Review Article

Application of Chaos Theory in Different Fields - A Literature Review

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Received: 1 October 2023; **Accepted:** 15 December 2023; **Published:** 5 January 2024

ABSTRACT

This comprehensive literature review delves into the multifaceted world of Chaos Theory and its pervasive applications across a wide spectrum of disciplines, including meteorology, economics, biology, engineering, medicine and social sciences. Chaos Theory's core principles, such as sensitivity to initial conditions and the discovery of hidden order within apparent chaos, are explored in-depth. This analysis delves into the intricate interconnections between Chaos Theory and dynamical systems, elucidating their shared objective of elucidating complex and dynamic phenomena. The research also investigates the application of the chaotic method as a problem-solving approach that acknowledges the inherent uncertainty and unpredictability of complex systems. The aforementioned approach is gaining traction in the realms of business, economics and the social sciences, despite facing criticism. The present study demonstrates the continued relevance of Chaos Theory in the contemporary era, as evidenced by its capacity to generate novel insights, provide comprehension of intricate scenarios and foster innovative advancements. The aforementioned aspect remains highly significant in addressing contemporary challenges and opportunities, as it profoundly influences our perception of the evolving global landscape in which we reside.

Keywords: Chaos Theory, Dynamical System, Literature Review

1. INTRODUCTION

The application of Chaos Theory has emerged as a potent framework for comprehending intricate systems and phenomena within a dynamic world characterised by ever-evolving scientific inquiry and practical applications. The concept of Chaos Theory originated from the notion of deterministic chaos, which was initially proposed by Edward Lorenz, a meteorologist, during the 1960s. Subsequently, this concept has transcended its initial meteorological origins and assumed significant relevance in various other disciplines, including physics, mathematics, biology, economics, engineering and numerous others (Biswas et al., 2018). The foundation of

Chaos Theory lies on the notion that seeming chaos conceals underlying order. This study examines the inherent unpredictability and sensitivity to initial conditions that complex systems exhibit (Sapini et al., 2017). Moreover, Chaos Theory endeavours to elucidate the underlying mechanisms via which seemingly random events and patterns in our world are intricately interconnected.

The article explores the intricate realm of Chaos Theory and elucidates its applications across diverse domains. The objective of this study is to conduct a comprehensive examination of the existing body of literature and demonstrate the profound impact of Chaos Theory on our cognitive and professional approaches in several domains. As our understanding deepens, we shall endeavour to elucidate the intricate interconnections that exist between chaos and order, unpredictability and predictability and complexity and simplicity. The theory of chaos is intriguing due to its capacity to stimulate cognitive processes and engender novel insights and transformative developments across diverse domains (Mashuri et al., 2023). Chaos Theory has been shown to be a strong and useful tool that can help us understand why the weather changes so quickly, study how money markets work, figure out how life works, or make things work better. Then, we will talk about chaos theory, the dynamical system, the chaos approach, how it can be used and its conclusion in this literature study.

2. CHAOS THEORY

The word "Chaos" comes from the Greek word *Khaos,* which means a huge empty space. Mathematicians often find it challenging to provide a precise definition for chaos but readily acknowledge the ability to "identify it upon observation". In essence, chaos refers to a state characterised by complete disorder or unpredictability in the behavior of intricate natural systems. Chaos theory, as described by Devaney and Keen (1989), revolves around the notion that a minor alteration in the present can lead to substantial consequences in the future. This mathematical field, which finds applications in various domains such as physics, engineering, economics, biology and philosophy, essentially asserts that even slight variations in initial conditions (for instance, those arising from rounding errors in numerical computations) can yield vastly divergent outcomes in chaotic systems, making long-term predictions generally unattainable (Peckham, 1980).

2.1. Overview of Chaos Theory

The chaotic dynamic system was discovered by Lorenz (1963), and the serial chaotic behavior in time has become a significant finding in the forecasting process from periodic observations of the system under investigation. A lot of work has been done with this idea in science and engineering (Lokibe et al., 1997). Moreover, Chaos theory is a field of physics and mathematics that looks at how dynamical systems behave when their starting conditions are very important. In other words, small changes in the starting conditions can cause big changes in how the system works over time (Kantz & Schreiber, 2004).

