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Editorial

Stochastic Processes and Their Applications: In Honor of Prof. Sally McClean

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1. Introductory Notes

Stochastic processes are foundational tools in many scientific disciplines, including biology, operational research, social sciences, and stochastic finance, among others. The important characteristics of systems in these areas evolve with time in a relatively random way, and since stochastic processes are mainly families of random variables, in which their index represents time, they are the natural tool to use. This origin aligns with its mathematical interpretation of randomness and probabilistic analysis.

The word "stochastic" comes from the Greek word "στοχαστικός", and in this context, it means "random". The same word, in its form as a verb, is used in Greek in a similar context, to express the process of thought when someone is searching for all the possible outcomes of a certain phenomenon that has an important influence on one's life.

The theory and applications of stochastic processes trace their roots to the development of one of the richest and most fundamental examples: Brownian motion. This was an unexpected starting point, as Brownian motion is a remarkable mathematical construct that simultaneously exhibits properties of a martingale, Gaussian process, diffusion, Lévy process, Markov process, and more—concepts that were formalized much later. The origins of Brownian motion can be traced back to the early 1900s.

On 29 March 1900, Louis Bachelier (11 March 1870–28 April 1946) successfully defended his celebrated thesis, *Theorie de la Speculation*, at the Sorbonne. In this groundbreaking work, he applied probability theory to stock markets, marking the first historical attempt to introduce stochastic thinking through mathematics. This thesis laid the foundation for what is now known as stochastic finance.

In 1933, Andrei Kolmogorov (1903–1987) published his seminal work *Foundations of the Theory of Probability*, which introduced the axiomatic foundations of probability theory. This groundbreaking book has withstood the test of time and remains the cornerstone upon which the entire field of probability and statistics has flourished. Following Kolmogorov's contributions during the 1930s and 1940s, the study of stochastic processes became one of the most mathematically rigorous disciplines, alongside certain areas of pure mathematics (see Cramer [1]).

The development of stochastic processes as a formal extension of probability theory owes much to the influential works of Joseph (Joe) Doob (1910–2004) and William Feller (1906–1970). Doob's *Stochastic Processes* [2] and Feller's two-volume *An Introduction to Probability Theory and Its Applications* [3,4] were instrumental in shaping the modern theory of stochastic processes. These foundational texts not only advanced the field, but also played a key role in establishing courses on probability and stochastic processes in mathematics departments worldwide.

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The term "probabilist", so commonly used today, owes much to the era in which Doob and Feller lived and collaborated. Their long and fruitful discussions helped define and solidify the identity of probabilists as a distinct group within mathematics, contributing to the global dissemination of probabilistic and stochastic ideas.

Doob's 1953 book, *Stochastic Processes*, became a classic in the John Wiley series and remains a "must read" for any probabilist. In this landmark work, Doob formally defined the concept of a martingale for the first time, which naturally led to the definitions of supermartingales and submartingales. He then developed the theory of martingales and Markov processes to a remarkable extent, laying the foundation for much of modern probability theory.

For an inspiring account of how this influential book came to be, one can refer to Doob's interview with Laurie Snell [5], where he shares fascinating insights into his writing process and the development of the field.

In a paper by Doob [6], we learn that Feller was tireless in revising his books, taking particular delight in discovering new approaches, applications, and examples to enhance them. His books are extraordinary for their almost bewildering diversity of perspectives and applications, both within and beyond pure mathematics. No other book remotely resembles Feller's work in its combination of the purest mathematics, dazzling technical virtuosity, and wide-ranging applications, all presented in a style that vividly conveys the author's enthusiasm.

2. In Honor of Prof. Sally McClean

A glance at the history of eminent mathematicians reveals a sobering truth: nature does not preserve its most exceptional minds indefinitely. Each had a finite lifespan and, eventually, they "left". For some, this span was tragically short, despite their profound contributions to the progress of mathematics. It is a common tradition, therefore, for colleagues to honor such individuals by publishing a volume of invited papers in their research area.

However, we believe this gesture of respect is far more meaningful when it occurs just before or at the time of their retirement, allowing them to witness and appreciate the recognition of their life's work.

The journal *Mathematics* (a Q1 journal in the Web of Science list) recognized the success of our first Special Issue by publishing a volume (book) containing all the papers we edited for that Issue [7]. Encouraged by this achievement, they invited us to edit another Special Issue. We proposed the theme, "Stochastic Processes and Their Applications: In Honor of Prof. Sally McClean", to mark her semi-retirement and to recognize her significant contributions to research. The Editorial Board was delighted to accept our proposal, expressing their enthusiasm for the project.

