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Stability Analysis of a Mathematical Model for Examination Malpractice Dynamics

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Abstract. Examination malpractice is one of the key challenges endangering the quality of education in Ghana. This negative act refers to any form of dishonesty or irregularity that compromises the integrity of any examination. In this paper, we proposed a mathematical model for exploring the dynamics of examination malpractice at the West African Senior School Certificate Examination (WASSCE) level in Ghana. The examination malpractice-free equilibrium is computed and shown to be both locally and globally stable if the examination malpractice reproductive number (R_0) is less than one. The examination malpractice endemic equilibrium is also derived and found to be globally asymptotically stable whenever R_0 is greater than one. Local sensitivity analysis is performed on the basic examination malpractice reproduction number to explore the contribution of the model parameters to the evil act of examination malpractice. Finally, numerical simulations are performed to illustrate the behavior of the model sub-classes.

1. Introduction

Examination remains a prominent tool for assessing and measuring students' academic performance throughout our educational system. It is used to determine the transition of students from one lower level to the next higher level. On the job market, examination also serves as a means for predicting a job seeker's knowledge level, skills, and competence in a given domain. Unfortunately, this valuable measurement tool is being compromised at all levels given room to what is popularly called examination malpractice [1,2]. Examination malpractice can be described as any deliberate act against the official rules and regulations of an examination, with the intention of giving undue advantage to a candidate [3–6]. Examination malpractice has been constantly recorded at all levels of our educational institutions. Data on examination malpractice at the Senior High School level are alarming. In Ghana for example, the cases of examination malpractice at the Senior High School Certificate Examination from 2020 to 2024 are shown in table 1. Also, it has been reported that in Nigeria 1,767 out of 13,595 and 842 out of 12,030 candidates who took part in the Senior High School Certificate Examination were involved in malpractices in 2022 and 2023 respectively [2].

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Examination malpractice has become a major concern in Ethiopia and Somalia [7]. According to studies conducted in [3, 6], people involved at the school level examination malpractice include academic authorities, students, teachers, and parents. This bad phenomenon may take place before, during and after an examination with the aim of achieving academic excellence for both the student and the school for a given examination. Specific forms of malpractice during examinations include, but are not limited to: tattooing, examination paper leakage, support from invigilators, impersonation, smuggling of unauthorized materials into the examination room, and giraffing in the examination room [3,4,6,8]. It is clear from the above-mentioned that examination malpractice poses a significant risk to the educational system of a nation. In a nutshell, examination malpractice lowers educational standards, discredits certificates obtained through examination, discourages hard work, leads to academic dishonesty and above all reduces productivity. Thus, contributing factors to this malfeasance need to be identified and tackled [1,2]. Mathematical modelling has become an effective toolbox for understanding the occurrence of dynamical phenomena [9,10]. However, mathematical models for studying examination malpractice are very scarce in the literature. The authors in [11] formulated and analyzed a dynamical model of examination malpractice taking into account key players in Nigeria. Their analysis indicated that leakages of examination question papers has the highest influence on the spread of examination malpractice. Ayoade and Farayola [11] developed a mathematical model for the mechanisms of examination malpractice with control strategies such as: social reengineering and orientation with proportional punishment/disciplinary action for examination malpractice victims. To fill this research gap, this work aims to propose a deterministic compartmental model to study exam malpractice at the West African Senior High School Certificate Examination (WASSCE) in Ghana.

