

# Compartmental Model for Unemployment Dynamics in Ghana: A Case of Caputo Fractional Derivatives

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## ABSTRACT

The study develops a fractional derivative-based compartmental model for the unemployment dynamics in Ghana. The model is first developed through the method of compartmental designs under certain assumptions which are consistent with literature and are also realistic situations associated to the labour market in Ghana. The developed model is finally redesigned into a Caputo fractional derivative model. The newly developed Caputo unemployment model is analysed to ascertain its invariant and boundedness, its fixed points and its stability. The unemployment basic reproduction number ( $\mathcal{R}_0$ ) which determines the threshold of recruitment is analysed using the Next Generation Method Approach, and the global stability for the unemployment-free equilibrium is also analysed through the approach of Lyapunov function. The results from the analysis show that, there is attraction of all the solution of the model in  $\mathbb{R}_+^4$  since the region is positively invariant. Again, the results indicate that, the model has two fixed points. Thus, unemployment-free equilibrium and risky-unemployment equilibrium. Notwithstanding, the analysis of the local stability of the model shows that the unemployment free equilibrium was local asymptotically stable (LAS) for  $\mathcal{R}_0 < 1$ , and the developed Caputo Unemployment model in Ghana is also global asymptotically stable (GAS). The results finally suggest that the developed model is well posed and can better examine the dynamics of unemployment in Ghana to enable policy makers in the country to make informed decisions.

*Keywords: Compartment; Caputo Fractional Derivative; Next Generation Method; Unemployment-Free Equilibrium; Basic Reproduction Number; Ghana; Lyapunov Function*

## 1. INTRODUCTION

According to [1], compartmental models (CM) are mathematical modelling which simplifies complex systems by monitoring the movements of several quantities or persons through a sequence of qualitatively diverse states in order to provide accurate and economical outcomes.

[2] noted that, compartmental models have gained increasing importance over the years in fields which study large population like sociology, ecology, epidemiology, demography, chemical kinetics, etc.

Additionally, compartmentalization offers a superior benefit in that it allows the modeler to build a model that is described by a fully deterministic system of differential or dynamic equations, which in turn allows the modeler to solve problems using simpler mathematical tools such as differential or analytical equations [1].

The area of mathematical modelling continues to play a very important role in explaining

complex systems with observable properties or behaviour in many different fields like, economics, finance, biology, physics, etc [3].

Economics, which study the implications of the scarcity of resources, economic growth of production, production of goods and services, and well-being of the people with respect to time, also considers unemployment as one of the critical economic indicators that shows the health of every economy and the welfare of its citizens [4]. However, one of the major economic and social challenge encountered by many economies in the world is unemployment, for which Ghana is not an exemption.

There are many factors that cause unemployment, however, in Ghana, [5] underpinned that, lots of civil servants and the employees of the formal sector in Ghana have become unemployed as a result of economic crisis that bedevils the country, and the implementation of structural adjustments. Again, Ghana has experienced labour market pressure as a result of large growing population. This is evident in all the twelve times population census organised by [6] in Ghana since 1891 with the population moving from 18,912,079 in the population census conducted in the year 2000 to 24, 658,832 in the population census conducted in the year 2010. However, the population stands at a little over 30.8 million in the 2021 population census.

Both [4,7] underscored that, understanding and addressing the dynamics of unemployment in an economy is very necessary for researchers and policy makers because of its vital role within every economy. In line with this, many researches have been conducted in the area of unemployment in Ghana using econometric and traditional models to understand the unemployment dynamics in the country, notwithstanding, the problem still persist. Generally, in understanding unemployment dynamics, there have been many approaches like traditional econometric models, traditional integer models, etc. applied in modelling unemployment dynamics with economies specific. However, one of those approaches is through compartmentalization which are analysed and solved with fractional derivatives due to its ability to add a very flexible and nuance view on the changes over time of the unemployment dynamics in an economy.

Fractional derivatives which have found applications in various fields like biology, economics, finance, etc., because of its ability to handle phenomenon which exhibits memory effects, long-range dependencies and anomalous behaviors, is classified to be a branch of mathematics which generalizes an idea of differentiation to a non-integer order [8]. The growing interest in applying fractional derivatives based mathematical modeling in recent times, have not been limited to modeling unemployment dynamics to gain a deeper insight into the realities in the labour market in many economies. Fractional derivative based models in understanding the unemployment dynamics in the labour market give more advantages but not limited to the following: Memory effect, long range dependencies, flexibility, etc. Furthermore, an additional importance of developing fractional derivative-based mathematical model for Ghana is the ability of these models to incorporate the following element: Fractional differential equation, parameter(s) estimation, sensitivity analysis, forecasting, etc.

