Research Journal of Applied Sciences, Engineering and Technology 11(11): 1265-1279, 2015
DOI: 10.19026/rjaset.11.2234
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: July 29, 2015 Accepted: August 30, 2015 Published: December 15, 2015

Review Article

Transfer Function Modelling: A Literature Survey

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Abstract: Monitoring and control is very important in maintaining quality outputs, reducing downtimes and improving operation's efficiency of processes. Transfer function modelling has been the heart of process monitoring and control. This study surveys the past, present and future of transfer function modelling. The survey found that continuous transfer function models used in modelling engineering control systems have the widest applications. Similarly, the discrete transfer function models are applied mostly in forecasting and have wide application in econometrics and the social sciences and to a little extent in the physical and life sciences. The current efforts by researchers in extending the frontiers of discrete transfer function modelling to fault diagnosis, improvement of maintenance and operation's efficiency, determination of production process capability etc were highlighted. Finally, the future directions of research in transfer function modelling which include but not limited to: leak detection and failure prediction, improved modelling software tools, performance evaluation and improvement in chemical industries, power systems, oil and gas industries, economic and management systems etc was suggested. Our findings show that transfer function would be very important in solving manufacturing dysfunction.

Keywords: Control systems, forecasting, modelling, performance indicators, transfer function

INTRODUCTION

Process monitoring and control is a very active area of research. According to Oakland (2003), a process is the transformation of a set of inputs, which can include materials, actions, methods and operations, into desired outputs, in the form of products, information, services or-generally-results. All processes, he said, can be monitored and brought 'under control' by gathering and using data. Control refers to measurements of the performance of the process and the feedback required for corrective action, where necessary (Oakland, 2003).

Process control is a statistics and engineering discipline that deals with architectures, mechanisms and algorithms for controlling the output of a specific process. Statistical process control is an effective method of monitoring a process through the use of control charts (Oakland, 2003). Much of its power lies in the ability to monitor both process centre and its variation about that centre.

According to Box *et al*. (2008), statistical process control which is quite different from engineering process control where various forms of feedback and feed forward adjustment have been used. Statistical process control is employed in industries concerned with the manufacture of discrete parts, while by contrast engineering process control is mostly used in process and chemical industries (Box *et al*., 2008).

Process monitoring and control makes uses of time series analysis as one of its tools (Box *et al*., 2008). Engineering process control makes extensive use of transfer function modelling and dynamic system modelling (Coughanowr, 1991; Thomas, 1999). Some of the works done towards improving engineering process control involve time series analysis and its application in transfer function modelling (Box *et al*., 2008).

Transfer function modelling, an integral part of process monitoring and control, is used to determine the causal relationship between input and output of a process. To buttress this fact, Nwobi-Okoye and Igboanugo (2011, 2012) proposed that in order to better understand the complex relationship between the input and output to the production system, this analytical technique known as transfer function modelling should be used.

Transfer function modelling as has been noted is an integral part of control theory; hence, the history of transfer function modelling is inseparable from the history of automatic control. Automatic control Systems were first developed over two thousand years ago. The first recorded existence of feedback control device is thought to be the ancient Ktesibios's water

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clock invented by the Greek craftsman, Ktesibios, in Alexandria, Egypt around the third century B.C (Zalewski, 2001). According to Zalewski, Ktesibios's water clock kept time by regulating the water level in a vessel and, therefore, the water flow from that vessel. This success of this device was evidenced by the fact that water clocks of similar design were still being made in Baghdad when the Mongols captured the city in 1258 A.D. Assorted types of automatic devices have been used over the centuries to accomplish useful tasks or simply used as toys for entertainment. The latter includes the automata, popular in Europe in the 17^{th} and 18^{th} centuries, featuring dancing figures that would repeat the same task over and over again; these automata are examples of open-loop control. Milestones among feedback, or "closed-loop" automatic control devices, include the temperature regulator of a furnace attributed to Drebbel, circa 1620 and the centrifugal flyball governor used for regulating the speed of steam engines by James Watt in 1788 (Mayr, 1975). In his 1867 paper "On Governors", J. C. Maxwell (who discovered the Maxwell electromagnetic field equations) was able to explain instabilities exhibited by the flyball governor using differential equations to describe the control system (Maxwell, 1867). This elucidated and demonstrated the importance and utility of mathematical models and methods in understanding complex phenomena and systems and signaled the beginning of mathematical control and systems theory and by extension transfer function modelling (Morari and Zafiriou, 1989). Elements of control theory had appeared earlier but not as dramatically and convincingly as in Maxwell's analysis (Morari and Zafiriou, 1989). Historically, modern continuous transfer function modelling started with advent of modern control systems at the onset of the industrial revolution. The industrial revolution started with design and development of various types of machinery and equipment for industrial and home use (Ashton, 1997; Jensen, 2010). Most of these machineries and equipment contain control and instrumentation systems, of which the engine governor earlier mentioned is one of the earliest examples. Control theory made significant strides in the next 100 years since Maxwell's paper in 1867. New mathematical techniques made it possible to control, more accurately, significantly more complex dynamical systems than the original flyball governor. These techniques include developments in optimal control in the 1950s and 1960s, followed by progress in stochastic, robust, adaptive and optimal control methods in the 1970s and 1980s (Mayr, 1975; Morari and Zafiriou, 1989). Applications of control methodology have helped make possible space travel and communication satellites, safer and more efficient aircraft, cleaner auto engines, cleaner and more efficient chemical processes, to mention but a few (Albarbar *et al*., 2008; Gebel and Fettis, 1974; Feron *et al*., 1998; Coughanowr, 1991).

