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MATHEMATICAL MODELING AND ANALYSIS OF BANK CAPITAL ADEQUACY DYNAMICS

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Abstract. Maintaining adequate capitalization is paramount for banks to ensure financial stability and regulatory compliance. This paper employs the Differential Transform Method (DTM) to solve a proposed dynamic model of bank capital adequacy, focusing on the relationship between a bank's capital and its risk-weighted assets (RWAs). Three settings of RWAs growth, namely constant, linearly increasing, and exponentially increasing, are explored, with their respective parameter setups embedded. The effectiveness of the DTM is validated through comparisons of the obtained solutions with their corresponding exact solutions, demonstrating its ability to accurately simulate capital adequacy dynamics under varying RWAs growth patterns. The equilibrium analysis reveals that the steady-state level of capital adequacy is directly proportional to the bank's assets, emphasizing the importance of asset growth for financial stability. Stability analysis indicates that a positive decay rate is crucial for resilience against perturbations. These findings underscore the application of mathematical modeling using DTM in aiding banks' capital management strategies amidst evolving financial landscapes, ensuring they maintain adequate capital levels and respond effectively to economic shocks.

Keywords: Stability, Financial Stability, Bank Capital Adequacy, Risk Management.
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1 Introduction

Bank capital adequacy is a vital component of financial stability, as it ensures banks have sufficient capital to absorb potential losses. The Basel Accords emphasize the importance of capital

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adequacy in maintaining bank solvency (Gehrig & Iannino, 2021). However, modeling capital adequacy dynamics is a complex task due to the nonlinear interactions between risk-weighted assets, capital, and other relevant factors (Imbierowicz et al., 2021). Traditional modeling approaches rely on linear methods, which may not accurately capture these dynamics (Hersugondo et al., 2021). Therefore, there is a need for more advanced modeling techniques to ensure accurate assessment and maintenance of capital adequacy (Corbae & D'Erasmo, 2021).

The Differential Transform Method (DTM) is a numerical technique that solves nonlinear differential equations using a transformation approach. DTM has been successfully applied in various fields, including finance, physics, and engineering (Lingfeng & Shiyuan, 2013; Han & Wu, 2013). In the context of capital adequacy modeling, DTM can capture the nonlinear effects of risk-weighted assets, credit losses, and regulatory requirements on capital adequacy dynamics. DTM offers several advantages over traditional methods, including ease of implementation, computational efficiency, and accuracy in solving nonlinear problems (Tuteja & Barara, 2021).

The literature on capital adequacy modeling has primarily focused on linear approaches, neglecting the potential nonlinear effects of risk-weighted assets and other factors (Etudaiye-Muhtar & Abdul-Baki, 2021). Recent studies have emphasized the need for more advanced modeling techniques to capture the complex dynamics of capital adequacy (Le, Nasir, & Huynh, 2023). Some researchers have applied nonlinear methods, such as neural networks and fuzzy logic, but these approaches have limitations in terms of interpretability and computational efficiency (Eguda et al., 2019). The application of mathematical modeling in capturing bank capital adequacy dynamics (BCAD) and its sensitive parameters is still unexplored, providing a research gap that this study aims to address (Moudud-Ul-Huq, 2021; Ndii et al., 2018).

Bank capital adequacy is influenced by various factors, including risk-weighted assets, credit losses, regulatory requirements, and economic conditions (Fang et al., 2022). Risk-weighted assets are a significant component of capital adequacy, as they reflect the bank's exposure to credit risk. Credit losses also impact capital adequacy, as they reduce the bank's capital base. Regulatory requirements, such as capital buffers and liquidity ratios, further influence capital adequacy dynamics (Biazar & Barandkam, 2013). The interplay between these factors is nonlinear, necessitating the use of advanced modeling techniques like DTM (Al-Ahmad et al., 2020).