Prof. Sally Ida McClean, a distinguished Northern Irish statistician and operations researcher, has significantly advanced the fields of mathematical modeling and health care planning. Sally Ida McClean was born in Belfast and earned her first degree, an M.A. in Mathematics, from the University of Oxford in 1970. She went on to complete an M.Sc. in Mathematical Statistics and Operations Research at Cardiff University in 1972 and earned her Ph.D. from Ulster University at Coleraine in 1976.

Her research spans a wide range of topics, including workforce modeling, health administration, interactive architecture, and survey methodology. She has authored over 300 publications in areas such as mathematical modeling, applied probability, multivariate statistical analysis, and the application of mathematical and statistical methods to computer science.

Prof. McClean's contributions to mathematical modeling, particularly in health care planning, are immense. Her research has significantly impacted elderly care, with models that optimize health care planning and resource allocation.

Prof. McClean is a Fellow of both the Royal Statistical Society and the Operational Research Society, as well as an Associate Fellow of the Institute of Mathematics and its Applications. Her extensive research output is reflected in citation metrics from major databases. According to Google Scholar, she has over 600 research publications, cited 12,674 times, with an h-index of 54. In the Web of Science (WOS) database, she has 218 publications, cited 2710 times, with an h-index of 25.

Prof. McClean's outstanding contributions to research have been recognized through her receipt of Ulster University's Senior Distinguished Research Fellowship.

3. Stochastic Processes and Their Applications: In Honor of Prof. Sally McClean

The Guest Editors would like to express their sincere gratitude to the Chief Editors and the Editorial Board of *Mathematics* for extending the invitation to edit this special volume. We warmly thank the authors for their significant contributions to this publication, as well as for their diligence and enthusiasm in addressing all comments and suggestions during the review process.

Our heartfelt appreciation goes to the anonymous reviewers whose invaluable assistance and rigorous comments were crucial to the successful completion of this endeavor.

We are also deeply grateful to the Editorial Manager, Dr. Syna Mu, for his tireless efforts in facilitating the workflow for this Issue, his excellent collaboration with the Guest Editors, and for arranging partial funding for the publication of this volume.

Special thanks are extended to Professors Michael Voskoglou and Maria Mariani for serving as Academic Editors for our own contributed articles. Their names were known to the Guest Editors after the publication of their papers.

Finally, we wish to acknowledge the numerous Editorial Assistants who skillfully managed the considerable workload involved in handling the large number of submissions for this volume. Their commitment and effectiveness played a crucial role in successfully completing this project.

The following section provides an organized overview of the articles in this Special Issue, categorized into key thematic areas. Additionally, we provide the reader with some useful references to help introduce the mathematical background relevant to the papers. The sub-areas (sections) are arranged to generally reflect the title of the Special Issue, with the articles in each section sorted according to their publication dates.

(i) Markov Chains, Processes, and Markov Systems.

Markov processes are stochastic processes that exhibit the Markov property, while Markov chains are their discrete time and discrete state space counterpart. That is, the probabilistic dependence on the past is only through the present state, which contains all the necessary information for the evolution of the process. Useful introductory texts on probability theory and stochastic processes can be found in [8], and on homogeneous and non-homogeneous Markov chains and processes in [9–12] and [13] (Chapter 3). For Markov systems or Open Markov models, which are generalizations of the Markov chain, a research monograph on the subject is detailed in [14]. We now provide a brief description of the articles of the Special Issue that could be included in this category:

(i1) Strong Ergodicity in Non-homogeneous Markov Systems with Chronological Order, by P.-C.G. Vassiliou [15]. Consider a stochastic system with a population of members categorized into different states. Three types of movements are possible within this system. First, members can transition between states; second, members may exit the system from various states; and third, new members may enter the system to replace those who have left or to expand the population. When the dynamics of these movements are modeled by a non-homogeneous Markov chain, the system is referred to as a non-homogeneous Markov system (NHMS).

An NHMS generalizes the classical Markov chain by accounting for multiple particles moving among the states, with the possibility of leaving the system and being replaced by others, potentially with different characteristics. This is in contrast to the classical Markov chain, which typically models a single particle transitioning among states without exits or replacements.

