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Application of System Dynamics in Forecasting: A Systematic Review

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Abstract

Forecasting is a part of decision-making system, and the outcomes gained from the businesses and industries are all resulted from the decisions taken in the past by relying upon the future forecasting. When it's difficult to forecast mentally, we need to use modeling. The system dynamics of a modeling tool is based on systems thinking approach; hence, it has the ability to model complex systems using feedback processes. In this paper, we have reviewed the ability of system dynamics to forecast various fields of study such as marketing, supply chain, environment by reviewing 28 research papers.

Keywords: System Dynamics, Forecasting, Evaluating, Decision Support System.

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Introduction

System dynamics (SD) is a well-known system modeling approach first introduced by Forrester in 1961. This modeling using a systematic approach provides the means to understand and characterize the behavior of complex systems. As a modeling tool, system dynamics allows us to visualize a system as a feedback process in the form of causal loop and stock & flow diagrams (Suryani et al., 2010). To construct an SD model, one must first define and identify the problem, and then design a dynamic hypothesis to explain the

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cause of the problem. The next step is to develop the problem formulation, which then can be used to run a simulation according to problem policies. The model behavior in the simulation should then be compared with the actual system behavior, and finally, the interaction between different scenarios should be measured (Sterman, 2000). The steps of SD modeling are illustrated in Fig. (1) .One important application of SD modeling and analysis is in forecasting. Forecasting is an integral part of the decision-making process, as decisions made based on forecasts may have wide-ranging implications for the future of an industrial or business system. When a phenomenon is difficult to forecast, we have to make a series of hypotheses about the future and SD models can help us analyze such hypotheses (Suryani et al., 2012).

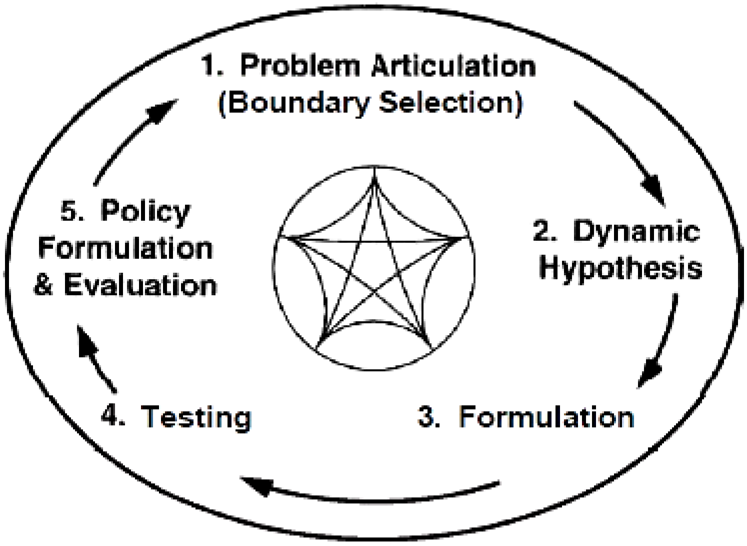

Fig (1). Steps of SD modeling (Sterman, 2000)

Data collection

To find the articles related to the subject, the authors run a search for keywords "Forecasting" and "System Dynamics" in leading scientific databases including WOS, Scopus, and ScienceDirect. This search produced a list of 63 articles that contained these two keywords. After reviewing the titles and abstracts, this list was narrowed down to 37 articles. Finally, after studying the content of these works, a total of 28 articles were found to be sufficiently related to the subject. These articles are reviewed in the following section.

Review of literature

In a study carried out by Bui and Loebbecke (1996), they used the system dynamics to forecast the demand for cellular telecommunications in Vietnam. The dominant theory of this article was cognitive science or the science of studying intelligence and intelligent entities. The time horizon of the SD model was the period between January 1994 and December 2005, which was divided into 44 periods each considered a time step. The results obtained from the SD model were analyzed according to cognitive science, and it

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was concluded that the cognitive feedback is the best approach for constructing a dynamic model with desirable applicability and operational quality for decision making.

2- Buongiorno (1996) used a combination of system dynamics, econometrics, and linear programming to forecast several parameters (supply, demand, exchanges, costs) of forest-dependent industries. The case studied in this article was the North American forest industry. This article used a hybrid model called PELPS, which consists of static and dynamic phases. The static phase is related to the short-term market equilibrium (demand equals supply) and the dynamic phase simulates the changes in the short-term equilibrium and over time. The main factor in the dynamic phase is the forecast of capacity variations. The time horizon of this model was the period 1972-2012, and it was implemented for any forest-related industry in the US (e.g. paper, recycling, etc.). The actual data pertaining to the period 1972-1993 was used as model input and for validation.