Table 1. WASSCE Provisional Data For Ghana (2020 - 2024)

Year	N(t)	M(t)	C(t)	Pending
2020	375, 763	2, 863	480	384
2021	446352	1, 513	174	3, 667
2022	422, 883	4, 363	518	117
2023	448, 674	4, 486	839	5, 285
2024	460, 611	4, 591	483	990

Source: https://www.myjoyonline.com/?s=Release+of+WASSCE+Results

2. Model Construction

To construct a compartmental model for examining the dynamics of examination malpractice, the total number of candidates sitting for the examination at time t (N(t)) is stratified into five subclasses. Namely: S(t), M(t), C(t), R(t) and H(t) (see table 2). Candidates are recruited into the susceptible class (S(t)) at rate Λ. Some susceptible candidates move to honest candidates class (H(t)) at rate β. Other susceptible candidates engage into malpractices and move to malpractice class (M(t)) at rate θ. Candidates in the malpractice class either recover from malpractice and move to recovered class (R(t)) at rate τ or have their entire results cancelled at rate δ. Some recovered candidates progress to honest candidates class at rate α. Each model sub-class is reduced at a rate μ due to natural death. The model assumes that there is no examination malpractice induced deaths. The variables and parameters used to describe the model are presented in Table 2 and Table 3 respectively.

Table 2. Model State Variables Definition

Symbol	**Definition**
$N(t)$	Total number of candidates sitting for the examination
$S(t)$	Number of candidates susceptible to examination malpractice
$M(t)$	Number of candidates who engage in any form of irregularities
$C(t)$	Number of candidates who have their entire results cancelled following misconduct
$R(t)$	Number of candidates who recover from malpractice
$H(t)$	Number of law abiding/honest candidates

Table 3. Model Parameter Description

Symbol	**Description**		
Λ	Candidates recruitment rate	50.0	Estimated
μ	Natural human removal rate	0.0005	Assumed
β	Rate at which candidates adhere to examination rules	0.5	Assumed
θ	Rate at which candidates engage into irregularities	0.0044	Assumed
τ	Rate at which candidates recover from malpractice	0.2	Assumed
δ	Rate at which candidate entire results are canceled	0.15	Estimated
α	Rate at which recovered candidates become honest	0.3	Assumed
γ	Rate at which honest candidate revert to susceptible	0.9	Assumed

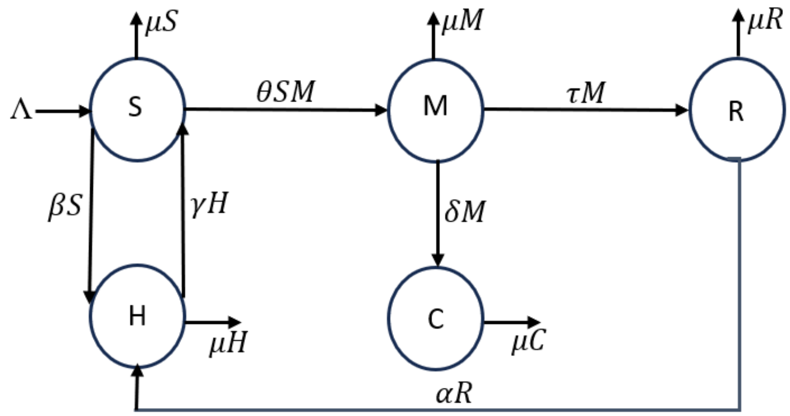

FIGURE 1. Flow Chart for Examination Malpractice

From the flow chart above, we obtain the following system of differential equations:

$$\begin{cases} \dfrac{dS}{dt} = \Lambda + \gamma H - \theta SM - (\beta + \mu)S \\[2ex] \dfrac{dM}{dt} = \theta SM - (\tau + \delta + \mu)M \\[2ex] \dfrac{dC}{dt} = \delta M - \mu C \\[2ex] \dfrac{dR}{dt} = \tau M - (\alpha + \mu)R \\[2ex] \dfrac{dH}{dt} = \beta S + \alpha R - (\gamma + \mu)H \end{cases} \tag{1}$$

The following notation will be used in the rest of the study:
$q_0 = (\beta + \mu)$, $\quad q_1 = (\tau + \delta + \mu)$, $\quad q_2 = (\alpha + \mu)$ *and* $\quad q_3 = (\gamma + \mu)$

2.1. **Well-Posedness of the Model.** Under this section, we establish that the system of differential equations representing model (1) admits only non-negative solutions. Furthermore, the set over which the model system of equations is contextually meaningful is also determined.