On the other hand, historically, efforts at relating the input to output of a system statistically started with regression analysis (Lai, 1979). Hence, regression analysis formed the basis of the traditional statistical method of modelling the relationship between the input and output to systems (Lai, 1979). Regression analysis has many deficiencies. For example: Regression Analysis is inappropriate in situations where the output lags the input and there exists a transient relationship between the input and output (Lai, 1979). Also, when there is a significant amount of noise in the system regression analysis cannot accommodate noise in the filter (Box *et al*., 2008).

Box and Jenkins (1970) introduces an improved statistical method of modelling the relationship between input and output to a system. This method was named Box-Jenkins transfer function modelling methodology (Lai, 1979).

Since the introduction of transfer function modelling in 1970, efforts have been made by various researchers to improve and extend its application in various fields of life. For example Lai (1979) applied it extensively in modelling geographical systems. DeLurgio (1998) applied it extensively in econometrics and economic forecasting. This literature review will bring to the fore the efforts of various other researchers, engineers and scientists on transfer function modelling.

In continuation, since parameter estimation is determined stochastically in transfer function modelling and fewer parameters are required in transfer function models than in regression models, this implies that transfer function models are expected to be more accurate than comparative regression models.

Furthermore, one of the major reasons for transfer function modeling is for forecasting the output from a process. According to Box *et al*. (2008), transfer function model forecasts usually have smaller forecasting errors than the forecasts based on univariate models which are based on the output. This assertion was further corroborated by Lai (1979) who said that since a transfer function model represents stochastic-dynamic model of the transient relationship, it usually gives good forecasts of the future output from a process. In the words of DeLurgio (1998), transfer function models have a general advantage over other multivariate and univariate models and their greatest advantage exists when lagged independent variables affect the dependent variable.

According to Box *et al*. (2008), estimation of transfer functions in industrial systems is made for the following purposes:

- To achieve better control of existing plants
- To improve the design of new plants

In spite of its popularity, the identification or specification stage of transfer function analysis is not sufficiently developed, in particular for multiple-input models (Liu and Hanssens, 1982).

According to Liu and Hanssens (1982), the best known transfer function identification technique was due to Box and Jenkins (1970), but their method could not be generalized for the multi input models. However works by other researcher have generally improved the transfer function model identification especially for the multi input models. These works include: Priestly (1971), who used double pre-whitening of both input and output series, Haugh and Box (1977), used the study of the SCCF of the pre-whitened input output series to identify the transfer function models. Others are Fask and Robinson (1977) who generalized the double prewhitening method to multivariate dynamic models, Granger and Newbold (1977a, 1977b) who applied this to identification of two way causal systems.

Liu and Hanssens (1982) stated that although double pre-whitening has been widely used, it is more difficult to apply than Box and Jenkins method, even in the one input situation. The major difficulties according to them are that a model is frequently over-structured due to the pre-whitening factors and the lag structure is often difficult to derive.

Tiao *et al*. (1979), used sample cross-correlation and partial correlation matrices of a set of multiple series for the identification of multiple ARIMA models of which transfer function model is a special case. However, their method has a major drawback because it imposes an extra structure between the factors on the residuals and the transfer function causing the transfer function model to be over structured.

Box and Jenkins (1976) and Priestly (1971) used the frequency domain approach (spectral method) instead of the time domain approach to multi input transfer function model identification. However, spectral method is difficult to apply in practice.

Liu and Hanssens (1982) adapted the least squares methods developed by Priestly (1969) and Caines *et al*. (1977) which worked very well for single input situations to multi input systems. Liu and Hanssens method is based on the least squares estimate of the original and filtered series and the corner method is used to identify a parsimonious rational form of the transfer function.

This study surveys the literature on transfer function modelling, highlighting its potential applications in solving industrial problems.

THEORETICAL BACKGROUND

Before reading on it is necessary to have background knowledge of the theory of Transfer function. Transfer function modelling is one of the major areas where time series analysis is applied. A transfer function (also known as the network function) is a mathematical representation, in terms of spatial or temporal frequency, of the relation between the input and output of a (linear time-invariant) system. Transfer function modelling is used in measuring the transient input-output relationship of non equilibrium systems. According to Lai (1979), transfer function is often used to determine the causal relationship between two variables.

Mathematically in its simplest form a linear transfer function model is represented by:

$$Y_\infty = gX \tag{1}$$

Here

Y_∞ = The steady state output

g = The steady state gain

X = The steady state input

According to Lai (1979), the major objective of the investigation of input-output relationship is to model the filter of the system and if the internal mechanism of the system is completely known, the filter can be represented deterministically by differential equations. Continuous transfer function models assume that transfer function observation are taken at continuous time intervals. What this means is that the period in between observation is so small that the time is assumed to be continuous. Continuous transfer function models are usually represented by differential equations which could be first order equations, second order equations or higher order equations (Box *et al*., 2008). According Box *et al*. (2008), the general method for representing continuous dynamic systems is the differential equation:

$$(1+\Xi_1 D+\ldots+\Xi_R D^R)Y_t = g(1+H_1 D+\ldots+H_s D^S)X_{t-b} \tag{2}$$

On the other hand, discrete transfer function models assume that the time series of transfer function observations are taken at discrete time intervals. Discrete transfer function models are usually represented by difference equations which could be first order equations, second order equations or higher order equations (Box *et al*., 2008). As stated by Box *et al*. (2008), the general method for representing discrete dynamic systems in difference equation form is:

$$(1+\xi_1\nabla+\ldots+\xi_r\nabla^r)\,Y_t = g(1+\eta_1\nabla+\ldots+\eta_S\nabla^S)X_{t-b} \tag{3}$$