In this context, the author studied the concept of strong ergodicity for NHMS, focusing on a novel relaxation of a critical assumption found in all prior studies, i.e., the study relaxes the standard assumption regarding the asymptotic behavior of NHMS. Specifically, the author did not assume that the underlying inhomogeneous Markov chain geometrically converges to a homogeneous Markov chain with a regular transition probability matrix as time approaches infinity. Instead, the author investigated and derived conditions under which the rate of convergence to strong ergodicity in an NHMS is geometrically fast, thereby broadening the understanding of NHMS dynamics.

(i2) Estimation–Calibration of Continuous-Time Non-Homogeneous Markov Chains with Finite State Space, by ML Esquivel, NP Krasii, and GR Guerreiro [16]. The paper is divided into three parts. The first proposes a method to estimate the parameters of a set of transition intensities from ideal observed data. The second presents the result on regime-switching Markov chains that establishes the possibility of considering transition intensities made up of different sorts of functional forms, with each one of the functional forms depending on different sets of parameters. Finally, in the third part, the norm of the difference of two probability transition matrices is quantified in terms of the norm of the corresponding matrices of transition intensities, which justifies the choice of arbitrary functional forms for the transition intensities in ways that are more adequate for parameter estimation.

(i3) Educational Status as A Mediator of Intergenerational Social Mobility in Europe: A Positional Analysis Approach, by G. Stamatopoulou, E. Tsouparopoulou, and M. Symeonaki [17]. The study aimed to investigate both nominal (absolute) and relative (positional) patterns of intergenerational educational mobility in Europe by analyzing transitions across the educational levels of respondents and their parents in Europe using raw data drawn from the European Social Survey (ESS) from the year 2002 and onwards. It reveals all the necessary information concerning the proposed methodology and the ESS data that are utilized in order to estimate intergenerational educational mobility in absolute and relative terms. It presents the measurement results of intergenerational educational mobility, nominal and positional, and the validation tests performed.

(i4) The Arsenal of Perturbation Bounds for Finite Continuous-Time Markov Chains: A Perspective, by A.Y. Mitrophanov [18]. This perspective article describes what can be regarded as deterministic perturbations of the Kolmogorov equations. Thus, in effect, it considers deterministic perturbations of a stochastic process (i.e., the Markov chain under study). One could possibly imagine perturbation scenarios involving various deterministic or stochastic systems under deterministic or stochastic perturbations. Clearly, each scenario would require its own set of theoretical developments. Yet, the types of results discussed could be relevant in a broader context and may be applicable to other possible (and, possibly,

far more complex) perturbation scenarios. At the very least, they can provide a relevant standard for comparison or even help generate a viable working hypothesis.

(i5) A Throughput Analysis Using a Non-Saturated Markov Chain Model for LTE-LAA and WLAN Coexistence, by Mun-Suk Kim [19]. The paper proposes an analytical model to calculate the throughput for each system in a scenario where a single LTE-LAA system, dedicated to downlink transmission, shares an unlicensed channel with multiple WLAN systems. This study employs a Markov chain approach to model the random backoff operations of LTE-LAA eNodeB (eNB) and WLAN nodes under non-saturated traffic conditions. The Markov chain approach is limited by the need to define LTE-LAA eNB and WLAN node transmissions in discrete timeslots. Nevertheless, it enables a clear and detailed analysis of all sequential random backoff operations in the distributed coordination function of LTE-LAA and WLAN. In addition, this study analyzes the throughput of LTE-LAA and WLAN systems by integrating the impact of the clear channel assessment (CCA) threshold, which represents the sensitivity level required to detect ongoing transmissions, with Markov chain modeling of random backoff operations.

(ii) Semi-Markov Chains, Processes, and Semi-Markov Systems.

Semi-Markov chains are generalizations of Markov chains where the time of transition from each state to another is now a random variable. The same applies for semi-Markov processes, except that the time is now continuous. A very good text on semi-Markov chains and processes for the interested reader can be found in [20]. For semi-Markov systems or open semi-Markov models, which are, again, generalizations of Markov chains, the first paper that introduced them was [21], and this is a reliable publication to start from. We provide below a brief description of the articles that could be categorized in this section:

(ii1) Semi-Markov Models for Processes Mining in Smart Homes, by S. McClean and L. Yang [22]. This paper is concerned with developing and illustrating some specific mathematical expressions and results for models of human activity. It develops and uses Markov-type models to represent ADL processes and corresponding key performance indicators (KPIs) in smart homes, as well as in describing and evaluating strategies to determine anomalies in such transitions and durations. The approach is illustrated and evaluated using a publicly available smart home dataset comprising an event log of sensor activations, together with an annotated record of the actual activities, which is used for model development and validation.