There have been many approaches like traditional econometric models, traditional integer models, etc. applied in modelling unemployment dynamics with economies specific. However, one of those approaches is through compartmental modelling analysed with

fractional derivative operators, which adds a very flexible and nuance view on the changes over time of the unemployment dynamics.

## 2. LITERATURE REVIEW

The proper usage of the resources of an economy is an integral aspect within every economy. This is so because, the workers of every economy happen to be an important resource within an economy. Hence, the goal of all policymakers is to keep workersemployed or to increase the labour force participation rate in an economy [9]. Using data from 199 families across 84 countries between 1960 and 2015, [9] created a database of national jobless rates including nations of all socioeconomic levels. They emphasized that, when compared to Japan and the US, the average jobless rate in Western Europe is greater. They additionally noted that, the average unemployment rates in poor countries are lower than that of the rich countries. They further added that, the less educated in rich countries are the most affected by unemployment, but there is an average constant unemployment among the more educated across the countries. They concluded that, unemployment was less among the more educated in rich countries but high in poor countries, and the vice versa.

[10] posited that, job vacancies become limited thereby increasing unemployment during economic contractional periods or economic crisis, while more vacancies are created during economic expansion periods. The Beveridge curves or the “unemployment vacancy job curves” which measures the existing labour market [11] was used among the European Union Countries and on the European Area. It showed that, in 2006 to 2019, the labour market for the European Union countries and the European Area had undergone significant increase in unemployment rate, and reduction in job vacancies as a result of the 2008 economic and financial crisis. Their findings with the Beveridge curves indicated a significant between the years 2010 and 2013 with emphasis on the period between 2010 and 2011 pinpointing a clear difference between the respective member states, in the sense that, there were more vacancies in countries that had low unemployment rates. The findings with the curve further unraveled that, there were changes in both the European Union and the European area which have been evident since 2014 and were brought about by the rise in the unemployment rate on the background of the reduction in the unemployment rate.

In Africa, many researches have been conducted to understand the factors causing the rise in unemployment in Sub-Saharan Africa by considering and examining both the demand and supply factors of unemployment, however, this canker still persists [12].

Ghana as the beacon of Africa for its first role in Gaining independence has consistently suffered the fate of unemployment. The population of Ghana has increased drastically having consequential increase on its labour force. However, the country's unemployment problems stem from the fact that new work prospects have not expanded proportionately.

[13] posited that, economic problems form part of dynamical problems, and can be studied with dynamic processes. Unemployment is an economic development problem which is among the economic problems that can also be modelled with dynamic systems. Unemployment growth and its control models modelled with compartmental models have shown a very high accuracy in understanding the spread or dynamics and how to strategically control or manage the social canker called unemployment in an economy as shown in the work of [14]. They developed and analysed a seven dynamic variable non-linear ODE model for unemployment dynamics in the three main economic sectors in Ghana. In developing their model, they assumed that all entrants in the labour force were

between the ages of 18 to 60 years, and were all qualified to work, but were all either employed or unemployed at any time  $t$ . They further assumed that, the three main sectors of the economy (Agricultural, Industry and Services) had different increase in the entrants of the unemployed labour force, with the creation of vacancies dependent on the number of employed and unemployed labour force in the respective sectors. They established the behaviour of the developed compartmental model over time by applying stability analysis to study the developed systems of equations, and found that, there was a positive and bounded solution to the system, with the addition of a non-negative equilibrium point associated to the systems of equations. Furthermore, they established that the equilibrium point was locally asymptotically stable after using the Routh-Hurwitz criterion, and they ultimately noticed the existence of a workable stability of the developed compartmental model under specific circumstances.

Again, [15] did a similar work to understand the problem of unemployment by proposing a simple two compartment model for unemployment with two systems of equation. The two compartments considered were the number of employed and unemployed persons. They considered the assumptions that, employment may directly be gotten by some unemployed persons, while others from the employed compartment may be unemployed as a result of resignation or a sack from the job. Other additional assumptions to the construction of their model were that, persons that entered the unemployment compartment were fully qualified to be employed, with the number of unemployed people continuously increasing as a result of migration of those persons from their locality to other places in search of job, with a limited number of vacancies being constant. They employed the Routh-Hurwitz criterion, which was later used by [14], to show that the suggested unemployment model has just one non-negative equilibrium with a locally asymptotically stable equilibrium. Additionally, they suggested that, the model of unemployment can generally be improved by introducing more compartments like inflation, salary, etc into the model as also suggested by [16].

Fractional derivatives models have proven to be very effective and superior than traditional or integer models [8]. Though there have been many works on nonlinear unemployment dynamics like the works by [17,18, 19, 20, 21, 22], etc, however, fractional derivatives as applied to compartmental unemployment models have not been extensively explored despite its superiority over traditional and integer models as a result of its memory effect.