Using the backward shift operator on Eq. (3), (4) is obtained:

$$(1-\delta_1 B-\ldots-\delta_r B^r)\,Y_t = (\omega_0+\omega_1 B-\ldots-\omega_S BS)X_{t-b} \tag{4}$$

$$\delta(B)Y_t = \omega\,(B)X_{t-b} \tag{5}$$

Equation (5) can be transformed into the following form:

$$\delta(B)Y_t = \omega(B)B^bX_t \tag{6}$$

Let:

$$\Omega(B) = \omega(B)B^b \tag{7}$$

$$\delta(B)Y_t = \Omega(B)X_t \tag{8}$$

$$Yt = \delta^{-1}(B)\Omega(B)X_t \tag{9}$$

Let v(B) represent the system transfer function in terms of the system impulse response weights, v. It follows that:

$$v(B) = \delta^{-1}(B)\Omega(B) \tag{10}$$

$$Y_t = v(B)X_t \tag{11}$$

Transfer function models with noise: According to Box *et al*. (2008), in practice, the output Y of a transfer function model could not be expected to follow exactly the pattern determined by the model, even if that model were entirely adequate. Box *et al*. (2008) went on to say that disturbances of various kinds other than X normally corrupt the system. Lai equally corroborated the assertion of Box *et al*. (2008) by saying that the ideal assumptions used in deterministic transfer function models rarely hold in practice and that systems are affected by random or non random disturbances which may be caused by spatial and temporal variations in the underlying environment in which the system operates. If it is assumed that the disturbance, or noise N_t, is independent of the level of X and is additive with respect to the influence on X, the transfer function could be written as:

$$Y_t = \delta^{-1}(B)\,\omega(B)\,X_{t-b} + N_t \tag{12}$$

If the noise can be represented by an ARIMA (p, d, q) process then:

$$N_t = \varphi^{-1}(B)\,\theta(B)\alpha_t \tag{13}$$

Here a_t is the white noise. Substituting Eq. (13) into (12), Eq. (14) is obtained below:

$$Y_t = \delta^{-1}(B)\,\omega(B)X_{t-b} + \varphi^{-1}(B)\,\theta(B)\alpha_t \tag{14}$$

According to Box *et al*. (2008), in the presence of appreciable noise, it is necessary to use statistical methods for estimating the transfer function.

For Multi input single output systems, allowing for several inputs, $X_{1,t}, X_{2,t}, \ldots, X_{m,t}$ we have:

$$Y_t = \delta^{-1}(B)\omega_1(B)X_{1,t-b} + \cdots + \delta^{-1}(B)\omega_m(B)X_{m,t-b} + N_t \tag{15}$$

APPLICATIONS OF TRANSFER FUNCTIONS

Transfer function concept has been applied in many fields including: economics, managment, engineering, education, computer science, sociology, biology etc (Box *et al*., 2008; DeLurgio, 1998). The various applications of transfer function will be briefly discussed in this section.

Applications of transfer function in production: Most applications of time series analysis and transfer functions to production in the surveyed literature have to do with quality control of produced goods. Webb and Hardt (1991) developed a transfer function modelling for quality control of sheet metal forming process. Fearn and Maris (1991) developed a model based on Box-Jenkins methodology for the feedback control of the addition of gluten during the milling of flour. Gluten, an animal protein, is a very essential constituent of flour and determines to a large extent its quality. Bulgrin and Richards (1995) and Tsai and Lu (1998) developed empirical models in the form of time series or Auto-Regressive Moving Average (ARMA) for the quality control of the plastic injection molding process. Most of the models involved using time series to model the output from a process and determining the appropriate feedback or feed forward adjustment in order to bring the process in control (Box and Luceno, 2001).

Hatch and Kazmer (2001) developed a methodology using the Design Of Experiments (DOE) for process characterization of DVD manufacture through transfer functions. In their study, they suggested that transfer function can be used to optimise a process, compare different processing systems, or predict the output quality from input processing conditions. As a result DVD manufacturers can increase productivity through cycle time reduction, improve quality, compare materials, or compare different machine and mould manufacturers. This study represents a first attempt to use transfer functions to estimate process capability, although the work is limited to only DVD manufacturing process and Box-Jenkins transfer function methodology was not used in their work. There is therefore the need to use Box-Jenkins transfer function methodology and extend this to other manufacturing processes. Furthermore, the process capability was not measured quantitatively.

Box *et al*. (2008) applied transfer function models to the monitoring and control of the production of carbon IV oxide in a gas furnace. Similar applications are used in industry in the monitoring of the production of chemicals. Schwartz and Rivera (2010) applied transfer function modelling to solving problems of production inventory management.

According to DeLurgio (1998) transfer functions are applied to production to determine the causal relationship between process output and input voltage, process output and material thickness, part dimensions and process adjustments, part dimensions and turning speed etc. In spite of all these novel applications, it has not been applied to maintenance of production facilities or to the determination of production process capability quantitatively.

Applications of transfer function in management, social and economic sciences: There are numerous applications of transfer function models in economics, business, management, finance and the social sciences. Edlund and Karlsson (1993), applied transfer function modelling in predicting unemployment in the Swedish economy. Nogales and Conejo (2006), Zareipour *et al*. (2006) and García-Martos *et al*. (2007) successfully developed a transfer function model for predicting electricity prices. Disney and Towill (2002) and Schwartz *et al*. (2005) applied transfer function modelling to supply chain management problems. Preciado *et al*. (2006) applied transfer function modeling in agricultural economics, specifically they used the model to obtain a census of fish catches and efforts of their fleets which are considered suitable for the elaboration of representative indices of catch rate (catch per unit effort). Johnson and Turner (1956) used transfer function model to determine the relationship between engineering efforts in an enterprise and sales in the enterprise which is used in company planning. Pardo *et al*. (2002) in their study developed a transfer function intervention model for forecasting daily electricity load from cooling and heating degree-days in Spain. They proved the influence of weather and seasonality and showed that it is significant even when the autoregressive effects and the dynamic specification of the temperature are taken into account.