Theorem 1. *Given the non-negative initial value set:* $\{S(0),\ M(0),\ C(0),\ R(0),\ H(0)\}$ *of the dynamical system (1), it follows that the solution set* $\{S(t),\ M(t),\ C(t),\ R(t),\ H(t)\}$ *is non-negative and bounded* $\forall\ t \geq 0$.

Proof. First, we consider the differential equation for the susceptible sub-class:

$$\frac{dS}{dt} = \Lambda + \gamma H - (\theta M + q_0)S$$

$$\implies \frac{dS}{dt} \geq -(\theta M + q_0)S$$
$$\implies \int \frac{1}{S} dS \geq -\int (\theta M + q_0) dt$$

$$\implies S(t) \geq S(0)e^{-(q_o t + \theta \int_0^t M(x)dx)} \geq 0$$

Similarly, the following results can be obtained:

$$M(t) \geq M(0)e^{-q_1 t} \geq 0$$

$$C(t) \geq C(0)e^{-\mu t} \geq 0$$

$$R(t) \geq R(0)e^{-q_2 t} \geq 0$$

$$H(t) \geq H(0)e^{-q_3 t} \geq 0$$

Therefore, for $\forall$ t ≥ 0, the state variables of the model have non-negative solutions. □

Theorem 2. *The feasible positive invariant region in which the solution set of the model system of equations is meaningful is the set:*

$$\mathcal{D} = \left\{ (S, M, C, R, H) \in \mathbb{R}^5_+ : S + M + C + R + H \leq \frac{\Lambda}{\mu} \right\} \tag{2}$$

Proof. The total population N at any given time t is:

$$\begin{aligned}
& N = S + M + C + R + H \\
\implies & \frac{dN}{dt} = \frac{dS}{dt} + \frac{dM}{dt} + \frac{dC}{dt} + \frac{dR}{dt} + \frac{dH}{dt} \\
\implies & \frac{dN}{dt} = \Lambda - \mu N \\
\implies & \frac{dN}{dt} = -\mu(N - \frac{\Lambda}{\mu}) \\
\implies & \frac{dN}{N - \frac{\Lambda}{\mu}} = -\mu dt \\
\implies & \int \frac{dN}{N - \frac{\Lambda}{\mu}} = -\int \mu dt \\
\implies & N - \frac{\Lambda}{\mu} = 0 \quad \text{as} \quad t \to +\infty
\end{aligned} \tag{3}$$

Thus, we deduce that $N \leq \frac{\Lambda}{\mu}$

Therefore:

$$\mathcal{D} = \left\{ (S, M, C, R, H) \in \mathbb{R}^5_+ : S + M + C + R + H \leq \frac{\Lambda}{\mu} \right\} \tag{4}$$

□

2.2. **The Examination Malpractice-Free Equilibrium (EMFE).** Equating the individual equations of system (1) to zero with the condition $M = C = R = 0$, we obtain the EMFE (ξ^*) given by $\xi^* = (S^*, M^*, C^*, R^*, H^*) = \left(\frac{\Lambda q_3}{q_0 q_3 - \beta\gamma}, 0, 0, 0, \frac{\beta\Lambda}{q_0 q_3 - \beta\gamma} \right)$

2.2.1. *The Basic Reproductive Number (R_0) of Examination Malpractice.* In this context, the basic reproductive number defines the average number of secondary candidates that will be influenced by just one candidate who engages into examination malpractice. The method of next generating matrix which is mostly used is also adopted to compute the model R_0. To achieve this, we expressed the malpractice sub-system of model (1) in the form $\frac{dX}{dt} = (\mathcal{F} - \mathcal{V})X^T$ where X^T is the transpose of $X = (M,\ C)$, $\mathcal{F}$ and $\mathcal{V}$ are the rates of generation of new misconducting candidates and transfer respectively. Using this malpractice/infected sub-system

$$\begin{cases} \dfrac{dM}{dt} = \theta S M - q_1 M \\ \\ \dfrac{dC}{dt} = \delta M - \mu C \end{cases} \tag{5}$$

we have:

$$\mathcal{F} = \begin{pmatrix} \theta S M \\ \\ 0 \end{pmatrix} \text{ and } \mathcal{V} = \begin{pmatrix} q_1 M \\ \\ -\delta M + \mu C \end{pmatrix} \tag{6}$$

