the variation in data. The noise in data can have different forms. Unlike the classical model EGM (1, 1), in the model EGM (1, 1, α, θ), the two parameters are not static but rather dynamic, and their values changes as the noise in data varies, thus helping us produce more accurate forecasts.

2.1.1 Finding the optimal values of θ and α. The relationship between θ and α is nonlinear. For the model EGM (1, 1, α, θ), the values of θ and α need to be estimated through an optimization problem. By following a few steps, as stipulated by Javed *et al.* (2020), their values can be predicted. The first step is to convert the MAPE formula (see the sub-section 2.1.2) into an optimization problem with the objective function containing the minimization of the MAPE (%) value, i.e.

$$\min_{\alpha,\theta} MAPE = \frac{1}{n-1} \times \sum_{k=2}^{n} \left| \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)} \right| \times 100$$

Subject to

$x^{(0)}(k)$ as defined in Section 2.1.

$\hat{x}^{(0)}(k)$ as defined in Section 2.1.

$\alpha \in (0,1]$

$\theta \in [0,1]$

The second step is to save the result in a temporary memory, such as

$$MEMORY = MAPE$$

The third step involves developing a constraint using the information stored in the memory. Then, the model in the first step is revised with the new constraint, as shown below, and the revised first step is executed.

$$MAPE \leq MEMORY$$

The fourth step involves repeating the second and third steps until no feasible solution is possible. Record the final value of MAPE (%) and corresponding optimum values of θ and α.

2.1.2 Forecast error measurement. The Mean Absolute Percentage Error (MAPE) is among the most popular goodness-of-fit measures widely used for *ex post* evaluation of grey forecasting models. It can easily be converted into accuracy (in percentage), and is defined as (Wu *et al.*, 2022; Guo & Guo, 2009),

$$MAPE(\%) = \frac{1}{n-1} \times \sum_{k=2}^{n} \left| \frac{x(k) - \hat{x}(k)}{x(k)} \right| \times 100 \tag{11}$$

where, $x(k)$ and $\hat{x}(k)$ represents actual observation and its simulation generated through the grey forecasting model, respectively.

C. D. Lewis developed a scale in 1982 that is being widely used to interpret the MAPE (%) values (Boamah, 2021; Klimberg *et al.*, 2015). According to the Lewis scale, a forecast error as high as 50% can be considered a "reasonable forecast." Javed and Cudjoe (2022) contested this view and updated the Lewis scale, which is given below.

$$MAPE(\%) = \begin{cases} < 10 & Highly\ accurate\ forecast \\ [10, 20) & Good\ forecast \\ [20, 30) & Reasonable\ forecast \\ \geq 30 & Inaccurate\ forecast \end{cases}$$

Literature (Gowrisankar *et al.*, 2022; Tulkinov, 2023) has confirmed the rationality and validity of the revised scale. The scale does not represent absolute truth, and a user may adjust it depending on the sensitivity of the forecasting problem.

3. The Posterior Variance Test

It has been observed that the fields (such as information systems) that emphasize the development of new methods address the evaluation of methods rather in a limited fashion (Moody, 2003). The methodology of the grey system, a system of "grey information" (Savić, 2019; Lin *et al.*, 2004), is no exception. Deng Julong, the founder of the Grey System Theory, knew the significance of this issue, which has not received much attention to date. The Posterior Variance Test (PVT), or posterior-error test, is a novel system of statistical hypothesis testing involving four hypotheses in two categories (two hypotheses in each category) and represents one of the significant scientific contributions of Deng. He also used the statistical theory of standard deviation for uncertainty quantification in his Grey Relational Analysis method (see, Javed *et al.*, 2022; Tan *et al.*, 2007). These facts show that statistical reasoning is essential in studying and evaluating novel grey models. This practice is consistent with scientific methods, where a new method must pass the evaluation by established method(s) to be considered valid (Loh *et al.*, 2022). Thus, in general, the grey system theory is not an alternative to statistics for data analysis; their role is complementary.