3- In a study conducted by Lyneis (2000), system dynamics was used to forecast the demand for commercial aircrafts. In this article, demand forecasting was performed using a regression model, a time series model, and an SD model, and their results were compared. The SD model was calibrated using the real data for the period 1977-1988, and then predicted the demand for the period 1988-1994 in 1-year time steps. The comparison of results showed that the system dynamics can provide better forecasts than traditional methods, thus enabling the managers to make better decisions.

4- Karavezyris et al. used a combination of system dynamics and fuzzy logic to forecast the future municipal solid waste (MSW) generation of Berlin, Germany. Using the fuzzy logic, the variables that are not easy to measure and yet have a significant impact on waste management were incorporated into the model. The model was designed for the simulation of 94 consecutive months in 1-month time steps. The results suggested that using system dynamics and qualitative variables greatly facilitate the MSW generation forecast and management.

5- In a study performed by Dyson and Chang (2005), system dynamics was used to forecast the MSW generation of San Antonio, Texas. In this work, a simple linear regression on the data of the period 1980-2000 was used to forecast the MSW generation during the period 2000-2010. The results of this regression were then used as a measure to draw a comparison with the SD model. The SD model developed in this article consisted of five sub-models, each simulating the MSW generation in terms of one variable. This model had a 1-year time step and used the data pertaining to the year 2000 as the initial value of the stock. The results of these five models were used in a matrix for forecasting under uncertainty conditions.

6- Fan et al. (2007) used the system dynamics to forecast coal production capacity in China. The model of this article takes accounts of the investment in the coal industry, existing reserves, mining structure and coal supply capacity. This model was used to simulate the behavior of all systems that are driven by investment in mines, investigate the impact of this investment on the coal production, and ultimately forecast the total coal production capacity for the years 2001 to 2020 in various scenarios. Real data from 1991 were used as the initial values of the stock, and the real data pertaining to the period 1991-

2001 were used to validate the model. In this model, coal demand was treated as an exogenous variable that should be calculated outside the SD model. Thus, coal demand during the period 2004-2020 was predicted by the combined use of elasticity coefficient approach, sectoral analysis, and a Grey model. In the end, the results were analyzed based on six different scenarios.

7- System dynamics was used by Kamath and Roy (2007) to forecast the demand in a supply chain with the goal of increasing production capacity. The case study of this article was a two-step supply chain of a short lifecycle product in India. In this study, the behavior of variables over a period of 100 months was estimated based on a bell-shaped demand curve. The supply chain consisted of a vendor and a buyer. The demand for goods over the 100-month period was predicted using the system dynamics approach by considering different cycles between two successive orders from retailer to producer and estimating the production capacity accordingly. This model was developed using a 1-month time step. The results showed that the information obtained from the SD model can significantly contribute to the decision-making with the aim of improving the production capacity.

8- Saeed (2008) used the system dynamics for demand forecasting in a supply chain. He first constructed an SD model for a traditional control mechanism that consisted of path variables and equilibrated by input values. Then, this model was formulated separately for two path variables (asset and cargo) for a simple supply chain. The time horizon of the model was 64 weeks with 1-week time steps. The results of both models were analyzed separately for four different policies. The results showed the utility of this model for improving the system performance through demand forecasting.

9- In the study performed by Chung et al. (2010), system dynamics was used to forecast the need for the nursing workforce, with the medical society of South Korea used as a case study. The SD model presented in this article, accounts for the concepts of feedback system, time delays and economic conditions. In this study, the model was designed for the period 2006-2020, with the existing data for 2006 used as initial values in the stock, and had a 1-year time step. The results of this study showed a gap between supply and demand in the last years of forecasting, indicating that the available workforce for nursing and medical positions is declining.

10- Ma et al. (2010) used system dynamics for forecasting the demand for hydrogen. The case studied in this article was the hydrogen required in the first to third tier industries and domestic sector in China. Real economic data collected from valid sources were used as inputs of the SD model. The target time horizon of the model was the period 2015-2050, and forecasts were made in 1-year time steps. The results were analyzed in two scenarios. The results showed that hydrogen demand of the second tier industry should be given a higher priority. It was also found that the change in hydrogen demand in China cannot be explained solely by economic factors and it is likely to depend on other factors as well.