### **3. DEVELOPMENT OF THE COMPARTMENTAL MODEL**

Compartmental modelling used to understand the dynamics of dynamical systems is a great tool to understanding unemployment in an economy as used by many researchers. Compartmental models are mostly built on assumptions which are consistent with literature and the realities surround the complexities of the system under study.

#### **3.1 Description of the Model**

This proposed unemployment model has four compartments. These are, the unemployment ( $U$ ), Employed ( $E$ ), Skill Training ( $A$ ) and New Created Vacancies ( $V$ ) created exclusively from existing firms.  $U$  is the chamber through which new entrants ( $\Lambda$ ) enter the labour market.  $E$  is the number of existing vacancies which are fully filled by the employed labour force. Again,  $A$  is the skill training compartment to train interested people in through formal and non-formal education (students in the Technical and Vocational Education

Training (TVET), and those who are not in TVET but are going through any form of skill training) whose skills have lost relevance or lack the requisite skills to be employed in a specialised sector within the economy over time, and  $V$  is the number of new vacancies created by the private sector and the government with key emphasis from the government investing into skill training cum tax cuts/holidays policy which increases investments thereby making a fraction of the already employed private sector to invest in areas that creates more vacancies. In compartment  $E$ , vacancies are only created as a result of death, retirement, migration to foreign countries, incapacitation, resignation and/or being sacked by employers.

The  $U$  persons can migrate into the  $E, A$  and  $V$ . However,  $A$  persons can only move into  $U$  if the rate of revenue  $r$  of government and corporate bodies do not cover a lot of the graduated skill trainees and/or those graduated trainees are not highly skilled and/or the trainees dropped out. In this case, a highly skilled trainee without funding falls back into the  $U$  and could be employed into  $E$  or  $V$ .

With respect to compartment  $V$ , this will be achieved with an associated incentive packages like tax cuts or tax holidays, reduction of utilities bills for industries like the consumption of electricity, water, etc and making the economy very investor friendly with a conscious effort of the government to create emergency vacancies like the National Builders Corpse (NABCO), etc.

Additionally, the rate of successful training and a skill trainee still becoming unemployed after their skill training is  $\phi, \rho$  respectively, with  $r, \gamma$  being the rate of effective government revenue and diminution rate due to limited support for more highly skilled graduates. Also, the rate of  $U$  persons moving into  $E$ , rate of  $E$  persons moving into  $U$ , the rate of desire of the unemployed to be trained, rate of logistics provision by government and corporate institutions, rate at which the private sector creates new vacancies as a result of tax cuts/holidays, rate at which government creates emergency vacancies, and the rate of startup capital is  $\eta, \varepsilon, \omega, \psi, \sigma, \tau, \theta$  respectively.

To represent that the number of labour force in the compartments  $U, E, A, V$  may change over time, while the specific numbers made a function of time  $(t)$  as  $U(t), E(t), A(t), V(t)$ . then, Letting  $Q$  be the total labour force in Ghana, the total labour force  $Q$  is then given by:

$$Q = U + E + A + V \quad (1)$$

In this model, though the system is nonlinear, however, it is noted that:

$$\frac{dU(t)}{dt} + \frac{dE(t)}{dt} + \frac{dA(t)}{dt} + \frac{dV(t)}{dt} = 0 \quad (2)$$

This implies that, at any given time,

$$U + E + A + V = \text{const} \tan t = Q(t) = Q \text{ for all } t \in [0, \infty) \quad (3)$$

The unemployment free state is represented as:

$$U(t) = 0, E(t) = 0, A(t) = 0, V(t) = 0 \quad \forall t \in [0, \infty) \quad (4)$$

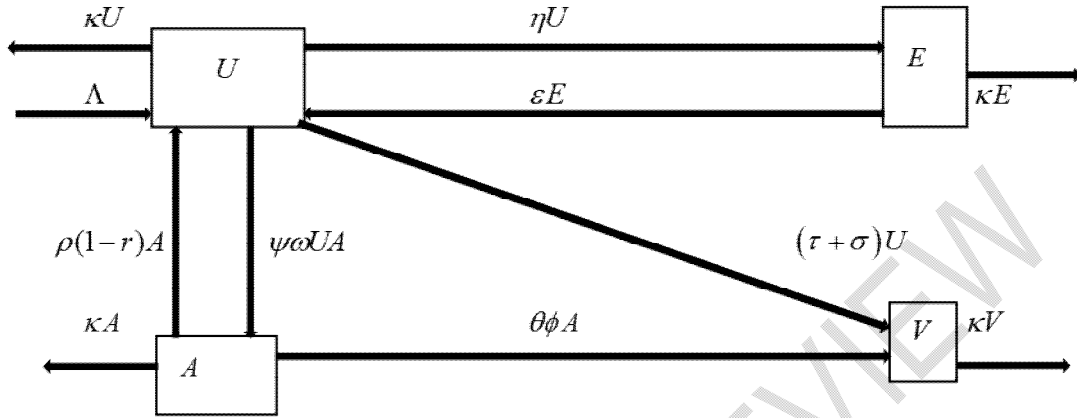
### 3.2 Assumptions of the Model

In developing the compartmental model to study the unemployment dynamics in Ghana, there are specific assumptions in relation to Ghana's economy. These are:

1. All the entrants of the labour force in Ghana to the unemployed class  $U$  fully qualify to perform any job. However, their skills loose relevance with respect to time.
2. Some of the employed in the existing vacancies may become unemployed as a result of incapacitation, resignation or firing by bosses as a result of loss of their relevant skills over time.
3. There are two categories of skilled trainees. Thus, low skilled trainees, and highly skilled trainees.
4. Unemployed persons with the desire to be trained can enrol into the skill training. The desire to be trained represented as  $\omega$ , operates on a probability with  $\omega \in (0, 1]$ .
5. The number of  $U$  people moving into  $A$  is jointly proportional to the number of people in  $U$  and the number of opportunities available for skill training.
6. The average of death rate, migration rate, retirement rate, and the incapacitation rate represented by,  $\kappa$ , is the same for all the compartment, and  $\kappa > 0$ .
7. The rate of diminution ( $\gamma$ ) of vacancies available due to financial crisis in the country is equal to  $\kappa$ .
8. Only highly skilled graduates can be supported with startup capital by government, and other corporate institutions like (non-governmental organizations (NGOs), banks, etc.) to create their vacancies for themselves and others.
9. New vacancies are created due to death, retirement, immigration to foreign countries, and incapacitation.
10. Low skilled trainees and few high skilled trainees become unemployed, but can be employed into  $E$  or  $V$ .
11. Tax cuts or tax holidays increases investment through creation of vacancies by a proportion of persons in  $E$  and  $V$ .
12. Government revenue impacts logistic provision for skill training, and provision of startup capital.
13. Governments creates emergency vacancies through the National Youth Authority to control unemployment.
14. Financial crisis in the economy reduces the number of vacancies to be created.

Considering the assumptions and facts for developing the model, these conceptualization of the evolutionary dynamics of unemployed labour force in Ghana is described through these

nonlinear systems differential equations in (5) with the flow of description of the parameters and its variables as shown in Figure 1.



**Figure 1** A compartmental diagram for unemployment control model in Ghana.

The set of differential equations deduced from figure 1 are displayed as:

$$\left. \begin{aligned} \frac{dU}{dt} &= \Lambda + \varepsilon E + \rho(1-r)A - \psi\omega UA - (\eta + \tau + \sigma + \kappa)U \\ \frac{dE}{dt} &= \eta U - (\varepsilon + \kappa)E \\ \frac{dA}{dt} &= \psi\omega UA - \rho(1-r)A - (\theta\phi + \kappa)A \\ \frac{dV}{dt} &= \theta\phi A + (\tau + \sigma)U - \kappa V \end{aligned} \right\} \quad (5)$$

With the initial conditions for the unemployment model variables given by:

$$U_0 = U(0), E_0 = E(0), A_0 = A(0), V_0 = V(0) \quad (6)$$

Model (5) has a biological feasible region on  $\Xi_1$  with

$$\Xi_1 = \left\{ (U, E, A, V) \in \mathbb{R}_+^4 : 0 \leq Q \leq \frac{\Lambda}{\kappa} \right\} \quad (7)$$

This means that, the model biologically feasible with the associated results holding for it. Also, since all the variables in model (5) are all associated to human beings, it is therefore nonnegative for which the region shown by  $\Xi_1$  is positive invariant for model (5). Hence, the

region shown for model (5) is very well posed, and all the initial values solutions belonging to  $\Xi_1$  remain in  $\Xi_1$  for every time  $t \geq 0$ .

#### 4THE FRACTIONAL DERIVATIVE UNEMPLOYMENT MODEL IN GHANA

This section presents the fractional derivative version of model (5) through the Caputo fractional derivative operator. In developing the Caputo unemployment dynamics model in Ghana, model (5) is represented in terms of integral form, and the value of the kernel is thereafter substituted as a power law correlation function.