Zvirblis (2003), formalized models of automated control schemes of transport services expressing the transfer functions of feedback loops and their characteristic equations.

Sometimes transfer function model could be used to analyse response of the populace to enactment of certain laws. Wilson *et al*. (2007) investigated whether a law in New Zealand making all indoor workplaces including bars and restaurants smoke free which became operational in New Zealand in December 2004 increased calls to the Quitline Service which is a national free-phone Quitline Service which has been operational since 1999 in New Zealand. They concluded that this would suggest there is an extra opportunity for health agencies to promote quitting at such times.

Transfer function modeling could be applied in environmental management. An important application of transfer function modeling to pollution control and environmental management is exemplified by the work of Issarayangyun and Greaves (2006), who used time series Box-Jenkins transfer function modelling as a tool to assess the relative importance of travel speed (which is known as a proxy for traffic conditions) and meteorological conditions on Fine airborne Particulate Matter (PM) exposure level.

Camargo *et al*. (2010) applied transfer function modeling to study the Brazilian inflationary process and suggested that Governmental controls of the price level should be avoided since they disrupt expectations and inevitably lead to higher inflation rates. Several applications of transfer functions in economics and business involve determining the causal relationship between business/economic variables such as the relationship between advertising and sales, prices and sales, sales and seasons of the year, earnings and stock prices etc. Cooray (2006), researched on the importance of dynamic transfer function models on analysis and evaluation of econometric time series models. Choudhury (2007) used intervention analysis for the event period using transfer function modeling to observe the direction of the effect of the United States Tax Reform Act and its magnitude on business failures. Berument *et al*. (2006) used transfer function modeling to analyze the relationship between the Turkish stock market performance and the performance of Turkish teams in the European football competitions. There are numerous literature on the application of transfer functions in economics, finance and business. Such applications could be found in DeLurgio (1998), Enders (1995), Kelejian and Oates (1974), Pindyck and Rubinfeld (1976), Limanond *et al*. (2011) and Forst (2011) etc.

Application of transfer function in biology and life sciences: Transfer function models have wide applications in the life sciences. Chance *et al*. (1985) developed the concept of transfer function for organ performance (work output vs. biochemical input) for skeletal and cardiac muscle under steady-state exercise conditions. Zhang *et al*. (1998) used transfer function analysis to model dynamic cerebral autoregulation in humans.

Loha and Lindtjørn (2010) carried out a study to determine if variations in specific meteorological factors are able to consistently predict P. falciparum malaria incidence at different locations in south Ethiopia. They collected retrospective data from 42 locations including P. falciparum malaria incidence for the period of 1998-2007 and meteorological variables such as monthly rainfall (all locations), temperature (17 locations) and relative humidity (three locations). They subsequently used Time series modeling using Transfer Function (TF) models and univariate Auto-Regressive Integrated Moving Average (ARIMA) when there was no significant predictor meteorological variable. From their research they concluded that past P. falciparum malaria incidence appeared to be a superior predictor than meteorology.

Yingthawornsuk (2003) and Fagergren *et al*. (2000) applied it in life sciences to study muscle behaviour in humans. For other applications of transfer function modelling life sciences (Bédard *et al*., 2010).

It is obvious from the foregoing that transfer function modeling has very useful applications in the life sciences and there exists extensive literature on its applications in the life sciences some of which were reviewed above.

Application of transfer function in engineering and physical sciences: There are numerous applications of transfer function modelling in engineering and physical sciences. As a matter of fact engineering and physical science applications represent the widest application of transfer function modelling. Transfer function modelling in engineering often involves the use of frequency based approach (Box *et al*., 2008; Shumway and Stoffer, 2006).

Often electrical engineers carry out transfer function analysis based on the frequency response of electrical circuits based on these analysis they could compare different circuit configurations. According to Hernandez (2008), the bandwidth, slew-rate, noise, input impedance and gain, among other characteristics of the operational amplifier, are often the performance limiting factors of photometer circuits. For this reason, he carried out in his study a comparative analysis between two photodiode amplifier circuits using input output transfer function analysis based on the frequency response of a photometer circuit based on operational amplifier (op amp). One circuit is based on a conventional current -to-voltage converter connection and the other circuit is based on a robust current-to-voltage converter connection. His results showed that the photodiode amplifier performance can be improved by using robust control techniques. The work of Hernandez (2008) shows the typical application of transfer function modeling in engineering.

Albarbar *et al*. (2008) carried out research to compare the performance of MEMS accelerometers for condition monitoring using input-output transfer function analysis based on frequency responses, as well as other performance indicators. They investigated the performances of three of the MEMS accelerometers from different manufacturers and compared them to a well calibrated commercial accelerometer which was used as a reference for MEMS sensors performance evaluation. Tests were performed on a real CNC machine in a typical industrial environmental workshop and the achieved results showed that MEMS sensors could be a good alternative to standard sensors mainly for wireless implementation as there is no need to carry heavy charge amplifiers, but the choice has to be made according to specifications and through validation tests. This study equally represented another important application of transfer function modelling in engineering.