11- System dynamics was used in the study of Suryani et al. (2010) to forecast the demand for air travel and the capacity of passenger terminals. The case study of this article was the Taiwan International Airport in Taiwan. The factors affecting the forecast of demand for air travel were divided into two groups: internal factors (ticket price, service quality) and external factors (economic and demographic factors). In the SD model, each of these factors was handled by a sub-model designed for this purpose. In addition to these sub-models, they also designed a bassline model that was focused on forecasting the demand and capacity of terminals. To validate the model, the simulation results for the years 1996 to 2007 were compared with real data. This comparison demonstrated an error of only 5% in simulation. After training the model with real data, it was used to make a forecast for the period 2008-2028 in 1-year time steps. The results were analyzed in optimistic and pessimistic scenarios, which yielded the number of flights in each year within the said period and the individual impact of each sub-model on the number of flights.

12- Suryani et al. (2010) also used system dynamics for demand forecasting with the aim increasing production capacity. The case studied in this paper was a short lifecycle product, such as cement. They used a lookup operator to derive a nonlinear relationship between economic factors. The SD model of this paper consisted of four sub-models (ordering, production, assets, and capacity surplus). The model was developed for a 16-year time horizon (1994-1998) and with 1-year time steps. The comparison of real data with simulated data showed 5% error in each sub-model. The results were analyzed in three different scenarios, which demonstrated the importance of making accurate forecasts and reasonable hypotheses about the future in production management, and the utility of system dynamics in this regard because of the use of feedback system.

13- In a study carried out by Tang et al. (2010), they used system dynamics to forecast the total demand for petroleum products and used a linear regression model to estimate the limit of renewable resources. In this article, first, the real data pertaining to the period 1973-2007 was used to develop a linear regression model for estimating the limit of renewable resources by 2060. Then, the SD model was used to predict oil production between 2002 and 2060 in 1-year time steps. The validity of the SD model was verified by comparing its results for the period 2002-2008 with the real data of the same period, which revealed an error of 0.7%. The results of this model were analyzed in three different scenarios and ultimately showed that the production of petroleum products in China will experience a steady decline.

14- Barlas and Gunduz (2011) used the system dynamics for order forecasting with the aim of reducing fluctuations and bullwhip effect in the supply chain. The case studied in this work was a three-stage supply chain in Turkey. This study used a discrete time setting to make the model more stable, and set the time step to 32 periods, which meant four time-steps for the 128-period horizon considered. The SD model was examined in several scenarios, and the results indicated that the main cause of bullwhip effect is the restriction of data obtained from demand forecasts to individual parts of the supply chain (the output of each part serves as the input of another part of the supply chain). To address this issue, the SD model was re-implemented with the assumption that forecasts are shared across all parts of the supply chain. The final results showed that demand forecasting with information shared across all parts of the supply chain reduces the bullwhip effect.

15- In the study of Qi and Chang (2011), system dynamics was used to predict urban water demand in Manitou, Florida, USA. In this study, the SD model consisted of three sub-models (economy-population, dynamic population, and water demand forecasting). Regression equations were used to adjust the relationships and investigate the effect of different factors in the sub-models on each other. The time horizon of this model was the period 2003-2010 and it had a 1-year time step. The magnitude of the impact of each variable on water demand was examined through a sensitivity analysis. The results showed that, despite the problem complexity, dynamism, and information constraints, system dynamics approach succeeded in delivering acceptable results.

16- Hein et al. (2012) used system dynamics to predict the development of and the competition between different ways of using an electric car battery as a power source in an electricity grid. For each method of battery use, they developed a sub-model that predicted the future behavior of the variables of the method over the model's time horizon, i.e. the period 2010-2050, in 10-year time steps. The results showed that given the challenge and complexity of using electric car batteries in a grid, this is unlikely to happen on a large scale, as the contribution of battery use is almost negligible.

17. In another study by Suryani et al. (2012), system dynamics was used to forecast the demand for air transport in order to determine the need for expansion in terminal capacities. They again used the Taiwan International Airport as a case study. They stated that given the high demand for air transports and great uncertainty in this variable, terminal capacity requirement is very difficult to predict. but making such forecast using a model with limited time horizon can assist the long-term management of terminal capacities. The SD model was developed accordingly based on optimistic and pessimistic scenarios. The SD model of this study was trained using the air transport data pertaining to the period 1996-2010 and then used to make a forecast for the period 2010-2026 in 1-year time steps. The result showed that GDP has a much stronger impact on demand for air transport than other variables (such as foreign investment, imports, and growth of transport).