Following the said approach, model (5) gives equation (8) after the introduction of the Caputo fractional derivative of order  $\alpha - 1$  as:

$$\left. \begin{aligned} {}^c D_t^\alpha \frac{dU}{dt} &= {}^c D_t^{\alpha-1} I_t^{-(\alpha-1)} [\Lambda + \varepsilon E + \rho(1-r)A - \psi\omega UA - (\eta + \tau + \sigma + \kappa)U] \\ {}^c D_t^\alpha \frac{dE}{dt} &= {}^c D_t^{\alpha-1} I_t^{-(\alpha-1)} [\eta U - (\varepsilon + \kappa)E] \\ {}^c D_t^\alpha \frac{dA}{dt} &= {}^c D_t^{\alpha-1} I_t^{-(\alpha-1)} [\psi\omega UA - \rho(1-r)A - (\theta\phi + \kappa)A] \\ {}^c D_t^\alpha \frac{dV}{dt} &= {}^c D_t^{\alpha-1} I_t^{-(\alpha-1)} [\theta\phi A + (\tau + \sigma)U - \kappa V] \end{aligned} \right\} \quad (8)$$

From model (8) which are both the inverse operators, the fractional order model of unemployment in Ghana with skill training, government revenue, logistics provision, startup capital provision applied in the Caputo fractional operator sense is given by:

$$\left. \begin{aligned} {}^c D_t^\alpha \frac{dU}{dt} &= \Lambda + \varepsilon E + \rho(1-r)A - \psi\omega UA - (\eta + \tau + \sigma + \kappa)U \\ {}^c D_t^\alpha \frac{dE}{dt} &= \eta U - (\varepsilon + \kappa)E \\ {}^c D_t^\alpha \frac{dA}{dt} &= \psi\omega UA - \rho(1-r)A - (\theta\phi + \kappa)A \\ {}^c D_t^\alpha \frac{dV}{dt} &= \theta\phi A + (\tau + \sigma)U - \kappa V \end{aligned} \right\} \quad (9)$$

$\forall \alpha$  being a fractional order and  $\alpha \in (0,1]$ .

Also, the initial values or conditions associated to the model variables in the fractional order model in equation (9) is given by:

$$U_0 = U(0) \geq 0, E_0 = E(0) \geq 0, A_0 = A(0) \geq 0, V_0 = V(0) \geq 0 \quad (10)$$

## 5 RESULTS AND DISCUSSIONS

### 5.1 The Invariant Region of the Caputo Unemployment Model in Ghana

The dynamics of the Caputo unemployment model in equation (9) is explored in a feasible region given by:

$$\Xi_2 \subset \mathbb{R}_+^4 : \Xi_2 = \left\{ (U, E, A, V) \in \mathbb{R}_+^4 : Q \leq \frac{\Lambda}{\kappa} \right\} \quad (11)$$

**Lemma 1** The region  $\Xi_2 \subset \mathbb{R}_+^4$  is positive invariant with non-negative initial conditions for the Caputo unemployment model in equation (9) in  $\mathbb{R}_+^4$ .

Proof: after adding the components of the labour force population in model (9), the total labour force is obtained as follows:

$${}^C D_t^\alpha Q(t) = {}^C D_t^\alpha U(t) + {}^C D_t^\alpha E(t) + {}^C D_t^\alpha A(t) + {}^C D_t^\alpha V(t) \quad (12)$$

After applying basic mathematics on equation (12) gives

$${}^C D_t^\alpha Q(t) = \Lambda - \kappa(U + E + L + H + V) \quad (13)$$

From equation (1)

$$Q(t) = U + E + A + V$$

Hence, equation (13) gives

$${}^C D_t^\alpha Q(t) + \kappa Q(t) \leq \Lambda \quad (14)$$

Again, after applying Laplace transform on equation (14), gives,

$$Q(\zeta) \leq \frac{\Lambda}{\zeta(\zeta^\alpha + \kappa)} + Q(0) \frac{\zeta^{\alpha-1}}{\zeta^\alpha + \kappa} \quad (15)$$

In considering the inverse Laplace, equation (15) becomes:

$$Q(t) \leq Q(0)E_{\alpha,1}(\kappa t^\alpha) + \Lambda t^\alpha E_{\alpha,\alpha+1}(\kappa t^\alpha) \quad (16)$$

Where the equation's Mittag-Leffler function is denoted by

$$E_{\alpha,\beta(z)} = \sum_{n=0}^{\infty} \frac{z^n}{\Gamma(\alpha n + \beta)} \quad (17)$$

And, also the Laplace transform is

$$L[t^{\beta-1} E_{\alpha,\beta}(\pm \alpha t^\alpha)] = \frac{\zeta^{\alpha-\beta}}{\zeta^\alpha \pm \alpha} \quad (18)$$

This means that,  $\Xi_2$  remains in  $\Xi_2$  of the Caputo unemployment model solution with the non-negative criteria or conditions. Therefore, there is attraction of all the solutions in  $\square_+$  since  $\Xi_2$  region is positively invariant.