Evaluating the Jacobian matrices F and V of $\mathcal{F}$ and $\mathcal{V}$ at the DFE gives respectively:

$$F = \begin{pmatrix} \theta S^* & 0 \\ \\ 0 & 0 \end{pmatrix} \quad \text{and} \quad V = \begin{pmatrix} q_1 & 0 \\ \\ -\delta & \mu \end{pmatrix} \tag{7}$$

Using F and V from (7), we obtain FV^{-1} given by:

$$FV^{-1} = \begin{pmatrix} \frac{\theta S^*}{q_1} & 0 \\ \\ 0 & 0 \end{pmatrix} \tag{8}$$

Consequently, we obtain R_0 as the spectral radius of FV^{-1} given by:

$$R_0 = \frac{\Lambda \theta q_3}{q_1(q_0 q_3 - \beta\gamma)} = \frac{\Lambda\theta(\gamma + \mu)}{\mu(\tau + \delta + \mu)(\beta + \gamma + \mu)} \tag{9}$$

2.3. **Stability Analysis of the Examination Malpractice-Free Equilibrium.**

2.3.1. *Local Stability.* To study the local stability of the EMFE, we adopt the linearization approach.

Theorem 3. *The equilibrium point* $\left(\xi^* = \left(\frac{\Lambda q_3}{q_0 q_3 - \beta\gamma}, 0, 0, 0, \frac{\beta\Lambda}{q_0 q_3 - \beta\gamma}\right)\right)$ *is locally asymptotically stable (LAS) if* $R_0 < 1$ *and unstable if* $R_0 > 1$

Proof. Let J_0 be the Jacobian matrix of system (1) evaluated at ξ^*, that is:

$$J_0 = \begin{pmatrix} -q_0 & -\theta S^* & 0 & 0 & \gamma \\ 0 & \theta S^* - q_1 & 0 & 0 & 0 \\ 0 & \delta & -\mu & 0 & 0 \\ 0 & \tau & 0 & -q_2 & 0 \\ \beta & 0 & 0 & \alpha & -q_3 \end{pmatrix} \tag{10}$$

Clearly, the matrix in (10) admits one negative eigenvalue, namely $\lambda_1 = -\mu$. Furthermore, the nature of the remaining eigenvalues of the matrix in (10) can be obtained from the sub-matrix in (11) below:

$$J_1 = \begin{pmatrix} -q_0 & -\theta S^* & 0 & \gamma \\ 0 & \theta S^* - q_1 & 0 & 0 \\ 0 & \tau & -q_2 & 0 \\ \beta & 0 & \alpha & -q_3 \end{pmatrix} \tag{11}$$

According to the Routh-Hurwitz stability theorem, matrix in (11) will be stable if its trace and determinant are negative and positive respectively [12,13]. Now:

$$Trace(J_1) = -\left(q_0 + q_2 + q_3 + q_1(1 - R_0)\right) < 0 \text{ if } R_0 < 1 \tag{12}$$

and

$$\det(J_1) = q_1(q_0 q_1 q_3 - \beta\gamma)(1 - R_0) > 0 \text{ if } R_0 < 1 \tag{13}$$

Thus, the EMFE state is locally asymtotically stable whenever $R_0 < 1$. ☐

Next, we examine the global stability of the examination malpractice-free state.