For applications of transfer functions in chemical engineering and chemical process control see Chang *et al*. (1992) and Huang and Yu (1989). Olason and Watt (1985) used multivariate transfer function model to forecast the average daily flow of a river in Canada. Otok (2009) successfully applied transfer function models in forecasting rainfall in various locations in Indonesia. The inputs to his transfer function models were Dipole Mode Index (DMI) and Sea Surface Temperature (SST) which were used to forecast rainfall.

Talmon *et al*. (2009) applied transfer function modeling in speech recognition application and speech signal processing. Gebel and Fettis (1974) applied transfer function modelling in image processing applications. Feron *et al*. (1998) successfully applied transfer function modeling to aeronautics in an attempt to better identify the aeroelastic behavior of NASA Dryden's F-18 systems research aircraft and to predict its flutter boundaries using in-flight experimental data.

Lai (1979) wrote on the applications of transfer function models in geography. In addition to giving an extensive write-up on the methodology of its application, he surveyed the literature of some authors/researchers that have applied transfer function models in geography and found out that transfer function models is very useful in geographical modelling. For other applications of transfer function modelling in physical sciences and engineering (Cluckie *et al*., 1982; Cluckie, 1993; Toth *et al*., 2000; Lees, 2000; Young, 2004; Hong *et al*., 2010; Sample *et al*., 2011; Rodriguez *et al*., 2011).

Transfer functions in education: Outside the traditional application of transfer functions in science and engineering, transfer functions could be applied in education to model the dynamic relationship between the impartation of knowledge from teachers and learning/acquisition of knowledge by students. Some authors like Losenický (2010a, 2010b) modelled the educational process as linear control system. His model assumed the controller to be the teachers and the controlled object to be students. His work as he reported proved that the agreement between results of his mathematical modelling and practical knowledge is surprisingly identical. For another application of transfer function modelling to education see Stepanov *et al*. (2010).

Transfer functions and game theory: There is a rich literature on game theory. Several authors such as Binmore (2007), Von Stengel and Turocy (2008), Von Stengel (2008), Gibbons (1992), Osborne (1998), Ritzberger (2003), Carmichael (2005), Nisan (2007), Chatterjee and Samuleson, (2002), Leyton-Brown and Shoham (2008), Nwobi-Okoye (2010) and Narahari *et al*. (2009), etc have researched and written extensively on game theory.

In the rich literature on game theory, attempts to formally relate transfer functions to game theory has been scanty. Although some authors such as Nwobi-Okoye and Igboanugo (2011) modelled some Bayesian games where the transfer function of a system was assumed to be its type.

Transfer functions and maintenance: The fact that the transfer function is an integral part of control systems and could be used as a performance indicator and condition monitor, means that it could be used in planning maintenance and replacement. Transfer function modelling is a forecasting technique and as pointed out by Razak *et al*. (2009) forecasting using time series analysis could be used in maintenance scheduling. There is a rich and extensive literature on maintenance. Several authors which include Dhillon (2002), Dhillon and Liu (2006), Zhao *et al*. (2006), Zhou (2006), Leou (2006), Chen and Liao (2005), Petcu and Faltings (2006), Garg and Deshmukh (2006), Koomsap *et al*. (2005), Mytakidis and Vlachos (2008), Al-Anzi and Al-Zamel (2005) and Limbourg and Kochs (2005) etc have researched and written on maintenance. The works of these authors has helped shape and define the direction of modern maintenance practices. An issue related to maintenance effectiveness is plant performance. Recently attempt has been made to formally link transfer function to maintenance scheduling and plant performance evaluation (Nwobi-Okoye and Igboanugo, 2012; Nwobi-Okoye and Igboanugo, 2015; Nwobi-Okoye *et al*., 2015).

Transfer functions and process capability measurement: There are many literatures on quality control and metrics of measuring the capability of a process. Several authors have researched and written about the process capability measurement indices. These researchers include: Oakland (2003), Kotz and Lovelace (1989), Grant and Leavenworth (1996), Owen (1993), Pyzdek (1990), Aquilana and Chase (1999), Wheeler and Chambers (1992), Kazmer and Hatch (2002) and Kazmer (2008), Czarski (2008), Abdolshah *et al*. (2009a, 2009b), Jeang and Chung (2009), Flaig (2009), Jeang *et al*. (2008) and Sadigh *et al*. (2009) etc. It is noteworthy that in none of the surveyed literature was transfer function ever used as a metric for accessing the capability of a process, but in a recent work, Igboanugo and Nwobi-Okoye (2011a) used transfer function in process capability measurements.

Transfer functions and artificial neural network: Many papers have been written on the application of ANNs to time series analysis. Kuligowski and Ana (1998) in their study described a simple precipitation forecasting model based on artificial neural networks. Their model used the radiosonde-based 700-hPa wind direction and antecedent precipitation data from a rain gauge network to generate short-term (0-6 h) precipitation forecasts for a target location. Guh and Hsieh (1999) in their study proposed an artificial neural network based model, which contains several back propagation networks, to both recognize the abnormal control chart patterns and estimate the parameters of abnormal patterns such as shift magnitude, trend slope, cycle amplitude and cycle length, so that the manufacturing process can be improved. Their numerical results showed that the proposed model also has a good recognition performance for mixed abnormal control chart patterns

Maier and Dandy (2000) reviewed 43 papers dealing with the use of neural network models for the prediction and forecasting of water resources variables in terms of the modelling process adopted. They identified inadequate model building as the obstacle militating against accurate predictions using artificial networks. They suggested that ANN models must be properly evaluated before its application in time series analysis.

Their assertion is corroborated by Chatfield (1993) when commenting on the suitability of ANNs for time series analysis and forecasting, who commented thus: “when the dust has settled, it is usually found that the new technique is neither a miraculous cure-all nor a complete disaster, but rather an addition to the analyst’s toolkit which works well in some situations and not in others”.