This research aims to develop a novel mathematical modeling framework using DTM to capture the nonlinear dynamics of bank capital adequacy. The proposed mathematical model will incorporate key factors affecting capital adequacy, including risk-weighted assets, credit losses, regulatory requirements, and economic conditions. Previous studies have utilized static models to assess capital adequacy, often focusing on snapshot analyses of capital ratios. Dynamic models, however, offer a more comprehensive view by considering temporal changes in RWAs and capital (Moudud-Ul-Huq, 2021). This paper builds on existing dynamic approaches, integrating continuous time analysis through differential equations (Narayana et al., 2021).

A set of an internationally agreed-upon regulations prepared by the Basel Committee on Banking Supervision in response to the 2007–2009 financial crisis (Basel III), places some guidelines with an emphasis on maintaining a minimum capital adequacy ratio to certify that banks can withstand financial stress. This research aligns with these regulatory requirements, providing a model that banks can use to meet and exceed these standards (Gehrig & Iannino, 2021).

The expected outcomes of this research include a better understanding of capital adequacy dynamics and the development of a more accurate modeling framework for banks and regulators. The proposed model will provide insights into the nonlinear interactions between risk-weighted assets, credit losses, and regulatory requirements, enabling banks to optimize their capital buffers and regulators to set effective capital adequacy requirements. The use of DTM will also offer a computationally efficient and interpretable approach to capital adequacy modeling, enhancing the reliability of capital adequacy assessments (Syafrizal et al., 2023).

2 Mathematical Model Assumptions and Formation

(i) Capital generation rate and decay rate. π and λ, respectively are constant over time.

(ii) The bank's capital is treated as a homogeneous entity without differentiating between Tier 1 and Tier 2 capital.

(iii) Risk-weighted assets (**RWAs**) $A(t)$ are given and can vary over time based on predefined scenarios. That is: RWAs $A(t)$ can vary over time according to different growth patterns such as:

  (a) Constant RWAs: $A(t) = A_0$.

  (b) Linearly Increasing RWAs: $A(t) = A_0 + kt$.

  (c) Exponentially Increasing RWAs: $A(t) = A_0 e^{bt}$.

Remark: Tier 1 and Tier 2 capital are two categories of assets that banks hold to meet regulatory requirements. Tier 1 capital is a bank's core capital, which consists of equity capital and stated reserves. Tier 1 capital is used to operate on a daily basis and is the foundation of a bank's financial strength. Tier 2 capital is a bank's supplementary capital, that consists of loan loss provisions and subsidiary debt.

Let $C(t)$ represents the bank's capital at time t, $A(t)$ represents the risk-weighted assets at time t, π is the rate of capital generation from the RWAs, and λ is the decay rate of capital due to expenses and losses. Then, the capital adequacy of a bank is modeled using the following differential equation:

$$\frac{dC(t)}{dt} = \pi A(t) - \lambda C(t). \tag{1}$$

To solve the differential equation, we use the method of integrating factors as follows:
Rewriting the equation gives:

$$\frac{dC(t)}{dt} + \lambda C(t) = \pi A(t). \tag{2}$$

Applying the integrating factor: $\mu(t) = e^{\int \lambda dt} = e^{\lambda t}$on both sides of (2) gives:

$$e^{\lambda t}\frac{dC(t)}{dt} + \lambda e^{\lambda t} C(t) = \pi e^{\lambda t}. \tag{3}$$

Further simplification gives the solution as:

$$C(t) = e^{-\lambda t}\left(\int \pi e^{\lambda t} A(t)dt + K\right). \tag{4}$$

For a constant risk-weighted assets, $A(t)$, we have:

$$\begin{aligned} &A(t) = A_0 : \\ &C(t) = \tfrac{\pi A_0}{\lambda} + \left(C_0 - \tfrac{\pi A_0}{\lambda}\right) e^{-\lambda t} \end{aligned} \tag{5}$$

where C_0 is the initial capital at $t = 0$.

2.1 Modeling Settings and Replication Analysis

We present some illustrative settings under various stages to understand the model's behavior. For example, in settings 1 and II (S1 and SII), we have:

SI: Constant RWAs:
$C(t) = \frac{\pi A_0}{\lambda} + \left(C_0 - \frac{\pi A_0}{\lambda}\right) e^{-\lambda t}$ ($A(t) = A_0$, a constant term).
This shows that the capital approaches a steady state $\frac{\pi A_0}{\lambda}$ as t increases.