(ii2) Attainability for Markov and Semi-Markov Chains, by B Verbeken and M.-A Guerry [23]. Firstly, the concept of attainability for Markov chains is reviewed and extended to systems with a growth factor $1 + \alpha$, where the parameter α signifies the rate of change in the size of the system over time. When α is negative, this indicates a contraction in the system size, i.e., a decline in the number of people in the system. Conversely, when α is positive, the system expands over time. Thereafter, it is introduced and the attainability is studied along with the state reunion attainability for semi-Markov chains starting from the concept of SR-maintainability for semi-Markov chains. It is shown that a general approach to state reunion attainability, where a structure is said to be state-reunion-attainable if there exists an arbitrary initial structure from which it can be attained, is not appropriate, and the concept of (n-step) state reunion attainability starting from a subset S of structures is introduced. A method to determine the associated region of attainable structures is also provided.

(ii3) Cost Evaluation for Capacity Planning based on Patient's Pathways via Semi-Markov Reward Modelling, by C. Chatzimichail, P. Kolias, and A. Papadopoulou [24]. In the study, a non-homogeneous semi-Markov reward model is considered, where rewards are random variables associated with state occupancies and transitions. The novelty of the paper lies in the inclusion of states' inflows and availability, which is critical for capacity-

planning based on service demands in an environment of fixed resources. The theory of the model is provided, followed by results related to the population's structure and states' inflows and the expressions related to the current availability of states. Also, expressions for the expected costs generated by the system and corresponding to patients' paths are developed.

(ii4) On a Mixed Transient–Asymptotic Result for the Sequential Interval Reliability for Semi-Markov Chains, by G. D'Amico and T. Gkelsinis [25]. The authors studied the sequential interval reliability, a measure recently introduced in the literature. This measure represents the probability of the system working during a sequence of non-overlapping time intervals. In their previous work, the authors proposed a recurrent-type formula for computing this indicator in the transient case and investigated the asymptotic behavior. The purpose of this work is to further explore the asymptotic behavior when only some of the time intervals are allowed to reach infinity while the remaining ones are not. In this way, a unique indicator that is able to describe the process evolution in transient and asymptotic cases is provided. It is important to note that this is not a straightforward result since, in order to achieve it, we need to develop several mathematical ingredients that generalize the classical renewal and Markov renewal frameworks.

(iii) Mathematical Optimization and Decision Analysis

This category addresses mathematical optimization and decision analysis with a specific focus on Data Envelopment Analysis (DEA) and stochastic programming. It addresses hierarchical efficiency evaluation and resource allocation, tailored for large organizations and enterprises, particularly within the banking sector. Key publications that can introduce the reader to this area of study are [26–28].

(iii1) A Bilevel DEA Model for Efficiency Evaluation and Target Setting with Stochastic Conditions, by A.C. Georgiou, K. Karapis, E.-M. Vretta, K. Bitsis, and G. Paltayian [29]. The paper presents a novel bilevel DEA model to evaluate organizational efficiency and set performance targets under stochastic conditions. It combines hierarchical decision-making with uncertainty modeling through discrete scenarios, which makes it particularly suitable for environments with volatile economic conditions. The model's integration of bilevel optimization and stochastic elements provides practical insights into resource allocation and output targeting while accommodating uncertainty. A major contribution of this work is its ability to address the complex interdependencies and hierarchical structures in large organizations, exemplified by a case study in the banking sector. This enhances its relevance to industries with similar operational complexities. The proposed approach offers dynamic strategies for decision-makers, allowing adjustments as scenarios unfold, thereby improving overall sustainability across economic, environmental, and social dimensions. The mathematical rigor and practical application make this paper a valuable addition to the literature on efficiency analysis, especially for sectors undergoing transformative changes such as banking.

(ix) General Stochastic Processes.