Optimising time series and transfer function models: He *et al*. (1996) presented a novel approach to assist the user in exploring appropriate transfer functions for the visualization of volumetric datasets. They treated the search for a transfer function as a parameter optimization problem and addressed it with stochastic search techniques. Starting from an initial population of (random or pre-defined) transfer functions, the evolution of the stochastic algorithms is controlled by either direct user selection of intermediate images or automatic fitness evaluation using user-specified objective functions. Their approach essentially shields the user from the complex and tedious "trial and error" approach and demonstrates effective and convenient generation of transfer functions. Igboanugo and Nwobi-Okoye (2011b) used genetic algorithm to optimize transfer function model developed for a production process. Other researchers such as Sheta and De Jong (2001), Wu and Chang (2002), Mani (1996), Ong *et al*. (2005), Gaetan (2000), Versace *et al*. (2004), Min *et al*. (2006), Vossa and Feng (2002) and Cordon *et al*. (1999) applied stochastic optimisation in time series modelling. The work of He *et al*. (1996) and other researcher mentioned above corroborated to the fact that optimisation of time series models could be done by any of the metaheuristics methods discussed above, but according to the "No Free Launch Theorem" by Wolpert and Macready (1997), the averaged performance of all search algorithms over all problems is equal. In other words, no search algorithm performs better in all problems, it is left for the modeller to find the algorithm that best suites a particular problem at hand (Haupt and Haupt, 2004).

Evaluation of previous researches: Box *et al*. (2008) did a very significant work in transfer function modelling by introducing ARIMA and noise models into transfer function modelling. This significantly improved the efficiency and reliability of transfer function models. In addition to this, transfer function model forecasts usually have smaller forecasting errors than the forecasts based on univariate models which are based on the output and gives good forecasts of the future output from a process which is very significant (Kinney, 1978; Nwobi-Okoye and Igboanugo, 2015).

The use of artificial neural network in the modelling brought more tools which improved transfer function models when properly utilized.

Meta-heuristic equally improved the efficiency of transfer function modelling through natural optimisation algorithms.

The application of transfer function models in quality control of industrial processes is very significant indeed and it is invaluable in quite a lot of industries ranging from food, chemical, metal industries etc.

Transfer function modelling is at the heart of process control and control engineering. Hence, it is invaluable in aeronautics, communications, power engineering, automobile engineering, systems engineering etc.

Generally, most application of transfer function modelling appears to be centred on forecasting and system dynamic response analysis.

Merits of previous studies: From the literature, the merits of previous studies on transfer function modelling are numerous. First, in comparison to regression analysis, transfer function modelling has many characteristics which make it superior to regression analysis in modelling the relationship between system input and output. First it can model appropriately and accurately the input-output relationship in transient systems where the output lags the output. Secondly, it can accommodate effectively systems with noisy filters (Box *et al*., 2008). Thirdly, parameter estimation is determined stochastically in transfer function modelling. Also, fewer parameters are required in transfer function models than in regression models, hence, models have better parsimony than regression models (Lai, 1979).

Again, as has been mentioned earlier, continuous transfer function models are at the heart of engineering process control. Thus controlling complex engineering systems such rockets, airplanes, helicopters, CNC machine tools, automobiles, robot, chemical reactors etc depends largely on transfer function modelling (Dunn, 2005; Albarbar *et al*., 2008; Gebel and Fettis, 1974; Feron *et al*., 1998; Coughanowr, 1991).

Discrete transfer function modelling has been applied to very successfully in econometric modelling and in other fields primarily in forecasting outputs from inputs (Box *et al*., 2008; Lai, 1979; DeLurgio, 1998; Cluckie *et al*., 1982; Cluckie, 1993; Toth *et al*., 2000; Lees, 2000; Young, 2004). From the literature, forecasts from transfer function models are more accurate than corresponding forecasts from univariate statistical models.

In general, transfer function models are extensively applied in studying the dynamic response of systems subjected to various forms of input such as: step input, impulse, ramp input etc. This dynamic response analysis is found in various fields such as: economics, engineering, biology and many other fields.

Nature of existing research: From the literature, existing research on continuous transfer function modelling is largely centred on developing and improving continuous transfer function models for engineering process control.

The nature of existing research in discrete transfer function modelling exists largely in the field of econometrics and physical sciences. It is usually applied to forecasting economic variables in econometrics. Currently there are applications of discrete transfer function models in other fields such as management, education, production, business, social sciences etc. But most of these applications are centered on forecasting.

Some researchers have been trying to direct efforts at transfer function modelling research away from forecasting. For example Nwobi-Okoye and Igboanugo in their work in 2011, applied transfer function modelling to manufacturing process capability calculations (Igboanugo and Nwobi-Okoye, 2011a). They took input-output data from a real life production process over a given period and developed a transfer function model for the process which they used in determining its process capability. After the analysis, 99.1269% of the output was found to conform to specification. The process capability calculated through their new method was found to be 0.75. The result of this study they opined is expected to open new ways to process optimisation. In addition to this, effective determination of the capability of a process will lead to better comparison of alternative materials, equipment or process and production of better quality goods.

Nwobi-Okoye and Igboanugo (2012) developed a new and better way of evaluating the performance of hydropower generation facilities in order to improve their performance using transfer function modelling. It involves taking input-output data from a hydropower generation process over a 10-year period and developing transfer function models of the process for the ten years, which were used as performance indicators. Based on the performance indicators they obtained from the models, the results show that the efficiency of the power generation facility was worst in the year 2006 and best in 2003. Generally the indicators (coefficient of performance) were undulating over the ten-year period. Finally based on the fact the power plant has underperformed over the years, a value of coefficient of performance which must be above the highest coefficient of performance of 7.523 obtained was suggested as a benchmark below which a hydropower plant is assumed to have underperformed.