2.3.2. *Global Stability of the Examination Malpractice-Free State.* To establish the long term stability behavior of the examination malpractice-free equilibrium state, we consider the following Lyapunov function:

$$V(t) = \frac{1}{q_1} M \tag{14}$$

Differentiating V(t) gives

$$\begin{aligned} \frac{dV(t)}{dt} &= \frac{1}{q_1}\frac{dM}{dt} \\ &= -(1 - R_0) M \end{aligned} \tag{15}$$

It is clear from (15) that $\frac{dV(t)}{dt} \leq 0$ if $R_0 \leq 1$. Hence, the EMFE point is globally asymptotically stable if $R_0 \leq 1$ and unstable otherwise

2.4. **Existence of Examination Malpractice Endemic Equilibrium Point (EMEEP).** Solving system (1) for the state variables at the EMEEP gives the following system of solutions:

$$\begin{cases} S^{**} = \frac{\Lambda q_2 q_3 + \alpha\gamma\tau M^{**}}{q_2 q_3(\theta M^{**} + q_2(q_0 q_3 - \beta\gamma)} \\ \\ M^{**} = \frac{q_1 q_2 (q_0 q_3 - \beta\gamma)(R_0 - 1)}{\theta(q_1 q_2 q_3 - \alpha\gamma\tau)} \\ \\ C^{**} = \frac{\delta q_1 q_2 (q_0 q_3 - \beta\gamma)(R_0 - 1)}{\theta\mu(q_1 q_2 q_3 - \alpha\gamma\tau)} \\ \\ R^{**} = \frac{\tau q_1 (q_0 q_3 - \beta\gamma)(R_0 - 1)}{\theta(q_1 q_2 q_3 - \alpha\gamma\tau)} \\ \\ H^{**} = \frac{\beta\Lambda q_2 q_3 + \alpha\beta\gamma\tau M^{**}}{q_2 q_3(\theta q_3 M^{**} + (q_0 q_3 - \beta\gamma))} + \frac{\alpha\tau q_1(q_0 q_3 - \beta\gamma)(R_0 - 1)}{\theta q_3(q_1 q_2 q_3 - \alpha\gamma\tau)} \end{cases} \tag{16}$$

It is clear from (16), that S^{**}, M^{**}, C^{**}, R^{**} and H^{**} exist if and only if $R_0 > 1$, this gives the condition for the existence of the EMEEP. In what follows, we examine the global stability of this endemic equilibrium point using Liapunov function.

2.4.1. *Global Stability of the Examination Malpractice Endemic Equilibrium Point.*

Theorem 4. *The model represented by system (1) admits a globally asymptotically stable non-trivial endemic equilibrium (ξ^{**}) whenever $R_0 > 1$*

Proof. Consider a positive definite function $\mathcal{L}$ defined by:

$$\begin{aligned} \mathcal{L}(\xi^{**}) = &\left((S - S^{**}) - S^{**}\ln\frac{S}{S^{**}}\right) + \left((M - M^{**}) - M^{**}\ln\frac{M}{M^{**}}\right) + \left((C - C^{**}) - C^{**}\ln\frac{C}{C^{**}}\right) \\ &+ \left((R - R^{**}) - R^{**}\ln\frac{R}{R^{**}}\right) + \left((H - H^{**}) - H^{**}\ln\frac{H}{H^{**}}\right) \end{aligned}$$

Taking the time derivative of $\mathcal{L}(\xi^{**})$ gives:

$$\begin{aligned} \frac{d\mathcal{L}(\xi^{**})}{dt} &= \left(1 - \frac{S^{**}}{S}\right)\frac{dS}{dt} + \left(1 - \frac{M^{**}}{M}\right)\frac{dM}{dt} + \left(1 - \frac{C^{**}}{C}\right)\frac{dC}{dt} + \left(1 - \frac{R^{**}}{R}\right)\frac{dR}{dt} + \left(1 - \frac{H^{**}}{H}\right)\frac{dH}{dt} \\ &= \left(\frac{S - S^{**}}{S}\right)[\Lambda + \gamma H - \theta SM - q_0 S] + \left(\frac{M - M^{**}}{M}\right)(\theta SM - q_1 M) \\ &+ \left(\frac{C - C^{**}}{C}\right)(\delta M - \mu C) + \left(\frac{R - R^{**}}{R}\right)(\tau M - q_2 R) + \left(\frac{H - H^{**}}{H}\right)(\beta S + \alpha R - q_3 H) \end{aligned}$$

$$= \Lambda + \gamma H + \theta M S^{**} + q_0 S^{**} - q_0 S - (\Lambda + \gamma H)\frac{S^{**}}{S} + q_1 M^{**} - q_1 M - \theta M^{**} S$$
$$+ \delta M + \mu C^{**} - \mu C - \delta M \frac{C^{**}}{C} + \tau M + q_2 R^{**} - q_2 R - \tau M \frac{R^{**}}{R} + \beta S + \alpha R + q_3 H^{**} - q_3 H$$
$$- (\beta S + \alpha R)\frac{H^{**}}{H}$$
$$= \mathcal{L}^+ - \mathcal{L}^- \tag{17}$$

where

$$\mathcal{L}^+ = \Lambda + \gamma H + \theta M S^{**} + q_0 S^{**} + q_1 M^{**} + \delta M + \mu C^{**} + \tau M + q_2 R^{**} + \beta S$$
$$+ \alpha R + q_3 H^{**}$$
$$\mathcal{L}^- = q_0 S + (\Lambda + \gamma H)\frac{S^{**}}{S} + q_1 M + \theta M^{**} S + \mu C + \delta M \frac{C^{**}}{C} + q_2 R + \tau M \frac{R^{**}}{R}$$
$$+ q_3 H + (\beta S + \alpha R)\frac{H^{**}}{H}$$

If we now assume $\mathcal{L}^+ \leq \mathcal{L}^-$
then, it follows from (17) that $\frac{d\mathcal{L}(\xi^{**})}{dt} \leq 0$ with the equality holding if and only if $S^{**} = S$, $M^{**} = M$, $C^{**} = C$, $R^{**} = R$ and $H^{**} = H$

Therefore, the largest compact invariant set within $\mathcal{D}$ (the model's invariant region) is the singleton $\{\xi^{**}\} = \{S^{**}, M^{**}, C^{**}, R^{**}, H^{**}\}$. Hence, following [14], the unique endemic equilibrium of system (1) is globally asymptotically stable whenever it exists. □

3. Local Sensitivity Analysis

To investigate the contribution of each model parameter to the occurrence of examination malpractice, we calculated the sensitivity indices of the parameters of the basic examination malpractice reproductive number using the forward sensitivity index expression. The output is tabulated in Table 4 below.

Table 4. Sensitivity Indices of R_0 Parameters

Parameter	**Sensitivity index**
Λ	$+1.00000$
θ	$+1.00000$
β	-0.35702
γ	$+0.35682$
τ	-0.57061
δ	-0.42796
μ	-1.00123

4. Numerical Simulations

To examine the dynamical evolution of the model sub-classes, we simulated the proposed model system of equations using Matlab ode45. We used the parameter values given in Table 3 with the following assumed initial values: $S(0) = 120$, $M(0) = 25$, $C(0) = 5$, $R(0) = 5$ and $H(0) = 15$. The simulation graphs are shown from Figure 2 to Figure 7