## 5.2 The Unemployment Model Fixed Points

This part indicates the possible fixed points of the unemployment model in Ghana specified by model (9). The possible equilibrium points of the stability analysis are obtained at this juncture. In the Caputo unemployment model (9), there are two possible equilibrium points that exists. Thus, the Unemployment Free Equilibrium  $U_f$  and the Endemic Unemployment Equilibrium  $U_e$ .

## 5.3 The Unemployment-Free Equilibrium

The equisetum points of the model are achieved by setting the time rate of change of the Caputo unemployment model (9) to zero. This is given by:

$${}^C D_t^\alpha U|_{U=0} = {}^C D_t^\alpha E|_{E=0} = {}^C D_t^\alpha A|_{A=0} = {}^C D_t^\alpha V|_{V=0} = 0 \quad (19)$$

Hence, equation (20) is the new expressions obtained as a result of setting the time rate of change to zero:

$$\left. \begin{aligned} \Lambda + \varepsilon E + \rho(1-r)A - \psi\omega UA - (\eta + \tau + \sigma + \kappa)U &= 0 \\ \eta U - (\varepsilon + \kappa)E &= 0 \\ \psi\omega UA - \rho(1-r)A - (\theta\phi + \kappa)A &= 0 \\ \theta\phi A + (\tau + \sigma)U - \kappa V &= 0 \end{aligned} \right\} \quad (20)$$

The risk-free unemployment equilibrium ( $U_f$ ) is that stable state where there is no unemployment in the labour force. At this risk-free unemployment equilibrium  $U_f$ , as denoted by  $U_f = (U^0, E^0, A^0, V^0)$ , in equation (20), this gives the results of the unemployment free equilibrium as stated in equation (21):

$$U_f = (U^o, E^o, A^o, V^o) = \left( \frac{\Lambda d_7}{d_0}, \frac{\Lambda \eta}{d_0}, 0, \frac{\Lambda d_7 d_8}{\kappa d_0} \right) \quad (21)$$

where,

$$d_0 = \kappa^2 + (\eta + \tau + \sigma + \varepsilon)\kappa + \varepsilon d_8, d_7 = \kappa + \varepsilon, d_8 = \tau + \sigma$$

#### 5.4 Existence of Risky Equilibrium Points

Also, at the endemic equilibrium of the Caputo unemployment model (4.6), the endemic equilibrium of the model is given by  $U_e = (U^*, E^*, A^*, V^*)$ .

Where;

$$U^* = \frac{\Lambda + \varepsilon E^* + \rho(1-r)A^*}{\psi\omega A^* + \eta + \tau + \sigma + \kappa} \quad (22)$$

$$E^* = \frac{\eta U^*}{d_7} \quad (23)$$

$$V^* = \frac{\theta\phi A^* + d_8 U^*}{\kappa} \quad (24)$$

#### 5.5 The Unemployment Basic Reproduction Number (UBR)

To derive the  $\mathfrak{R}_0$  or (UBR) for the unemployment dynamics in Ghana, the next generation technique in the work of Diekmann *et al.*, (2010) is applied.

In calculating  $\mathfrak{R}_0$ , we begin with the equations of equation (9), which explain how fresh unemployment is created and how the conditions in state of unemployed people change. However, in this context,  $\mathfrak{R}_0$  refers to the threshold for recruitment into unemployment labour force or compartments  $U$ . We consider the  $E, A, V$  compartments, and use the approach of the next generation matrix (NGM). The equations are:

$$\left. \begin{aligned} {}^c D_t^\alpha \left[ \frac{dE}{dt} \right] &= \eta U - (\varepsilon + \kappa) E \\ {}^c D_t^\alpha \left[ \frac{dA}{dt} \right] &= \psi\omega UA - \rho(1-r)A - (\theta\phi + \kappa) A \\ {}^c D_t^\alpha \left[ \frac{dV}{dt} \right] &= \theta\phi A + (\tau + \sigma)U - \kappa V \end{aligned} \right\} \quad (25)$$

From equation (9), Let  $F_1 = {}^C D_t^\alpha \left[ \frac{dE}{dt} \right]$ ,  $F_2 = {}^C D_t^\alpha \left[ \frac{dA}{dt} \right]$ , and  $F_3 = {}^C D_t^\alpha \left[ \frac{dV}{dt} \right]$ . Using the approach of the Next Generation Matrix (NGM), let  $x = (E, A, V)^T$ . Decomposing equation (25) as  $\frac{dx}{dt} = T - M$  where  $T$  is the transmission part, and  $M$  is the transition part gives.

$$\frac{d}{dt} \begin{bmatrix} E \\ A \\ V \end{bmatrix} = \left[ \begin{bmatrix} \eta U \\ \psi \omega U A \\ \theta \phi A + d_8 U \end{bmatrix} - \begin{bmatrix} d_7 E \\ \rho(1-r)A + (\theta \phi + \kappa) A \\ \kappa V \end{bmatrix} \right] \quad (26)$$