Nwobi-Okoye and Igboanugo (2015) equally developed an improved way of determining the efficiency of gas power generation facilities using transfer function modelling. It involved taking input-output data from a gas power generation process over a 10-year period and developing transfer function models of the process for the ten years, which are used as performance indicators. Based on the performance indicators they obtained from the models, the results show that the efficiency of the gas power generation facility was worst in the years 2002-2006 with a coefficient of performance of 0.002073617. Similarly, with a coefficient of performance of 0.002343345, plant performance/efficiency was best in the years 2007-2011. The result is remarkable because given the state of the facilities, it correctly predicted the period of expected high system performance i.e. 2007-2011 period.

The result of their research described above is expected to open new ways to improving maintenance effectiveness and efficiency of gas power generation facilities. The study would be of immense help in improving power generation in Nigeria and elsewhere.

Challenges of transfer function modelling: Although most transfer function models are linear, quite a few are nonlinear. Modelling nonlinear transfer function models is quite challenging and constitutes one of the most difficult challenges faced in modelling transfer functions. Also, identifying the appropriate noise models for transfer function is quite tasking and constitutes a difficult challenge in developing appropriate transfer function models. Similarly, modelling Multi-Input-Single-Output (MISO), Single-Input-Multi-Output (SIMO) and Multi-Input-Multi-Output (MIMO) systems is a daunting task and considerable research efforts are being directed towards this area.

Again, the complexity of transfer function modelling requires the development of complex and sophisticated software to aid in the modelling. Developing such software is quite challenging. Similarly, optimization of transfer function models using metaheuristics is quite challenging.

Gaps in past works and future direction for research: Approaches to maintenance as has been identified in the literature rely heavily on the use of charts and tables for predictive maintenance. Transfer function characteristics could act as predictive and diagnostic tools. Hence, applying transfer function to maintenance scheduling would be a very attractive area of research.

In the literature on past works, no attempt has been made to determine process capability using Box-Jenkins transfer function modelling methodology. Similarly, there has not been any formal application of transfer function modelling to performance evaluation of production systems and the development of methodology for application of transfer function modelling to maintenance and assessment of production operations efficiency.

Also there appears to be dearth of software dedicated to transfer function model identification, estimation and diagnostics. Development of highly sophisticated software dedicated to transfer function modelling would be a very attractive area of research considering the versatility of transfer functions as a processing tool.

Game theory has been in at heart of economic theory and is increasingly being used in diverse fields of life. Applying transfer functions to game theoretic analysis would be very novel. This powerful theory and method of modelling strategic interaction is expected to help optimise and improve decisions taken by competing industrial organizations.

Increased improvement and use of modern artificial neural network models is expected to define the future direction of transfer function modelling. It is expected that transfer function modelling will increasingly be used in maintenance scheduling and management. It is equally expected that transfer function modelling will be increasingly used in performance evaluation and assessment of production operations efficiency. In addition to these, better optimisation techniques currently being developed would be of great benefit to transfer function modelling and time series analysis.

According to DeLurgio (1998), many more potential applications for transfer function modelling exist and these applications will grow as more powerful and user friendly software becomes available to more users. Hence, a potential future direction for research is in the area of development of more powerful and user friendly transfer function modelling software, especially those based on artificial intelligence.

In continuation, it is expected that it would be increasingly used in game theoretic modelling. It is expected that the modelling of multi-input production processes should be a focus of future research. It is equally expected that the concept of Coefficient of Performance (COP) introduced by Nwobi-Okoye and Igboanugo (2012, 2015), which was used in analysis of two types of electric power generation systems be further applied to other types of power generation systems such as: wind power generation systems, steam power generation systems etc. Also this should be extended to Multi Input Single Output (MISO) systems, Multi Input Multi Output (MIMO) systems, Multi Output Single Input (MOSI) systems etc. Currently, Nwobi-Okoye *et al*. (2015) are introducing the concept of COP to MISO systems.

Furthermore, the concept of Coefficient of Performance (COP) should be applied extensively to oil and gas industries, power transmission and distribution systems, chemical and communication industries, as well as every system in general.

Also, the concept of transfer function modelling could be applied to the prediction of pipeline failure/fracture/rupture as well as failure of critical parts of machineries or equipment. Even pipeline leaks could be detected by discrete transfer function modelling. These should be the subject of future investigation. In addition application of transfer function modelling to Material Requirement Planning (MRP) in the process industry should be a subject for future research.

DISCUSSION

The use of the transfer function tools as an aid in the manufacturing sector would likely engender economic growth and development in the industrial sector.

The transfer function model as we have from the literature could be used to compare the performance of different materials or equipment used in a production process. As different materials or equipment are likely to have different transfer functions poor quality materials or equipment could easily be detected (Igboanugo and Nwobi-Okoye, 2011a; Hatch and Kazmer, 2001).

With transfer function modelling, the behaviour and process capability of existing plant, equipment or process will be better monitored and accessed which will lead to improved plant design and product quality. In general, the analysis here has shown that transfer function modelling is a very good quality control and production management tool which compares very favourably with conventional quality control tools. In addition to this process capability of non discrete items cannot be measured by the conventional methods but this new method can do it very effectively.