Chaos theory is a way of looking at complicated and often uncertain systems. These systems include meteorological phenomena (Wong et al., 2008), financial markets (Klioutchnikov et al., 2017) and human being system (Kyriazis, 2003). This lack of predictability is because these systems are very sensitive to their starting states. Chaos theory can be used in many real-world situations, such as predicting the weather, making systems that are strong and flexible and better understanding how people behave (Zhang & Dong, 2010). The main ideas of chaos theory include nonlinearity, sensitivity to initial conditions, interconnectivity and self-organization. For nonlinearity, chaotic systems do not follow regular rules. Small changes at the beginning can lead to very big changes later on. It is like a tiny push that can make a huge difference (Levy, 1994). Chaotic systems are markedly sensitive to their initial conditions, rendering their subsequent behavior highly susceptible to minute perturbations in the starting state. This sensitivity poses substantial challenges for the precise forecasting of their future trajectories (Levy, 1994; Kaplan & Glass, 1995). Chaotic systems often show complex connections (interconnectivity) between parts of them, where each part affects the others. These connections make it even harder to predict how they will behave (Campbell, 2015). Chaotic systems often exhibit self-organization, spontaneously forming discernible patterns and structures. This phenomenon is exemplified in natural occurrences such as snowflake formation, plant growth and urban development (Abel, 2009).

Additional aspects relevant to chaos theory involve its description as the exploration of "order within disorder." This comes from the observation that chaotic systems, even though they are hard to predict in the short term, often reveal hidden patterns and structures over time. Moreover, chaos theory is based on the concept of deterministic chaos, where the behavior of a chaotic system is determined by its starting conditions and the fundamental laws of physics (Abarbanel, 1996). Due to the extreme sensitivity of chaotic systems to their initial circumstances, precise estimations are unattainable (Shen et al., 2021). The use of chaos theory extends to various domains, encompassing meteorology, economics, biology, psychology and the development of novel technologies such as weather prediction models and traffic flow simulations (Biswas et al., 2018).

2.2. Dynamical System

A dynamical system is a mathematical construct used to model the temporal evolution of a system within the framework of chaos theory. The system is comprised of a collection of equations or principles that dictate the temporal evolution of the state variables. These state variables show the different qualities or traits of the system. In chaos theory, one important trait of chaotic systems is that they are sensitive to their starting conditions (Abarbanel, 1996). This sensitivity means that even a small change in how the system starts out can have big effects on how it works in the long run (Peitgen et al., 2004). Consequently, chaotic systems possess inherent long-term unpredictability, despite their deterministic character (Kaplan & Glass, 1995).

Moreover, dynamical systems have the capacity to manifest intricate phenomena such as periodic motion, bifurcations (abrupt shifts to novel behaviours) and naturally, chaotic behaviour distinguished by a dearth of long-range predictability. Complex geometric patterns known as weird attractors in phase space are frequently used to illustrate the long-term behaviour of chaotic dynamical systems. The Lorenz system, proposed by Edward Lorenz, a prominent meteorologist during the 1960s, stands as a widely recognised illustration of a chaotic dynamical system (Lorenz, 1963). The present system elucidates the dynamics of a basic atmospheric convection model, frequently employed as a pedagogical tool to exemplify the phenomenon of chaos. This model exhibits a pronounced sensitivity to initial conditions, leading to divergent outcomes and manifests the emergence of a peculiar attractor with intricate properties (Peitgen et al., 2004).

In addition, dynamical systems can be broadly categorised into two principal types; Linear dynamical systems and Nonlinear dynamical systems (Strogatz, 2018). Linear dynamical systems adhere to linear differential equations, which are characterised by relative ease of analysis and comprehension. Nonlinear dynamical systems are dictated by nonlinear differential equations, presenting greater complexity and analytical challenges. Nevertheless, they often reflect real-world systems more accurately, as many natural phenomena exhibit nonlinear behavior. Dynamical systems are used to model a wide variety of phenomena such as the weather such as rainfall (Shen et al., 2021), the spread of diseases such as Covid-19 cases

(Mashuri et al., 2023), the behavior of financial markets such as market stocks (Litimi et al., 2019), transportation such as traffic flow (Adenan et al., 2021), hydrology such as flood disaster (Mashuri et al., 2022) and many more. Here are some of the key concepts of dynamical systems theory:

a) Differential equations: Differential equations are used to model the behavior of dynamical systems.
b) Stability: A dynamical system is said to be stable if small changes in the initial conditions do not lead to large changes in the system's behavior.
c) Chaos: A dynamical system is said to be chaotic if it is sensitive to initial conditions and exhibits unpredictable behavior.