The PVT is a statistical technique used by Deng Julong to estimate the accuracy of grey forecasting models (Deng, 1996). Despite its known advantages (Liu *et al.*, 2014), the test has seen relatively fewer applications (Yu *et al.*, 2022; Ayvaz & Kusakci, 2017) and is generally underused as most of the grey forecasting literature only involves *ex post* evaluation of forecast accuracy, which is usually done through Mean Absolute Percentage Error (Tian *et al.*, 2021; Guo & Guo, 2009). Deng's other works, such as grey relational analysis, grey forecasting, and grey numbers, have received much greater attention. While refining the PVT, Javed and Cudjoe (2020) have recently emphasized the significance of the PVT as an *ex ante* measure for grey forecasting models.

Ex ante evaluations are indispensable for forecasting models (Steece, 1986). If the result of *ex ante* evaluation is unsatisfactory, it provides an opportunity to revisit data or modify the model. The PVT provides an *ex ante* performance measure of a time-series forecasting model to see whether the selected model is suitable for forecast or not (Yu *et al.*, 2022). The PVT is guided by two metrics: the "ratio of root-mean-square deviations" (C) and the "small-error probability" (P). For highly accurate forecasts, C should be the minimum, and P should be the maximum. If needed, the root-mean-square deviation can be replaced by the standard deviation. The PVT's goal is to confirm whether the simulations (forecasts) are C-satisfactory or P-satisfactory, or both. A highly reliable forecast is both C-satisfactory and P-satisfactory. The procedure to execute the PVT is explained below.

If $X = \{x(1), x(2), \dots, x(n)\}$ represents the set of actual observations, $\hat{X} = \{\hat{x}(1), \hat{x}(2), \dots, \hat{x}(n)\}$ represents the model-generated simulation of X, and $\epsilon = \{\epsilon(1), \epsilon(2), \dots, \epsilon(n)\}$, $\epsilon(k) = x(k) - \hat{x}(k)$, $k = 2,3, \dots, n$ represents the set of absolute errors (residuals) then the root-mean-square deviations S_1 and S_2 are calculated as

$$S_1 = \sqrt{\frac{1}{n-1}\sum_{k=2}^{n}(x(k) - \bar{x})^2}, \bar{x} = \frac{1}{n-1}\sum_{k=2}^{n} x(k) \tag{12}$$

And

$$S_2 = \sqrt{\frac{1}{n-1}\sum_{k=2}^{n}(\epsilon(k) - \bar{\epsilon})^2}, \bar{\epsilon} = \frac{1}{n-1}\sum_{k=2}^{n} \epsilon(k) \tag{13}$$

The square of S_1 and S_2 gives variance in the data sets. If the ratio of root-mean-square deviations $C = \frac{S_2}{S_1} < 0.35$, then the model (or simulation) is said to be C-satisfactory, or the model is significant with respect to C. In the aforementioned equations, k is starting from 2 because, in most grey forecasting models, the first simulated value is usually the same as the first actual observation and thus can be ignored. If this is not the case, k should start from 1. C is a cost-type metric ("lower, the better").

The small-error probability $P = \mathrm{P}\{|\epsilon(k) - \bar{\epsilon}| < 0.6745 S_1\}$. Here, 0.6745 represents the root-mean-square value for the 75th percentile in the z-scores statistical table. P is a profit-type metric ("higher, the better"). A larger P value implies that at more points (k) the residuals are below the threshold of $0.6745 S_1$. In short, if $P > 0.95$, this means the probability of smaller errors (P) is higher than that of larger errors, and therefore the model is P-satisfactory, or the model is significant with respect to P. $P = 1$, when $|\epsilon(k) - \bar{\epsilon}| < 0.6745 S_1$ for every value of k, and $P = 0$ when the inequality does not hold for any value of k. If a grey forecasting model is both C-satisfactory and P-satisfactory, then its predictions are considered reliable. Otherwise, it shows that the model is unsuitable for forecasting the given variable because of considerable variations in data

(Javed & Cudjoe, 2022). The Deng scales (Deng, 1996), shown in Table 1, can guide us in judging whether a grey forecasting model is suitable for use or not.