SII: Variable RWAs: For scenarios where $A(t)$ varies, the integral $\int \pi e^{\lambda t} A(t)dt$ can be computed numerically.

2.2 Differential Transform Method (DTM)

The Differential Transform Method (DTM) is a semi-analytical numerical technique used to solve differential equations. It transforms the differential equations into a series of algebraic equations, which are easier to solve (Eguda et al., 2019).
The DTM formula for a function $C\left(t\right)$ and its derivative is defined as:

$$\frac{dC(t)}{dt}=\sum_{k=0}^{\infty}(k+1)C_{k+1}t^{k}. \tag{6}$$

For the differential equation

$$\frac{dC(t)}{dt}=\pi A(t)-\lambda C(t), \tag{7}$$

the DTM provides recurrence relation as:

$$C_{k+1}=\frac{\pi A_k-\lambda C_k}{k+1},\ k=0(1)n. \tag{8}$$

The differential transform of $C\left(t\right)$ is denoted by $C\left(k\right)$, and:

$$C(k+1)=\frac{\pi A(k)-\lambda C(k)}{k+1} \tag{9}$$

is the index of the transform. This is the recurrence relation for DTM in this context.
Given $C\left(0\right)=C_0$, the initial value of the capital, the inverse differential transform gives the solution as a series:

$$C(t)=\sum_{k=0}^{\infty}C(k)\frac{t^k}{k!}. \tag{10}$$

The solution of this capital adequacy model and similar models in finance can be obtained by means of semi-analytical or numerical methods (Edeki et al., 2014; Hu et al., 2021; Edeki et al., 2016; Ouyang et al., 2015).

2.3 Equilibrium and Stability Analysis of the Capital Adequacy Dynamics

Here, we analyze the projected differential dynamics associated with the capital adequacy dynamics:

$$\frac{dC(t)}{dt}=\pi A(t)-\lambda C(t).$$

2.3.1 Equilibrium and Stability Analysis

To find the equilibrium points, in (1), we set the time derivative $\frac{dC(t)}{dt}$ to zero. This implies

$$C(t)=\frac{\pi}{\lambda}A(t). \tag{11}$$

The equilibrium point depends on the assets $A\left(t\right)$. If we assume that $A\left(t\right)$ is constant (say A), then:

$$C^{*}=\frac{\pi}{\lambda}A. \tag{12}$$

To analyze the stability of the equilibrium point, we consider small perturbations around the equilibrium. Hence, let

$$C(t)=C^{*}+\epsilon\left(t\right) \tag{13}$$

be is a small perturbation. So, substituting (12) into the original differential equation in (1), gives:

$$\frac{d}{dt}(C^{*}+\epsilon\left(t\right))=\pi A-\lambda(C^{*}+\epsilon\left(t\right)). \tag{14}$$

Since C^{*} is the equilibrium point, we know that $\pi A-\lambda C^{*}=0$, so (14) simplifies to:

$$\frac{d\epsilon(t)}{dt} = -\lambda\epsilon(t), \tag{15}$$
$$\epsilon(t) = \epsilon(0)e^{-\lambda t} \tag{16}$$

2.3.2 Stability Condition

The stability of the equilibrium point C^* depends on the sign of λ, Thus,

(i) If $\lambda > 0$, the perturbation $\epsilon\,(t)$ decays exponentially to zero as t increases, indicating that the equilibrium $C^*$is stable.

(ii) If $\lambda \leq 0$, the perturbation $\epsilon\,(t)$ either remains constant (if $\lambda = 0$) or grows exponentially (if $\lambda < 0$, indicating that the equilibrium C^* is unstable.