2.3. Relationship of Chaos Theory and Dynamical Systems

The essential connection between chaos theory and dynamical systems theory is in their mutual focus on the dynamics exhibited by intricate systems (Velickov, 2004). Both chaos theory and dynamical systems theory acknowledge the significance of nonlinearity in both physical and social systems. Both chaos theory and dynamical systems theory utilise differential equations to model system behaviour, which frequently results in equations that are not linear. According to chaos theory, chaotic systems do not follow the rules, and dynamical systems theory employs differential equations to model system behaviour (Kaplan & Glass, 1995; Levy, 1994). The idea that things are sensitive to their initial conditions is a fundamental concept that is present in both theories. Chaos theory shows how small changes can have big effects, and dynamical systems theory says that chaos happens when things are so sensitive that they can't be predicted.

The logistic map is widely recognised as a prominent illustration of a dynamical system within the field of chaos theory. The logistic map is a mathematical equation of a straightforward nature that has the potential to display chaotic behaviour given specific parameter values (Strogatz, 2018). This implies that the dynamics exhibited by the system as represented by the logistic map might exhibit a high degree of sensitivity to initial conditions and manifest as seemingly random or unpredictable behaviour when a particular parameter, designated as r, falls within a given range (Gleick, 2008). The mathematical expression for the logistic map is given by $x_{n+1} = r.x_n(1 - x_n)$, where x_{n+1} is the estimation of the population's value at the subsequent time step, the variable x_n represents the population value at the present time step, whereas the parameter r governs the system's behaviour and might induce chaotic dynamics for specific values.

The logistic map is a mathematical model that can exhibit chaotic behavior, but this chaos only emerges when the parameter r falls within a specific range of values. Outside of this range, the system may exhibit more predictable or periodic behavior. The identification and study of these chaotic regimes in dynamical systems like the logistic map are fundamental to chaos theory and have applications in various fields, including physics, biology, economics and engineering.

Additionally, both theories intersect in their exploration of system interconnectivity, as chaotic systems often exhibit intricate connections between components, complicating predictability, while dynamical systems theory considers stability, where stability implies predictability and an absence of chaotic behavior in certain scenarios (Alligood et al., 1996). These shared concepts underscore the interplay between chaos theory and dynamical systems theory in the study of complex, dynamic phenomena. So, we can conclude that the relationship between chaos theory and dynamical systems is that chaos theory is a subfield of dynamical systems theory that studies systems that are chaotic.

3. CHAOTIC APPROACH

The chaotic approach is a way of solving problems that acknowledges that complex systems can be very uncertain and unclear. It has become important in fields like business, economic and social sciences (Biswas et al., 2020). Basically, it understands that complex systems are often hard to predict. Small changes in the beginning can have big effects on the outcome (Gleick, 2008). This approach is disliked by certain individuals due to its potential difficulty in comprehension and application. Additionally, determining its correctness can be ambiguous at times (Popper, 2002).

Even so, the chaos approach is becoming more and more seen as a good way to understand and manage complicated systems (Biswas et al., 2020). This way of thinking is based on the ideas that things are not always linked in easy ways, that small changes can make a big difference and that systems can organise themselves (Gleick, 2008). These concepts possess versatile applications, such as facilitating decision-making among uncertainty, forecasting economic patterns, analysing the functioning of social networks and devising robust systems capable of managing unforeseen challenges (Biswas et al., 2020).

This chaotic approach has been widely used in various fields, both domestically and internationally, for analysing and forecasting deterministic time series data. Examples of studies that have utilised the chaotic approach include the traffic flow time series forecasting study conducted by Adenan et al. (2021), river water level time series forecasting by Mashuri et al. (2022) and Zakaria et al. (2021), analysis of carbon dioxide time series by Ruslan et al. (2020), and river flow time series forecasting by Adenan et al. (2017). Chaotic time series data possesses distinct characteristics that do not like other forecasting methods. Some of the characteristics stated by Kaplan and Glass (1995) and Abarbanel (1996) are as follows:

a) Chaotic time series data is non-periodic. The evolution of a time series reading will not return to its original position upon iteration.
b) Deciphered chaotic time series data remains within a limited and bounded range.
c) Chaotic time series data exhibits deterministic behaviour guarded by underlying system dynamics.
d) It is sensitive to initial conditions, and forecasting is limited to short-term predictions.
e) Time series data moves according to its rules within phase space.