18- Kreng and Wang (2013) used the system dynamics for forecasting the sales of new products, and conducted a case study on two new generations of Nike golf products. Contrary to traditional approach, this research used a multi-product model designed to predict the sales of new generation of products and used the system dynamics to calibrate the model for the competitive environment. In this work, data were divided into two groups of calibration (January 2007 to September 2009) and forecast (October 2009 to December 2009). To ensure the validity of the model, the calibration data was used to train it to forecast the data in the other group. The final forecasts of this model were made for the period 2008-2009 (coinciding with a great recession) in 1-month time steps. The results indicated that the use of system dynamics approach with real observations can facilitate the development of a reliable and accurate model for forecasting the sales of new products.

19- System dynamics approach was used by Lee et al. (2013) to predict the sales of green vehicles, namely electrical vehicles (EVs) and hydrogen fuel cell vehicles (HFCVs) in South Korea. In this work, the previous sales forecasting models (technology diffusion, discrete choice model, repurchase) were combined with system dynamics. The model was designed to predict the market share over the period 2010-2050 in 1-year time steps. The results were analyzed in two infrastructure and baseline scenarios, and the result demonstrated the ability of SD model to predict the sales of green cars.

20- In a study conducted by Lewe et al. (2014), demand for urban transportation was predicted by the combined use of system dynamics and agent-based model. Given the complexity and dynamicity of the studied system, these researchers used a model called system of systems for analysis. The agent-based model is an inferential and bottom-up model for assessing the actions of autonomous agents based on the rules of their interactions, whereas dynamic model is a top-down approach focused on dynamic complexity due to system structure, feedback, and time delays. In this work, these two techniques were combined in different modes to produce a mixed model consisting of parallel and series sub-models. Both models were developed to make a forecast for the time horizon of 1995-2011 in 1-year time steps, with the real data pertaining to the year 1995 used as input. After comparing the results, it was found that the agent-based model can provides a good overview of the system, but combination with dynamic model can facilitate the examination of system variables by accelerating the computations and improving the simulation of different scenarios.

21- Peng et al. (2014) used the system dynamics to predict the condition of road networks and relieve efforts after an earthquake in China. The case studied in this research was the supply chain of water bottles after an earthquake. In this work, the delays in information transfer were formulated in a fuzzy setting and were categorized into long delays and short delays. The SD model was implemented with three strategies for asset planning and four delivery time forecasting methods. For each scenario, the SD model was executed for 60 half-day cycles to cover the first 30 days after the earthquake. The earthquake energy and its impact on the road network and transport delays were calculated by the use of existing formulas and introduced into the model as exogenous variables. Finally, the results obtained from different combinations of strategies and methods were examined to construct a decision tree that would allow a good decision to be made based on circumstances.

22- In a study carried out by Thiel et al. (2014), system dynamics was used to forecast the impact of a medical crisis on the sales in a food supply chain. The case study of this work was the French chicken supply chain during the bird flu crisis. In this work, the SD model was first implemented for a supply chain in equilibrium in the absence of crisis, and then it was adjusted using the real data pertaining to 161 days of bird flu in France. The model was then re-implemented for a six-month horizon in 1-month time steps. In addition to the SD model, this study used a diffusion model to predict the customer behavior during such crisis. The diffusion model can examine the effect of viva voce propagation of information and rumors (during a medical crisis) on the tendency of customers to buy food products. After comparing the data obtained from these models, it was concluded that even a small health risk can have major economic implications for producers and customers through its impact on demand and production.

23- Fan et al. (2016) used the system dynamics to forecast the quantity of recycled electronic waste and conducted a case study on the recycling of personal computers in Taiwan. Given the very complex, dynamic and non-linear nature of the problem, it was modeled using the system dynamics approach. In this work, the input data of the model were produced by the use of two forecasting methods called moving average (MA) and Exponentially Weighted Moving Average (EWMA). The model was calibrated using the real data pertaining to the period 1992-2008 as training data, and was validated using the real data of the period 2009-2011. The SD model was then implemented with the data generated by MA and EWMA to predict the quantity of recycled electronic waste for the period 2012-2020 in 1-year time steps. The results demonstrated the ability of the model to handle the complexity and dynamicity of the electronic waste recycling problem for long-term periods.