Unlike C, the precise formula to estimate P was unavailable in the literature. By building upon the frequentist approach to probability, Javed and Cudjoe (2022) defined the small-error probability P as a function of the ratio of the number of favourable outcomes and the total number of outcomes such as,

$$P = \frac{F}{U + F} \tag{14}$$

where, F and U and represent the number of favourable and unfavourable outcomes, whereas favourability imply $|\epsilon(k) - \bar{\epsilon}| < 0.6745 S_1$. Thus, $F = f_F\{|\epsilon(k) - \bar{\epsilon}| < 0.6745 S_1\}$, and $U = f_U\{|\epsilon(k) - \bar{\epsilon}| \geq 0.6745 S_1\}$, where f represents the number of times (frequency) the inequality holds (f_F) or not (f_U). The sum of f_F and f_U equals the total number of simulations. In most grey forecasting models, the first observation is not simulated and is used as a seed in the forecasting process. Thus, $f_F + f_U = n - 1$, where n represents the sample size. For further details about the PVT, Javed and Cudjoe (2020) can be consulted.

4. Data and results

Methane is the second most abundant anthropogenic greenhouse gas after carbon dioxide (CO_2), accounting for about 20% of global emissions, and its warming capacity is 80 times greater than CO_2 over a 20-year period (UNEP, 2021; EPA, 2023). Forecasting methane emissions is of great significance for energy policy makers and environmentalists. To test the PVT on the grey forecasting model, data on "Methane emissions (kt of CO_2 equivalent)" was collected from the World Bank Indicators for Australia and India. Data from 2009 to 2017 was used for generating simulations from 2018 to 2028. Data from 2018 to 2020 played no role in the forecast and was kept for out-of-sample testing. The actual data and simulations are shown in Table 2.

The in-sample MAPE (%) was 9.11% for Australia and 0.16% for India. One may think the model is suitable for both cases; however, out-of-sample testing is still needed to monitor the problem of overfitting. The out-of-sample MAPE (%) was 6.26% for Australia and 0.36% for India. According to the MAPE scale (Javed & Cudjoe, 2022), in both cases, the forecast is "highly accurate," and *ex post* evaluation is passed. It is very tempting to discuss the results without touching the difficult question; was the chosen model suitable for the given problem? One can hardly answer the question without performing *ex ante* evaluation.

The *ex ante* assessments done through the PVT for Australia and India are shown in Tables 3 and 4, respectively. The assessments are summarized in Table 5. One can see that C is close to 1, and P is much lower than 0.7 for Australia. Thus, the model is neither C-satisfactory nor P-satisfactory. The model is unqualified to forecast methane emissions (kt of CO_2 equivalent) from Australia. For India, C < 0.35 and P > 0.95. Thus, the model is both C-satisfactory and P-satisfactory. The model is good for forecasting India's methane emissions (kt of CO_2 equivalent).

Data visualization also sheds important insights into this matter. For instance, if one looks at Figure 1 (Australia) and Figure 2 (India), it can be seen that in the case of Australia, the trend of methane emissions is less linear and more unpredictable, as compared to the case of India. In the case of Australian methane emissions, the simulation of actual data generated through the model

Table 1. The evaluation scales of the Posterior Variance Test

Forecast Accuracy	P	C
Good	> 0.95	< 0.35
Qualified	0.80 ~ 0.95	0.35 ~ 0.50
Barely Qualified	0.70 ~ 0.80	0.50 ~ 0.65
Unqualified	≤ 0.7	≥ 0.65

Table 2. Forecasting methane emissions (kt of CO_2 equivalent) from Australia and India

	Australia		**India**	
	Actual	**EGM (1, 1, α, θ)**	**Actual**	**EGM (1, 1, α, θ)**
2009	137198	137198	651519	651519
2010	129412	156129	658933	659079
2011	177597	155136	666188	662984
2012	176798	154149	665448	666902
2013	140884	153168	669582	670837
2014	154126	152194	674058	674792
2015	151225	151225	678829	678768
2016	134687	150263	684446	682766
2017	157518	149307	686785	686785
2018	*156428*	148357	*695494*	690828
2019	*144212*	147413	*696432*	694893
2020	*131485*	146475	*697655*	698981
2021		145544		703093
2022		144618		707229
2023		143697		711388
2024		142783		715571
2025		141875		719779
2026		140972		724011
2027		140075		728268
2028		139184		732549
MAPE % (in-sample)		9.11%		0.16%
MAPE % (out of sample)		6.26%		0.36%
a		0.006382625		-0.005855098
b		157503.6963		653278.457
α		1		0.999871968
θ		0.411832364		0.576532684

NOTE: Italic numbers did not participate in modelling and forecasting processes, and were only used for out-of-sample testing.

