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Editorial: Advances in data-driven approaches and modeling of complex systems

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Editorial on the Research Topic
Advances in data-driven approaches and modeling of complex systems

This Research Topic discusses the latest developments in complex systems research and intends to give exposure to prospective readers about the data-driven approaches and modeling aspects of distinct complex physical, biological, and social systems. To address these issues, different modeling techniques e.g., ordinary and partial differential equations, discrete maps and stochastic models are employed to examine the complex systems of interest. Additionally, data-driven techniques e.g., agent-based modeling, machine learning, persistent homology, and big data analytics have also been discussed in greater detail so as to provide another paradigm on how data analysis and data interpretation are being performed in complex systems research. Special attention is given to various applications on the techniques of complex systems in examining the socio-environmental issues, epidemiology, ecological and physical problems, engineering, agriculture and financial applications. Many realistic examples from recent research are also employed in this Research Topic as illustrations. The main purpose of this article collection is to emphasize a unified approach to complex systems analysis, which goes beyond examining complicated phenomena of numerous real-life systems; this is done by investigating a huge number of components that interact with each other at different microscopic and macroscopic scales; new insights and emergent collective behaviors can evolve from the interactions between individual components and also with their environments. These tools and concepts will allow us to better understand the patterns of various real-life systems and help us comprehend the mechanisms behind which distinct factors shape some complex systems phenomena. As mentioned above, this Research Topic is specially designed to take into account a multidisciplinary approach in complex systems analysis that will encourage the transfer of ideas and methodology from data-driven techniques and modeling fields to the other areas of knowledge (and vice versa).

One of the main themes received by this Research Topic is on the modeling of COVID-19 epidemiology and the complex nature of diseases' progression. In general, the simplest mathematical frameworks that are widely used in infectious disease modeling is the deterministic ordinary differential equations (ODE) model. Traditional ODE models of disease transmission are often employed to predict disease trajectories and evaluate the effectiveness of alternative treatment or intervention strategies. For instance, in the recent COVID-19 global outbreaks, differential equations-based model constitutes an important tool to examine the effectiveness of (non-)pharmaceutical interventions and to guide policymaking in different countries. In this line of research, Aini et al. employed compartmental epidemic ODE to examine the effects of mass mobility on the COVID-19 transmission between localities in Indonesia. One of the contributions of this this study to complex system modeling is to formulate a useful method of estimating the movement of people by representing mobility in the form of a function; it is discovered that the predictions obtained using this technique yield a reasonably good result, compared with the actual data. Another modeling work by Inayaturohmat et al. also used compartmental modeling to investigate the combined influences of co-infection with tuberculosis and distinct intervention measures on the COVID-19 outbreaks. The optimal control approach has been incorporated into this modeling framework to study the effectiveness of isolation and treatment on the prevention for COVID-19 and tuberculosis. Other possible determinants of COVID-19 disease transmission are the impacts of stochasticity, vaccination strategies and also the reinfection problem. These factors have been considered by Campos et al. where they have developed stochastic differential equations model to envisage the interplay of stochasticity, booster shots and waning of immunity on the control of COVID-19. Their results show the importance of booster shots that enhance the vaccine-induced immunity duration. Incorporating uncertainties in the COVID-19 simulation can be beneficial, particularly for the policy makers to obtain better projection in designing more robust and refined intervention strategies.

Apart from incorporating stochasticity into differential equation-based model, other realisms can also be included to gain realistic insights on the physical and biological phenomena of interest. Inclusion of spatial diffusion component through the use of partial differential equations (PDE) model has played a pivotal role in better understanding the influences of spatial and dispersion process in shaping dynamical behavior of certain complex systems. For instance, Babajanov and Abdikarimov employed a PDE system to investigate the dynamics of traveling wave solutions using the functional variable method. The proposed method is found to be effective in constructing the exact traveling wave solutions of non-linear wave equations arising in mathematical physics and engineering. Additionally, another realism such as the growth process can also be considered in formulating the deterministic systems, and this approach has been widely used in the biological applications. In general, the growth of species can happen either by continuous breeding or this process can also occur seasonally at discrete times. Examples of species that breed seasonally are annual plants and insects; and apes are an example of species that breed continuously. Thus, depending on the type of growth process, this consideration can lead to distinct deterministic systems: (i) continuous-time models (e.g., ODE and PDE, for continuous breeding process), which have been discussed thoroughly in the previous paragraph; (ii) discrete-time models (e.g., discrete maps, for seasonal breeding process). For the contribution on discrete-time modeling framework, Hasibuan et al. have examined the competitive outcomes of some semelparous species and they discovered that the local stability condition of the coexistence equilibrium is determined by the degree of interspecific and intraspecific competition. This intriguing observation may have some applications in comprehending the dynamics of complex natural ecosystems and also crucial in devising sustainable management plans of the natural resources, such as in the fisheries industries.

Most of the aforementioned modeling studies discussed are based on the mechanistic system paradigms, meaning that these models are being constructed using the fundamental laws of natural sciences, including physical and biological principles. From practical viewpoints, these models can be employed to gain some beneficial insights on our complex natural world, particularly in the case of limited real data. However, the availability of vast and ever-increasing quantities of data has invoked a new paradigm in modeling and simulation fields with the advancement of data-driven modeling techniques such as agent-based modeling (ABM), machine learning, persistent homology, and big data analytics. In this area of research, Vinyals et al. proposed an integrated modeling approach that combined the ABM and machine learning techniques with related applications in digital technologies for agriculture. Another contribution on the agent-based modeling reviewed the state-of-the-art techniques on the inclusion of multiple levels of analysis, abstraction, and representation in the ABM frameworks. This innovative technique is often helpful in order to analyze different physical domains and applications (e.g., urban planning, land-use change, adaptation to environmental changes, biodiversity protection in socio-ecosystems, environmental pollution control, etc.) where interactions between individuals and their environments can give rise to emergent phenomena that are difficult to study otherwise. Another kind of data-driven modeling approach is the persistent homology (PH), which extracts the topological features from non-linear time series data. This technique is particularly useful for deeper understanding of the dynamical systems behavior and early detection or warning signals of catastrophe. Motivated by the capability of PH, Ismail et al. utilized this method combined with critical slowing down and some statistical correlation tests to examine the early warning signals of financial crises. Overall, PH approach provides a robust and accurate analysis of a dynamical system as this technique reveals the system topology at different spatial resolutions. This often leads to the persistence of only the major features of the underlying system and removes spurious effects of noise. It can also be seen that the big data analytics and statistical techniques play significant roles in the advent of data-driven modeling frameworks of distinct complex systems. This theme has inspired the formulation of a hybrid modeling system of autoregressive integrated moving average and fuzzy time series Markov chains by Devianto et al. to study the long pattern of the crude oil movement price using data from the West Texas Intermediate oil price for the year 2003 till 2021.

The modeling frameworks and problems presented in this Research Topic offer an overall outlook of the many facets of modeling approaches, analysis, and practical implications. However, the works covered in this Research Topic are far from exhaustive. Rather, they point to a selected range of problems that can be addressed by the mathematical modeling and data-driven computational approaches, and hopefully this insight can inspire the development of novel tools and techniques in the future.

Author contributions

MM, TN-H, JP, JA, and HH conceived and wrote the editorial. All authors contributed to the article and approved the submitted version.

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