24- System dynamics was used by Kwon et al. (2016) to forecast the price of heavy fuel in Europe. In this work, the NPL model was used to formulate the problem and derive the relationships in order to produce a model consisting of two sub-models for forecasting the demand and supply of heavy fuel respectively. The price of heavy fuel was also predicted using the statistical method (SM), the exponential smoothing method (ESM) and the artificial neural network (ANN) model. Then, to evaluate the accuracy of the SD model, its results were compared with the results of mentioned methods. The SD model was trained with the real data of the period 2008-2010. Forecasts were made for the period 2010-2012 in 1-month time steps. The results suggested that the SD model is more suitable for long-term forecasting of heavy fuel prices, while other models, which operate based on time series, are more suitable for short-term forecasts.

25- Marzouk et al. (2016) used the system dynamics to predict the housing supply and demand and the behavior of key elements affecting the housing market. The case studied in this work was the Egyptian housing market. The SD model of this article was developed by the use of real data pertaining to the period 2000-2011 as inputs. To verify the validity of the model, its forecasts for the period 2006-2011 were compared with the real data pertaining to the same period. This comparison showed a less than 5% error in the model outputs. The model was used to predict the variables of Egyptian housing market for the period 2011-2016 in 1-year time steps. A sensitivity analysis was also performed for the three main variables of the model (economic strength, housing demand, housing stock). The results showed that in 2016, Egyptian housing supply would be 50% of the housing demand.

26- In a study conducted by Ponnurangam and Umadevi (2016), they used system dynamics to predict the growth of the number of private and public vehicles in order to perform an urban traffic analysis on the city of Chennai in India. In this work, a field study was performed to measure the volume of different types of vehicles on a certain street at peak traffic hours. Then, this data was used as the input of the SD model, which was developed for the time horizon of 2009-2020 with 1-year time steps. The results were examined in three different scenarios. It was found that this model can be used not only for short-term management of city traffic but also to devise a comprehensive traffic plan that would provide a sustainable solution for this issue.

27- Sahin et al. (2016) used the system dynamics to forecast the drinking water supply and demand in Australia. The SD model of this paper consisted of three sub-models (demand, supply, asset management) and was developed to make forecasts for a 100-year period from 2013 to 2113, in 1-year time steps. The input data of each sub-model was generated according to the existing data by the use of multivariate Monte Carlo technique or based on researcher's judgment. The results were analyzed in five different scenarios, and it was found that with the current water demand trends, inadequate response to environmental changes and population growth will results in severe water shortage and economic challenge.

28- In a study carried out by Feng et al (2017), the system dynamics approach was combined with the Markov chain to predict the total water footprint of agriculture sector and its impact on the freshwater ecosystem in the Heine river basin in China. In this work, the SD model consisted of four subsystems called agriculture, economic development, population, and total agricultural water consumption. The model was used to simulate the population in the study area over the period 1991-2009 in 1-year time steps. The effect of water resource constraints on agriculture and agricultural economics was modeled using the Cobb-Douglas function. Parameters and relationships were set by the use of regression and curve fitting. Using the real data of previous years, the resulting SD model was utilized to forecast the changes in agricultural water footprint over the period 2010-2030.

Discussion and Conclusion

A review of the articles listed in Table (1) will show the wide variety of fields where researchers have used the SD models for forecasting purposes. This variety is an indicator of the most important feature of SD models that is the ability to incorporate the complexity and dynamicity of the studied phenomenon into the analysis. Another important feature of system dynamics is that it accounts for feedbacks and time delays. Feedback, which refers to the return of information, is one of the most fundamental aspects of system behavior and is described by Sterman (2000) as a product of cause and effect. The importance of feedback is due to its ability to reveal the cause of a behavioral pattern in the system, which is very important for feedback sensitive systems such as business, ecological, socioeconomic, agriculture, transportation, and environmental systems. Time delays act as a source of dynamism, causing instability and fluctuation in the system performance. The ability of system dynamics to facilitate the modeling and simulation of complex phenomena and analysis of their nonlinear behavior over time makes it perfectly suitable for predicting complex systems under uncertain situations. Furthermore, the variety of tools and methods used in conjunction with system dynamics for forecasting purposes indicates that system dynamics can be viewed as a complementary approach rather than an alternative to traditional methods. Examination of time horizons and time steps in different works shows that system dynamics is more suitable for long-term forecasts, but can also be used to make forecasts for short-term horizons. System dynamics can also be implemented using a discrete time to make a forecast for prolonged time horizons and improve the accuracy of prediction. Suryani et al., (2012) have mentioned the following as the major advantages of system dynamics over traditional forecasting methods:

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1- System dynamics allow us to model highly nonlinear behaviors and also integrate the expert knowledge into the model.