4. CHAOS APPROACH IN VARIOUS FIELDS

Chaos theory, a branch of mathematics and physics, has become a valuable tool for understanding complex systems characterized by inherent uncertainty and unpredictability. Its applications extend across a wide array of fields, ranging from meteorology to economics and from biology to engineering. Table 1 provides an overview of how chaotic approach have been employed in different disciplines, shedding light on its diverse applications and contributions to various domains. Every discipline poses distinct difficulties, and the study of chaos theory provides significant perspectives on the dynamics of intricate systems within these realms. Please examine the following examples to observe how chaos theory has been utilised to decipher the complex dynamics within each respective discipline. Chaos theory has been very useful in many fields, including health, biology, engineering, the weather and finance. It helps us understand and deal with things that are hard to guess. There are useful things to learn from chaos theory, like how the weather works and how to make better stock market decisions. It shows that there is some kind of order even when things look like they are in chaos. The more we use chaos theory, the more patterns in the world around us become clear. This last sentence wraps up the table by stressing how chaos theory helps us understand complicated systems in many areas, even when things look like they are going chaotic.

Table 1. Applications of Chaos Approach in Various Fields

No.	Field	Reference(s)	Description
1	Meteorology and Climate Science	"Applying the 0-1 Test on the Analysis of Climate and Weather Data using Chaos Theory" (Mesbahzadeh, 2016)	Chaos theory reveals the sensitivity of weather systems to initial conditions, known as the "butterfly effect."
2	Economics and Financial Markets	"Chaos Theory in Finance" (Klioutchnikov et al., 2017)	Chaos theory helps understand financial markets, price movements and risk assessment through fractal analysis.
3	Biology and Ecology	"Chaos and Fractals: New Frontiers of Science" (Peitgen et al., 2004)	Chaos theory applied to study population dynamics ecological modelling and complex biological systems.
4	Engineering and Control Systems	"Chaos in Dynamical Systems" (Ott, 2012)	Chaos theory aids in designing control systems and studying nonlinear dynamics in engineering.
5	Medicine and Physiology	"Practical Applications Of Chaos Theory To The Modulation Of Human Ageing: Nature Prefers Chaos To Regularity"(Kyriazis, 2003)	Chaos theory applied to analyze heart rate variability, physiological system dynamics, and disease prediction in medicine.
6	Social Sciences and Sociology	"Chaos Theory in the Social Sciences: Foundations and Applications" (Kiel & Elliott, 1996)	Chaos theory is used in the social sciences to look at complicated social processes and events.

5. CURRENT APPLICATIONS OF CHAOTIC APPROACH

The field of chaos theory pertains to the examination of deterministic nonlinear dynamical systems that exhibit a pronounced sensitivity to their beginning circumstances. The behaviour of these systems is frequently characterised by unpredictability, as even minor alterations in the initial conditions can result in significant and unforeseeable changes in the system's long-term dynamics. The application of chaos theory has been observed across various disciplines, encompassing domains such as meteorology, economics, biology, engineering, sociology and healthcare. In recent times, there has been an increasing scholarly focus on the utilisation of chaos theory to address practical issues. Table 2 presents a comprehensive overview of the contemporary applications of chaos theory spanning the period from 2020 to 2023. The applications have been methodically categorised based on their respective domains.

The utilisation of chaos theory extends across multiple academic fields, including meteorology and climate science, economics and financial markets, biology and ecology, engineering and control systems, medicine and physiology, as well as social sciences and sociology. This theory functions as a significant tool for understanding and predicting complex systems within these several disciplines. The utilisation of chaos theory is currently undergoing significant growth, displaying substantial potential for future applications across a wide range of fields. The potential utilisation of chaos theory encompasses various domains, including the advancement of innovative and improved therapeutic strategies for diseases, the building of energy systems that are more efficient and sustainable and the construction of financial systems that are more resilient and reliable. The topic of chaos theory is widely recognised for its dynamic and progressive nature, offering significant potential to profoundly impact different aspects of human existence.