For which  $T$  and  $M$  are gotten as:

$$T = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \psi \omega \Pi & 0 \\ 0 & \theta \phi & 0 \end{pmatrix}, \text{ and } M = \begin{pmatrix} d_7 & 0 & 0 \\ 0 & \rho(1-r) + \theta \phi + \kappa & 0 \\ 0 & 0 & \kappa \end{pmatrix}, \text{ and } \Pi = U$$

Finding the inverse of  $M$  gives:

$$M^{-1} = \begin{pmatrix} \frac{1}{d_7} & 0 & 0 \\ 0 & \frac{1}{\rho(1-r) + \theta \phi + \kappa} & 0 \\ 0 & 0 & \frac{1}{\kappa} \end{pmatrix} \quad (27)$$

In obtaining the threshold for recruitment, it represents the spectral radius of the NGM which is mathematically written as  $\mathfrak{R}_0 = \rho(TM^{-1})$ .

Finding  $TM^{-1}$  gives:

$$TM^{-1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\psi \omega \Pi}{\rho(1-r) + \theta \phi + \kappa} & 0 \\ 0 & \frac{\theta \phi}{\rho(1-r) + \theta \phi + \kappa} & 1 \end{pmatrix} \quad (28)$$

The dominant eigenvalue of  $TM^{-1}$  is

$$TM^{-1} = \frac{\psi\omega\Pi}{\rho(1-r) + \theta\phi + \kappa} \quad (29)$$

So,

$$\mathfrak{R}_0 = \rho(TM^{-1}) = \frac{\psi\omega\Pi}{\rho(1-r) + \theta\phi + \kappa} \quad (30)$$

It is noted that,  $\mathfrak{R}_0$  controls the unemployment labour force. When  $\mathfrak{R}_0 < 1$ , it becomes the situation where  $E, A, V$  are more than the unemployed labour force, and this is closely monitored, else Ghana's economy will seriously be affected.

### 5.6 Local Stability

**Theorem2** For any  $a, b \in \mathbb{R}$  such that  $\gcd(a, b) = 1$  for  $\alpha = \frac{a}{b}$  and  $M = b$ ,

theunemployment free equilibrium of the system (9) is locally Asymptotically stable (LAS) if

$|\arg(\lambda)| > \frac{\pi}{2M}$  for every root  $\lambda$  belonging to the characteristic equation (31) of matrix

$J(U_f)$ .

$$\det(\text{diag}[\lambda^{q_1} \lambda^{q_1} \lambda^{q_1} \lambda^{q_1}] - J(U_f)) = 0 \quad (31)$$

The Jacobian matrix  $J$  of equation (9) which is evaluated at the unemployment free equilibrium of equation (21) is:

$$J(U_f) = \begin{pmatrix} -d_5 & \varepsilon & d_6 & 0 \\ \eta & -d_7 & 0 & 0 \\ d_1 & 0 & -d_{10} & 0 \\ 0 & d_8 & d_9 & -\kappa \end{pmatrix} \quad (32)$$

Where,

$$d_1 = \psi\omega A^*; d_2 = \psi\omega U; d_3 = \rho(1-r) + \theta\phi + \kappa; d_4 = \eta + \kappa + d_8; d_5 = d_1 + d_4$$

$$d_6 = \rho(1-r) - d_2; d_9 = \theta\phi; d_{10} = d_3 - d_2$$

The obtained associated characteristic equation of equation (32) is as:

$$(\lambda^{q_1} + \kappa) [y_0 \lambda^{3q_1} + y_1 \lambda^{2q_1} + y_2 \lambda^{q_1} + y_3] = 0 \quad (33)$$

From equation (33), the argument of the root of equation  $\lambda^{q_1} + \kappa = 0$  is indicated below:

$$\arg(\lambda_k) = \frac{\pi}{q_1} + k \frac{2\pi}{q_1} > \frac{\pi}{M} > \frac{\pi}{2M}, \forall k = 0, 1, \dots, (q_1 - 1) \quad (34)$$

It is seen from equation (33) that, the root or eigenvalues have negative real part. Thus,  $-\kappa$ , and the remaining roots are computed from equation (35)

$$G(\lambda) = [y_0 \lambda^{3q_1} + y_1 \lambda^{2q_1} + y_2 \lambda^{q_1} + y_3] = 0 \quad (35)$$

The coefficients of equation (4.28) are of the form:

$$y_0 = 1; y_1 = d_5 + d_7 + d_{10}; y_2 = (d_5 + d_7)d_{10} + d_5 d_7 - d_1 d_6 - \eta \varepsilon; y_3 = (d_5 d_7 - \eta \varepsilon)d_{10} - d_1 d_6 d_7$$

Hence,

$$y_1 = d_5 + d_7 + d_3(1 - \mathfrak{R}_0)$$

$$y_2 = d_3(d_5 + d_7)(1 - \mathfrak{R}_0) + d_5 d_7 - d_1 d_6 d_7 - \eta \varepsilon$$

$$y_3 = d_3(d_5 d_7 - \eta \varepsilon)(1 - \mathfrak{R}_0) - d_1 d_6 d_7$$

It can be clearly seen that, for  $y_i$  where  $y_i = 1, 2, 3$  give positive values if  $\mathfrak{R}_0 < 0$ .