2- SD models can be strongly calibrated with observed or existing data in order to make an accurate forecast of the future based on different scenarios.

3- SD models are more reliable than statistical models, and allow us to estimate the sensitivity of results to variables and employ stronger scenarios accordingly.

Moreover, traditional methods of forecasting based on existing data may not be able to accurately predict the impact of major changes in strategies. Also, traditional forecasting techniques are not suitable for the prediction of dynamic and complex phenomena involved with uncertainty, dynamic behaviors, model evaluation, and optimization. The traditional methods also have the following shortcomings:

1. They cannot properly handle the discontinuities in the external environment.

2- The quality of their result is sensitive to interactions between different parameters, as such interaction may generate a false correlation between the variables and result in a false prediction following a change in one of the variables.

Table 1 Summary of literature Review

Row	Author(‘s) / year	country	Field	Complementary techniques	Time Horizon	Time Step
1	(Bui & Loebbecke, 1996)	Vietnam	Technology Management	Cognitive Science	44 periods of time	1 period of time
2	(Buongiorno, 1996)	USA	Environment	L .Programming	40 years	1 year
3	(Lyneis, 2000)	USA	Transportation	L. Programming	6 years	1 year
4	(Karavezyris et al., 2002)	Germany	Urban Management	Fuzzy Logic	94 month	1 month
5	(Dyson & Chang, 2005)	USA	Urban Management	Statistical Method	10 years	1 year
6	(Y. Fan et al., 2007)	China	Environment	Grey Theory	20 years	1 year
7	(Kamath & Roy, 2007)	India	Supply Chain	Statistical Method	100 month	1 month
8	(Saeed, 2008)	USA	Supply Chain	Statistical Method	64 week	1 week
9	(Chung et al., 2010)	South Korea	Human Resource	Statistical Method	15 years	1 year
10	(Ma et al., 2010)	China	Environment	Statistical	35 years	1 year

				Method		
11	(Suryani, Chou, & Chen, 2010)	Taiwan	Transportation	Statistical Method	20 years	1 year
12	(Suryani, Chou, Hartono, et al., 2010)	Taiwan	Production Management	Statistical Method	16 years	1 year
13	(Tang et al., 2010)	China	Environment	Statistical Method	60 years	1 year
14	(Barlas & Gunduz, 2011)	Turkey	Supply Chain	Concept of Whip	128 periods of time	32 period of time
15	(Qi & Chang, 2011)	USA	Environment	Statistical Method	8 years	1 year
16	(Hein et al., 2012)	Germany	Technology Management	Statistical Method	40 years	10 year
17	(Suryani et al., 2012)	Taiwan	Transportation	Statistical Method	16 years	1 year
18	(Kreng & Wang, 2013)	Taiwan	Marketing	Statistical Method	2 years	1 month
19	(Lee et al., 2013)	South Korea	Technology Management	Traditional forecast models	40 years	1 year
20	(Lewe et al., 2014)	USA	Transportation	Agent Based Model	16 years	1 year
21	(Peng et al., 2014)	China	Supply Chain	Concept of Whip	30 days	12 hour
22	(Thiel et al., 2014)	France	Supply Chain	Distribution Model	6 month	1 month
23	(C. Fan et al., 2016)	Taiwan	Technology Management	EWMA, MA	8 years	1 year
24	(Kwon et al., 2016)	South Korea	Petrochemical	SM,ESM,ANN	2 years	1 month
25	(Marzouk et al., 2016)	Egypt	Urban Management	Statistical Method	5 years	1 year
26	(Ponnurangam & Umadevi, 2016)	India	Transportation	Statistical Method	12 years	1 year
27	(Sahin et al., 2016)	Australia	Environment	Monte Carlo	100 years	1 year
28	(Feng et al., 2017)	China	Environment	Markov Chain	20 years	1 year

Suggestions for future research

• Use of system dynamics to predict short lifecycle products like cultural and artistic products or to predict the box office revenues of movies

• Combination of system dynamics with soft operational research techniques such as Soft Systems Methodology (SSM) and Strategic Options Development Analysis (SODA).

• Use of system dynamics for brand assessment and management in the field of marketing and for evaluating the supply chain flexibility.

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