Table 2. Current Applications of Chaos Theory

Field	Author	Research Title	Country
Meteorology and Climate Science	Shen et al., (2021)	Is Weather Chaotic?: Coexistence of Chaos and Order within a Generalized Lorenz Model	China
	Mashuri et al. (2022)	Performance of Water Level Forecasting Based on Chaos Approach Using Data Splitting	Malaysia
	Schemm et al. (2023)	Learning from Weather and Climate Science to Prepare for a Future Pandemic	United State
	Ruslan et al. (2020)	Nonlinear Forecasting for a Time Series of Carbon Monoxide in Areas with High Population Density in Sabah	Malaysia
Economics and Financial Markets	Hadizadeh et al. (2022)	Examining the Forex Market Based on Chaos Theory	Iran
	Debnath (2022)	The Effect of Chaos Theory in the Field of Business: A Review	Bangladesh
	Soloviev et al. (2020)	Lyapunov Exponents as Indicators of the Stock Market Crashes	Ukraine
Biology and Ecology	Owolabi (2021)	Numerical Approach to Chaotic Pattern Formation in Diffusive Predator–Prey System with Caputo Fractional Operator	Vietnam
	Shirazi and Subramaniam (2020)	Attractor Ranked Radial Basis Function Network: A Nonparametric Forecasting Approach for Chaotic Dynamic Systems	United State
Engineering and Control Systems	Gupta (2022)	Application of Chaos Theory for Arrhythmia Detection in Pathological Databases	India
	Alexan et al. (2021)	Image Encryption Through Lucas Sequence, S-Box and Chaos Theory	Egypt
Medicine and Physiology	Mashuri et al. (2023)	The Application of Chaos Theory on Covid-19 Daily Time Series Dataset in Malaysia	Malaysia
	Pathak et al. (2022)	Chaos And Complexity: Entrepreneurial Planning During Pandemic	Iran
	Tahir et al. (2022)	A Novel Binary Chaotic Genetic Algorithm for Feature Selection and its Utility in Affective Computing and Healthcare	Pakistan
Social Sciences and Sociology	Iirmdu (2022)	A Chaos Theory Approach To Understanding The Impact Of The COVID-19 Pandemic On Tourism Businesses In Plateau State, Nigeria	Nigeria
	Sumiyana & Sriwidharmanely (2020)	Mitigating the Harmful Effects of Technostress: Inducing Chaos Theory in an Experimental Setting	Indonesia

6. CONCLUSION

In essence, chaos theory has emerged as a prominent and flexible theoretical framework that transcends traditional constraints, significantly transforming our understanding and interaction with complex systems in various disciplines. The current literature review has conducted a thorough examination of the intricate domain of chaotic theory, exploring its fundamental principles, its close relationship with dynamical systems and the application of chaotic approaches. Furthermore, an extensive analysis has been conducted on the diverse range of uses of this phenomenon in other disciplines like meteorology, economics, biology, engineering, medicine and social sciences.

The persistent allure of Chaos Theory arises from its ability to unveil concealed order inside seemingly chaotic phenomena, highlighting the responsiveness of intricate systems to initial circumstances and the gradual formation of complex patterns over time. The intrinsic unpredictability of an event poses challenges when attempting to formulate precise long-term predictions. Nevertheless, this inherent lack of predictability also affords us the chance to cultivate a deeper comprehension of the complex mechanisms that dictate the environment in which we exist. The connection between chaos theory and dynamical systems underscores their shared pursuit of understanding complex and evolving phenomena.

As the world advances into the 21st century, the widespread impact of Chaos Theory becomes more apparent, as its applications expand to address present challenges and exploit upcoming prospects. The utilisation of chaos theory remains advantageous in diverse domains, including climate research, financial markets, ecological modelling and healthcare, facilitating comprehension of the intricate processes within our environment. The persistent impact of Chaos Theory in the domains of scientific inquiry and practical application is ascribed to its ability to provide fresh viewpoints, clarify seemingly chaotic occurrences and foster innovative progress. This statement emphasises the enduring significance of Chaos Theory as a driving force in the pursuit of knowledge and societal progress amongst the dynamic realm of scientific investigation and real-world implementations.

Declaration of Interest
The authors declare that there is no conflict of interest.

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