Table 3. *Ex ante* forecast error analysis by the PVT for Australia

	$\epsilon(k)$	$(\epsilon(k)-\bar{\epsilon})^2$	$(x(k)-\bar{x})^2$	$\lvert\epsilon(k)-\bar{\epsilon}\rvert$	$\lvert\epsilon(k)-\bar{\epsilon}\rvert< 0.6745S_1$	**Favourability**
2010	-26717	718319361	546095062	26801	No	U
2011	22461	500688568	615810730	22376	No	U
2012	22649	509160436	576817511	22565	No	U
2013	-12284	152989808	141543471	12369	No	U
2014	1933	3415047	1809519	1848	Yes	F
2015	0	7152	2420112	85	Yes	F
2016	-15576	245247576	327379282	15660	No	U
2017	8211	66043203	22443286	8127	Yes	F

Table 4. *Ex ante* forecast error analysis by the PVT for India

	$\epsilon(k)$	$(\epsilon(k)-\bar{\epsilon})^2$	$(x(k)-\bar{x})^2$	$\lvert\epsilon(k)-\bar{\epsilon}\rvert$	$\lvert\epsilon(k)-\bar{\epsilon}\rvert< 0.6745S_1$	**Favourability**
2010	-146	99383	198816266	315	Yes	F
2011	3204	9207525	46865978	3034	Yes	F
2012	-1454	2635095	57544003	1623	Yes	F
2013	-1255	2029105	11913213	1424	Yes	F
2014	-734	817065	1048754	904	Yes	F
2015	61	11765	33587745	108	Yes	F
2016	1680	2281929	130237202	1511	Yes	F
2017	0	28763	189109033	170	Yes	F

Table 5. Key parameters and final assessment of the suitability of the model through the PVT

Parameters	Australia	India
S_1	16711.97	9145.51
S_2	16567.56	1462.47
C	0.991 > 0.65 (Unqualified)	0.160 < 0.35 (Good)
0.6745 S_1	11272.2	6168.6
f_F	3	8
f_U	5	0
P	0.375 < 0.7 (Unqualified)	1.00 > 0.95 (Good)

is not well-fitted with the actual data. Thus, the conclusions drawn from the PVT are reliable, while those from the MAPE are debatable. It is found that by using the PVT, poor forecasts and interpretations can be avoided.

5. Conclusion and recommendations

Forecasting is an important problem in several disciplines and industries. Grey forecasting models represent an emerging methodology of forecasting. They have seen applications in various areas of practical importance. It has been observed that most of the literature involving grey forecasting only includes *ex post* evaluation of forecast accuracy, and the Mean Absolute Percentage Error (MAPE) is a popular choice among scholars. The current study argues that *ex ante* evaluation of forecast accuracy is essential, but it did not receive due attention from the grey forecasting community even though the founder of the grey forecasting methodology himself emphasized its significance when he proposed the Posterior Variance Test (PVT).

The study forecasted the methane emissions (kt of CO_2 equivalent) from Australia and India using the optimized even grey forecasting model EGM (1, 1, α, θ). The *ex ante* evaluation of