In the same way, it is therefore deduced that, the arguments of the equation  $(y_0 \lambda^{3q_1} + y_1 \lambda^{2q_1} + y_2 \lambda^{q_1} + y_3) = 0$  are all bigger than  $\frac{\pi}{2M}$  if  $\mathfrak{R}_0 < 1$ , and has an argument

of less than  $\frac{\pi}{2M}$  for  $\mathfrak{R}_0 > 1$ . Hence, the unemployment free equilibrium is LAS for  $\mathfrak{R}_0 < 1$ .

## 5.7 Global Stability

The suggested Caputo unemployment model's global asymptotical stability in the unemployment free equilibrium state is examined in this part using the Lyapunov function approach. This is made possible by the subsequent theorem.

**Theorem 3** The unemployment free equilibrium of the Caputo unemployment model is global asymptotically stable (GAS) if  $\mathfrak{R}_0 < 0$ .

**Proof** consider the following appropriate Lyapunov function:

$$H(t) = p_1 E + p_2 A + p_3 V \quad (36)$$

Where the coefficients,  $p_i$  for  $i = 1, 2, 3$  are unknown constants. However, they will be later selected. The time Caputo fraction derivative of  $H(t)$  along model (9) gives:

$${}^C D_t^\alpha H(t) = p_1 {}^C D_t^\alpha E(t) + p_2 {}^C D_t^\alpha A(t) + p_3 {}^C D_t^\alpha V(t) \quad (37)$$

Considering the Caputo model in (9), we have:

$${}^C D_t^\alpha H(E, A, V) = \left. \begin{aligned} & p_1 (\eta U - (\varepsilon + \kappa) E) + p_2 (\psi \omega U A - \rho(1-r)A - (\theta\phi + \kappa) A) \\ & + p_3 (\theta\phi A + (\tau + \sigma)U - \kappa V) \end{aligned} \right\} \quad (38)$$

$$\leq (p_2 (\psi \omega U - d_3) + p_3 (\theta\phi)) A + (p_1 \eta + p_3 d_8) U - p_1 d_7 E - p_3 \kappa V \quad (39)$$

At this point, we select

$$p_1 = p_3 = 0; p_2 = 1, \text{ which results into:}$$

$${}^C D_t^\alpha H(t) \leq (d_3 \mathfrak{R}_0 - (\rho(1-r) + \theta\phi + \kappa)) A \quad (40)$$

But,  $d_3 = \rho(1-r) + \theta\phi + \kappa$  into equation (40) gives:

$${}^C D_t^\alpha H(t) \leq (\rho(1-r) + \theta\phi + \kappa) [\mathfrak{R}_0 - 1] A = d_3 (\mathfrak{R}_0 - 1) A \quad (41)$$

From equation (41), at  $\mathfrak{R}_0 \leq 0$  gives  ${}^C D_t^\alpha H(t) \leq 0$ . It implies that, the parameters are non-negative with  ${}^C D_t^\alpha H(t) \leq 0$  if and only if  $E = A = V = 0$ . Hence,  $(E, A, V) \rightarrow (0, 0, 0)$  with  $t \rightarrow \infty$ .

Additionally, the solutions with  $t \rightarrow \infty$  approaches the  $U_f$  according to the Caputo unemployment model as seen in the feasible region. It therefore means that the risk-free unemployment equilibrium is global asymptotically stable.

## 6 CONCLUSIONS

In this research work, compartmental model for the unemployment dynamics is developed, and the developed model is redeveloped with a fractional derivative operator, specifically the Caputo fractional derivative operator which takes into consideration the memory effect of the labour market to understand the unemployment dynamics in Ghana's labour market. It found

that there are two fixed points with the unemployment-free equilibrium being LAS, indicating that, all solutions close to the equilibrium point ultimately converges to the equilibrium point. Additionally, the global stability also proved through the application of the Lyapunov function that, the unemployment-free equilibrium is GAS.

## **7RECOMMENDATIONS**

- a) Movement into the various compartments with a variation in parameter values should be further studied.
- b) With different assumptions, the model can be modified to suit future situations that would be experienced in the country's labour market.

## **DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Authors hereby declare that, no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscript.

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