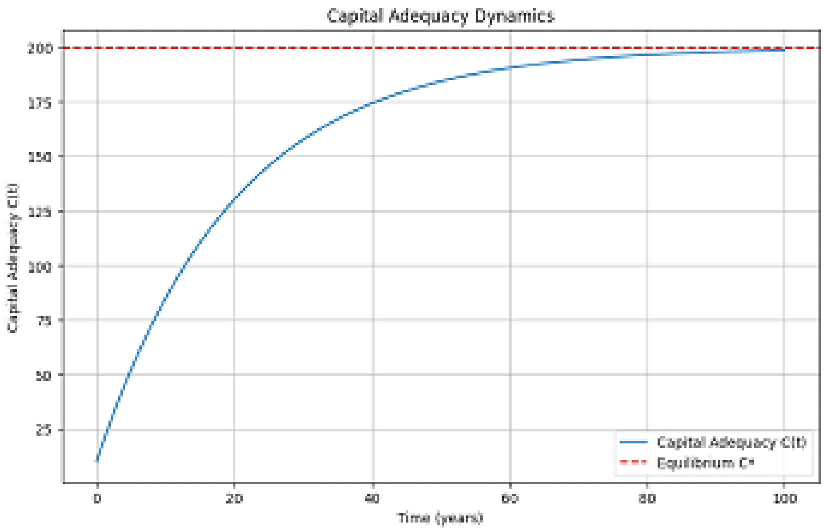

Figure 1: Capital adequacy dynamics and equilibrium settings

The resulting graph in Figure 1 shows how the capital adequacy C(t) evolves over time, starting from the initial value and approaching the equilibrium value C^*. The equilibrium line helps to visually verify the stability and convergence of the capital adequacy to its equilibrium state.

2.3.3 Implications of the Analyses

The equilibrium capital adequacy (ECA) C^*as in (12) is the steady-state level of capital adequacy that the bank will maintain over time if its assets remain constant and there are no external shocks. At this equilibrium, the capital adequacy is balanced such that the contributions from the assets exactly offset the decay rate of capital adequacy. This implies that a bank with higher assets will have higher ECA, assuming π and λ are constant.
The stability of the equilibrium capital adequacy is determined by the decay rate λ. Thus,

(i) If $\lambda > 0$, the system is stable. Any deviation from the ECA will decay over time, bringing the capital adequacy back to its equilibrium value. This suggests that the bank's capital adequacy is resilient to small shocks, provided the decay rate is positive.

(ii) If $\lambda \leq 0$, the system is unstable. Deviations from the equilibrium will not decay, and may even grow, indicating that the bank's capital adequacy is sensitive to disturbances and may not return to equilibrium without intervention.

2.3.4 Financial Implications of the Equilibriums and Stability

It is worth remarking that banks must ensure that their assets (represented by A) are sufficient to maintain an adequate level of capital adequacy (C). The ECA, $C^* = \frac{\pi}{\lambda}A$, indicates that capital adequacy increases with assets, highlighting the importance of asset growth for maintaining financial stability. Hence, regulators and bank management can use this relationship to set targets for asset accumulation and capital adequacy.

The parameter πup represents how effectively assets contribute to capital adequacy. A higher πup means assets more significantly boost capital adequacy, which could reflect efficient asset management or high-quality assets.

The decay rate λ represents factors that decrease capital adequacy, such as operational losses, loan defaults, or regulatory penalties. Banks need to manage these factors by focusing on risk management practices to ensure λ remains positive and ideally low, ensuring stability.

Regulatory bodies can use these insights to enforce capital adequacy requirements, ensuring banks hold sufficient assets relative to their decay rates, thus promoting overall financial system stability.

2.4 Illustrative Settings and Examples (with Exact Solutions)

Here, the solution method (DTM), in Python programming code is applied to the proposed model, with three examples being considered viz cases of constant, Linearly Increasing, and Exponentially Increasing RWAs as follows. The graphical views are presented in Figures 2 through 4, thereafter interpretations follow.