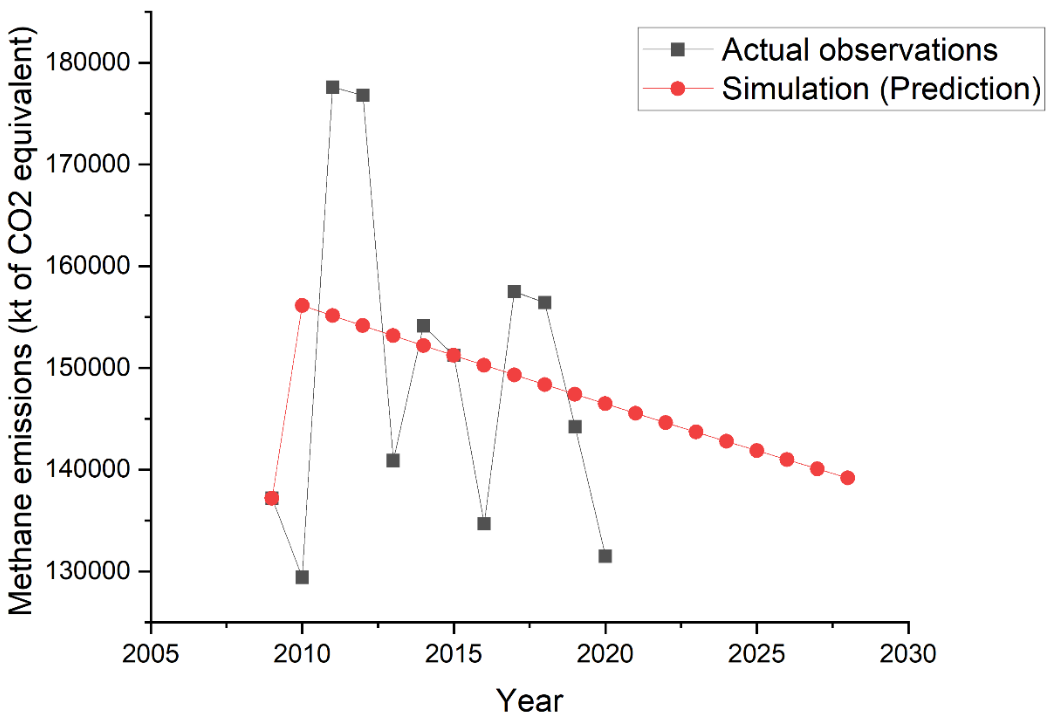

Fig 1. "Unqualified" forecast of methane emissions in Australia through EGM (1, 1, α, θ)

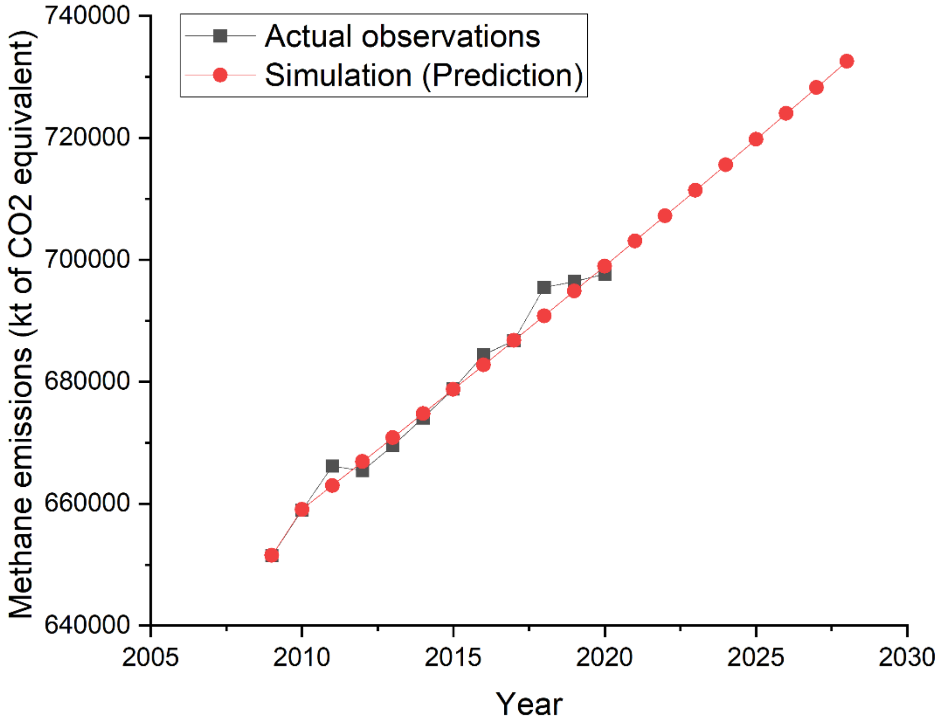

Fig 2. "Good" forecast of methane emissions in India through EGM (1, 1, α, θ)

forecast accuracy was performed through the PVT, and *ex post* evaluation was done through the MAPE. It was found that even though the MAPE certified that the model is suitable for forecasting methane emissions from both Australia and India, the PVT contested this argument (for Australia) and only certified the model's validity for India.

The results serve as a wakeup call for those who are applying the grey forecasting models without using the PVT or other *ex ante* measures. The study argues that the *ex post* evaluations, done through the MAPE or other metrics, are insufficient to establish trust in the forecast generated through mathematical models like grey forecasting models. New *ex ante* measures of grey forecasting models can be proposed in the future. Also, the validity of the PVT for different kinds of grey forecasting models is yet to be seen.

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