5. Discussion and Conclusion

A five-compartmental model is constructed to study the phenomenon of examination malpractice at the West African Senior School Certificate Examination (WASSCE) level in Ghana. The well-posedness of the model is established. The examination malpractice free equilibrium is shown to possess both a local and global asymptotic stability whenever the examination malpractice reproductive number (R_0) is less than one. Furthermore, the examination malpractice persistent equilibrium is derived and shown to be globally stable if $R_0 > 1$. We carried out local sensitivity analysis on the parameters of R_0 and established that candidates recruitment rate (Λ), the rate at which candidates engage into irregularities (θ) and the susceptibility rate (γ) of honest or law abiding candidates have positive impact on the examination malpractice reproductive number (R_0). On the other hand, the rate at which susceptible candidates progress to honest or law abiding candidates (β), the rate at which candidates recover from malpractice (τ) and the rate of cancellation of examination results (δ) have a negative impact on R_0. In other words, increasing the value of any parameter with negative impact on R_0 will lead to minimizing examination malpractice at the WASSCE level in Ghana. Thus, we recommend that to control the evil act of examination malpractice during WASSCE, the examination bodies should intensify the orientation programs for candidates, recruit honest and principle invigilators who can strictly monitor the candidates in the examination rooms, strictly enforce punishment or disciplinary actions against examination malpractice perpetrators.

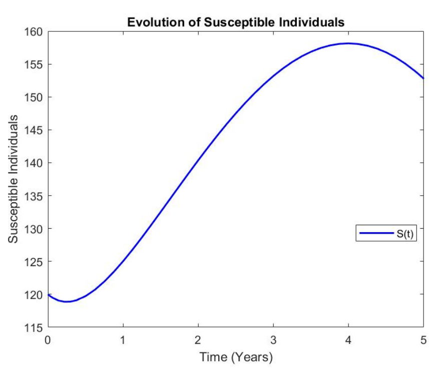

Figure 2. Plot of susceptible sub-population

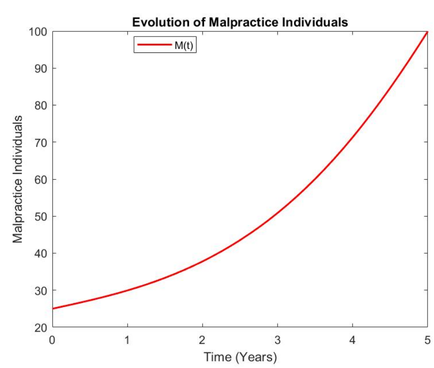

Figure 3. Plot of malpractice sub-population

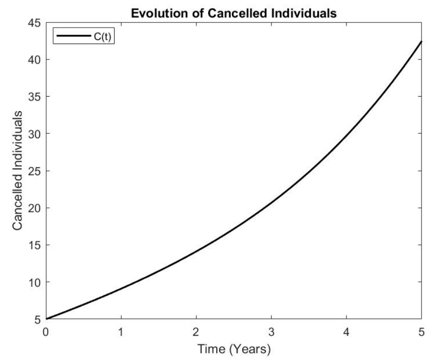

Figure 4. Plot of cancelled sub-population

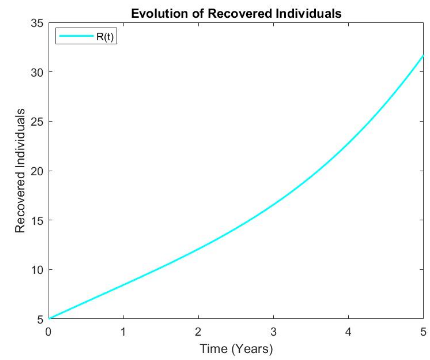

Figure 5. Plot of recovered sub-population

Figure 6. Plot of honest sub-population

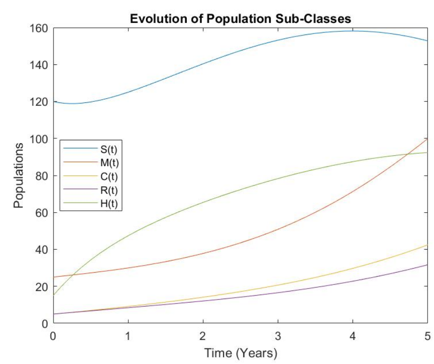

Figure 7. Plot of all sub-population

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