Example 1. For the *Constant RWAs*, the concerned data values are as follows:

$$\begin{aligned} A(t) &= A_0 = 500, \\ \pi &= 0.02, \\ \lambda &= 0.0, \\ C(0) &= 100, \end{aligned}$$

while the exact solution is:

$$C(t) = \frac{\pi A_0}{\lambda} + \left(C_0 - \frac{\pi A_0}{\lambda}\right) e^{-\lambda t}. \tag{17}$$

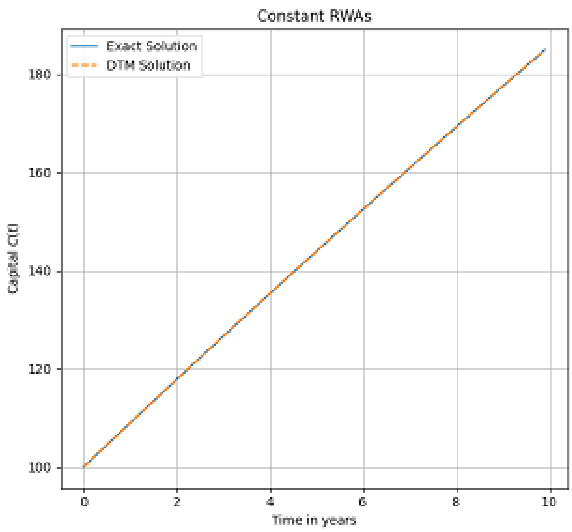

Figure 2: Solution pattern with Constant RWAs

2.4.1 Interpretation regarding Example 1 For the Constant RWAs:

(i) The exact solution shows an initial rapid increase in capital $C(t)$ due to the capital generation rate πup and the initial level of RWAs A_0.

(ii) Over time, capital experiences an exponential decay, governed by the capital decay rate λup.

(iii) The DTM solution closely approximates this behavior, demonstrating its accuracy in capturing the initial growth and subsequent decay of capital under constant RWAs.

Example 2. For the Linearly Increasing $RWAs$**,** the concerned data values and the exact solution are as follows:

$$A(t) = A_0 + kt,\ A_0 = 500,\ k = 10,\ \pi = 0.02,\ \lambda = 0.01,\ C(0) = 100, \tag{18}$$

$$C(t) = \frac{\pi(A_0 + kt)}{\lambda} + \left(C_0 - \frac{\pi(A_0 + kt)}{\lambda}\right) e^{-\lambda t}. \tag{19}$$

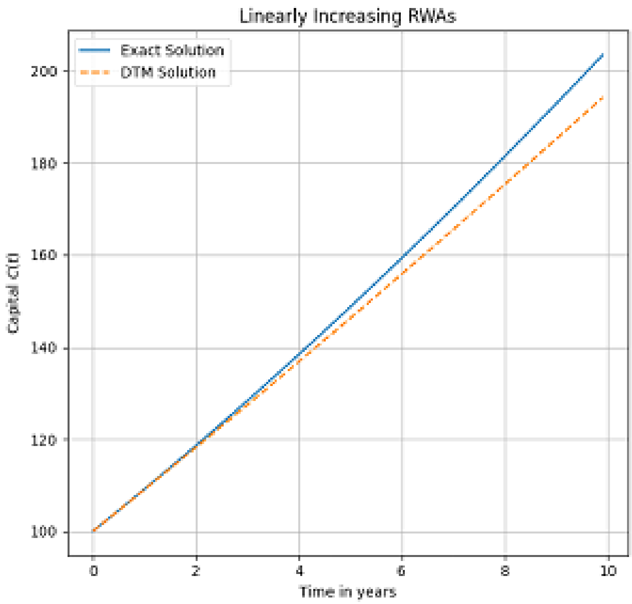

Figure 3: Solution pattern with Linearly Increasing Constant RWAs

2.4.2 Interpretation regarding Example 2 for Linearly Increasing RWAs:

(i) This scenario depicts non-linear growth in RWAs over time, leading to a corresponding non-linear growth in capital $C(t)$.

(ii) The exact solution shows that as RWAs increase linearly, the capital growth accelerates initially and then decays exponentially due to the capital decay rate λup.

(iii) The DTM solution accurately mirrors this behavior, validating its applicability in modeling capital dynamics under linearly increasing RWAs.