(ix1) A Class of Power Series q-Distributions, by Charalambos A. Charalambides † [30]. This is a seminal paper extending the work of the author devoted to q-distributions published on the research monograph Charalambides [31]. For example, the q-binomial distribution is the distribution of the number of successes in a sequence of n independent Bernoulli trials, with the odds of success at a trial varying geometrically with the number of trials. As a second example, the negative q-binomial distribution of the second kind is the distribution of the number of failures until the occurrence of the nth success in a sequence of independent Bernoulli trials, with the probability of success at a trial varying geometrically with the number of successes. A class of power series q-distributions, by considering a q-Taylor expansion of a parametric function, provides a unified approach to the study of

these distributions. Its q-factorial moments, for $0 < q < 1$ and $1 < q < \infty$, are obtained in terms of q-derivatives of its series function. Moreover, it is proven that a power series q-distribution is completely determined from its first two q-cumulants (or q-moments). Also, the convolution of power series q-distributions, using probability-generating functions, is shown to be a power series q-distribution. Furthermore, as part of demonstrating this approach, the q-factorial moments for $0 < q < 1$ and $1 < q < \infty$ of the q-Poisson (Heine and Euler) distributions, q-binomial distribution of the first kind, negative q-binomial distribution of the second kind, and q-logarithmic distribution are obtained as members of this class of distributions. In addition, interesting and useful structural information about these distributions is obtained through their probability-generating functions.

† Prof. Charalambos A. Charalambides has "left" us unexpectedly just after submitting the final form of his paper.

(ix2) Analyzing the Asymptotic Behavior of an Extended SEIR Model with Vaccination for COVID-19, by V.E. Papageorgiou, G. Vasiliadis, and G. Tsaklidis [32]. The paper provides valuable corrections concerning the theoretical results displayed in previous publications that pertain to the non-negativity and boundedness of a system of seven differential equations, which describe the transition of COVID-19 after the onset of the vaccination period. These modifications are crucial in validating the suitability of the epidemiological model for accurately describing the spread of COVID-19. More importantly, it provides novel properties regarding the global asymptotic stability of both the disease-free and endemic equilibria based on the values of the basic reproduction number. These theoretical aspects are more crucial than the local stability analysis, offering insights into long-term behavior when the system approaches the aforementioned equilibria. Finally, a novel addition to the literature is the computation of the convergence rate to the endemic equilibria, offering a more comprehensive understanding of the system's asymptotic behavior.

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Short Biography of Author



Panagiotis-C.G. Vassiliou is an Emeritous Professor at the Department of Mathematics, Aristotle University of Thessaloniki and was an Honorary Professor at the Department of Statistical Sciences, University College London for ten years. He has spend research and teaching time in cronological order at Ulster University, Ioannina University, Aristotle University of Thessaloniki, University College London. He has also spend research time at Imperial College London. He has also taught at the London Taught Course Center (LTCC), for 3rd and 4th year Ph.D. students of UCL, LSE, King's, Brunel and Kent. He has published more than 58 papers, indexed in the web of science mainly in the areas of non-homogeneous Markov systems, non-homogeneous semi Markov systems, and stochastic finance. His publications time span is 51 years and the two journals with the highest frequency were *Journal of Applied Probability* (11 papers, in 140 pages) and *Linear Algebra and its Applications* (8 papers in 224 pages). He has also written 4 books in English (J. Wiley, Chapman and Hall, UCL, MDPI) and 14 books in Greek. He has been the supervisor of 9 completed Ph.D thesis. Academic Services: Referee in more than 25 scientific journals, Guest Editor in 2 scientific journals and currently a member on the Editorial Board of *Mathematics*. Metrics: more than 915 citations in Web of Science, H-index = 19.



Andreas C. Georgiou is a Professor of Operational Research and the Director of the Quantitative Methods and Decision Analysis Lab in the Department of Business Administration at the University of Macedonia. He also serves as the Director of the MBA program and previously held the position of Director for the Master's Program in Business Analytics and Data Science. His research interests encompass a broad range of topics, including Mathematical Methods in Business Analytics, Stochastic Processes, Markov Chains, Mathematical Human Resource Planning, and Operations Research methodologies in Operations Management. He has also specialized expertise in discrete event simulation, multi-objective optimization, and efficiency and productivity evaluation using Data Envelopment Analysis (DEA). Prof. Georgiou has played a pivotal role in numerous research projects and doctoral dissertations, making significant contributions to the field. He has served on organizing and scientific committees for various conferences and holds positions on the editorial boards of several academic journals. His work has been published extensively in international conference proceedings and high-impact journals, earning over 1300 citations to date. In addition, Prof. Georgiou has provided peer reviews for more than 50 international journals and conferences, collaborating with leading publishing houses such as Elsevier, Springer, Sage, Emeral, Wiley, Taylor & Francis, and MDPI.

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