Example 3. For the Exponentially Increasing $RWAs$**,** the concerned data values are as follows

$$\begin{aligned} &A(t) = A_0 e^{bt},\ A_0 = 500, \\ &b = 0.01,\ \pi = 0.02, \\ &\lambda = 0.01,\ C(0) = 100 \end{aligned} \tag{20}$$

while the exact solution is:

$$C(t) = \frac{\pi A_0}{\lambda}\left(1 - e^{-\lambda t}\right) + C_0 e^{-\lambda t}. \tag{21}$$

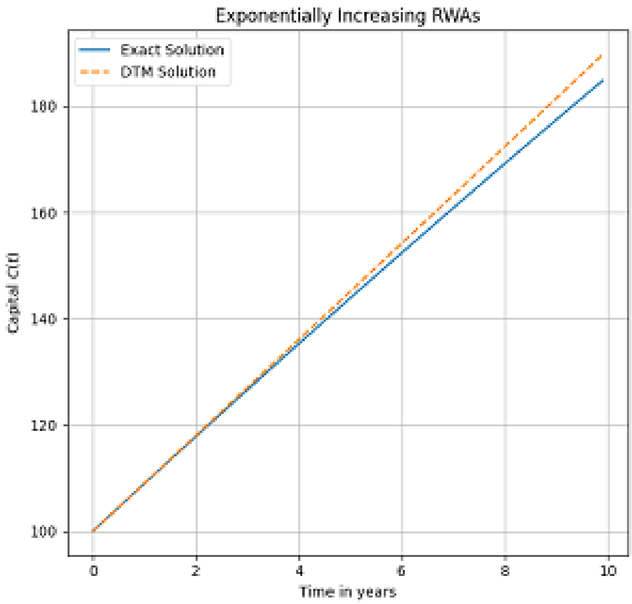

Figure 4: Solution pattern with Exponentially Increasing RWAs

2.4.3 Interpretation regarding Example 3 for Exponentially Increasing RWAs

(i) RWAs grow exponentially over time, leading to an initial rapid growth in capital $C(t)$.

(ii) As time progresses, capital experiences an exponential decay influenced by the capital decay rate λ.

(iii) The DTM solution captures this exponential growth and subsequent decay accurately, demonstrating its effectiveness in modeling capital adequacy dynamics under exponentially increasing RWAs.

3 Discussion and Interpretation of Findings

The graphs visually demonstrate the close alignment between the exact solutions and the solutions obtained through the Differential Transform Method (DTM) for each setting. For the Constant RWAs, both the exact and DTM solutions exhibit an initial rise in capital followed by a decay phase, validating the DTM's ability to model steady-state capital dynamics effectively. The DTM solution tracks the exact solution closely, illustrating its robustness in capturing the non-linear growth of capital under varying RWAs. As regards the Exponentially Increasing RWAs, the DTM accurately depicts the exponential growth and subsequent decay of capital, confirming its applicability in scenarios with rapid changes in RWAs.

4 Conclusion

Proper mathematical modeling of bank capital adequacy dynamics is essential for financial institutions to maintain stability, comply with regulatory requirements, and strategically manage their capitalization. By examining different scenarios of risk-weighted assets (RWAs) growth viz: constant, linearly increasing, and exponentially increasing, this work gains insights into the capital evolution over time. Employing the Differential Transform Method (DTM) demonstrates that capital initially rises due to capital generation before stabilizing or decaying, depending on the decay rate. For linearly and exponentially increasing RWAs, capital shows non-linear growth, highlighting the complexity of capital dynamics under varying financial conditions. DTM's accuracy in capturing these behaviors reaffirms its value as a robust modeling technique for bank capital adequacy. The application of DTM opens up multiple avenues for further research, such as investigating stochastic variations in RWAs, incorporating additional risk factors like market and operational risks, and extending the analysis to multi-period models for comprehensive long-term planning. As a remark, the DTM offers a powerful and flexible approach to understanding and accurately predicting bank capital dynamics. This capability is crucial for financial institutions to enhance their risk management, ensure regulatory compliance, and maintain overall financial stability in a dynamic economic environment.

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