As one of the triumphs of game and contract theories, governments and organizations are increasingly resorting to competitive bidding and auctions before contract awards and by so doing generating billions of dollars in revenue in addition to improved efficiency in the execution of public works (Binmore, 2007; von Stengel and Turocy, 2008). Consequently, firms, especially contracting firms must be able to determine to a very high degree of accuracy the process capability of their facilities in terms of the quantity they are capable of processing within a given period of time. Hence, the model relating transfer functions to Bayesian games and mechanism design is extremely useful

Furthermore, from the literature initial transfer function models developed by Box-Jenkins method are tentative and require more efficient estimation. Hence, optimisation is needed. Igboanugo and Nwobi-Okoye (2011b) demonstrated this assertion by developing software based on genetic algorithm which was used to optimise a developed transfer function model.

The success of genetic algorithm in transfer function model optimisation necessitates the need to try other meta-heuristics methods such as Tabu Search and Ant Colony Optimisation. A comparison of the various meta-heuristics methods would reveal the best method for transfer function model optimisation (Winker and Gilli, 2004).

Furthermore, performance evaluation is very important in every system. From this survey it is apparent that transfer function modelling would be invaluable in systems performance evaluation. The works of Nwobi-Okoye and Igboanugo (2012, 2015) and Nwobi-Okoye *et al*. (2015) are very strong evidences to support this. In view of the foregoing facts, it is obvious that transfer function could determine operations and maintenance effectiveness.

CONCLUSION

The importance of production process transfer functions and its relationship to quality control and production management as elucidated in the literature will help engineers and managers have a better understanding of transfer functions and its relationship to achieving effective and optimum utilization of raw materials and production of high quality goods and effective management of production processes.

Furthermore, several factors work conjointly to affect manufacturing dysfunction. The transfer function modelling approach is effective in dealing with the problem of process variability and degraded output.

In continuation, effective maintenance and efficient performance of plants and facilities is highly desirable (Ghedamsi and Aouzellag, 2010; Alves de Sousa *et al*., 2010; Zhang *et al*., 2011). This is indeed applicable to all manufacturing and production facilities. From the literature a very sound and statistically robust method of evaluating the performance of hydropower and gas power plants using transfer function modelling has been successfully developed. This research could be extended to other production and manufacturing systems. Transfer function models are extremely useful and have wide application in industry. They are widely used in forecasting, plant design and redesign etc, hence excellent models results to excellent forecasts and designs.

NOMENCLATURE, SYMBOLS AND NOTATIONS

γ = Cross correlation function
δ = Difference equation variable for output
∇ = Difference operator
ξ = Difference equation variable for output
η = Difference equation variable for input
θ = Moving average operator
Ξ = Output variable of differential equation
ρ = Auto correlation function
σ = Population standard deviation
$\boldsymbol{\varphi}$ = Autoregressive operator
ω = Difference equation variable for input
Ω = Difference equation variable for input
a_t = Error term/white noise
b = Transfer function lag
B = Backshift operator
D = Differential operator
d = Number of differencing
H = Input variable of differential equation
k = Lag variable
r = Order of the output series
RSE = Residual standard error
S = Sample standard deviation
s = Order of the input series
t = Time
v(B) = Transfer function
X_t = Process input
x_t = Differenced input series
$\hat{X}_t$ = Input forecast
Y_t = Process output
y_t = Differenced output series
$\hat{Y}_t$ = Output forecast

REFERENCES

Abdolshah, M., R.M. Yusuff, T.S. Hong and B. Ismail, 2009a. Overall process capability index for assembly production lines. J. Appl. Sci., 9(20): 3764-3769.

Abdolshah, M., R.M. Yusuff, T.S. Hong and B. Ismail, 2009b. New process capability index using taguchi loss functions. J. Appl. Sci., 9(20): 3775-3779.

Albarbar, A., S. Mekid, A. Starr and R. Pietruszkiewicz, 2008. Suitability of MEMS accelerometers for condition monitoring: An experimental study. Sensors, 8: 784-799.

Ashton, T.S., 1997. The Industrial Revolution 1760-1830. OUP Catalogue, Oxford University Press, Oxford, UK, ISBN: 9780192892898.

Aquilana, N. and B. Chase, 1999. Fundamentals of Operations Management, McGraw Hill, USA.

Al-Anzi, F.S. and K. Al-Zamel, 2005. Efficient maintenance scheduler for near optimum utilization of oil tanks. Am. J. Environ. Sci., 1(4): 254-258.

Alves de Sousa, M.P., M.R. Filho, M.V. Alves Nunes and A. da Costa Lopes, 2010. Maintenance and operation of a hydroelectric unit of energy in a power system using virtual reality. Int. J. Elec. Power, 32(6): 599-606.

Bédard, C., S. Rodrigues, N. Roy, D. Contreras and A. Destexhe, 2010. Evidence for frequency-dependent extracellular impedance from the transfer function between extracellular and intracellular potentials. J. Comput. Neurosci., 29(3): 389-403.

Berument, H., N.B. Ceylan and E. Gozpinar, 2006. Performance of soccer on the stock market: Evidence from Turkey. Soc. Sci. J., 43(2006): 695-699.

Binmore, K., 2007. Game Theory a Very Short Introduction. Oxford University Press, Oxford, UK.

Box, G.E.P. and G.M. Jenkins, 1970. Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco, USA.

Box, G.E.P. and G.M. Jenkins, 1976. Time Series Analysis: Forecasting and Control. 2nd Edn., Holden Day, San Francisco.

Box, G.E.P. and A. Luceno, 2001. Feed forward as a supplement to feedback adjustment in allowing for feedstock changes. Report No. 180, Centre for Quality and Productivity Improvement, University of Wisconsin, USA.

Box, G.E.P., G.M. Jenkins and G.C. Reinsel, 2008. Time Series Analysis Forecasting and Control. John Wiley and Sons, Inc., Hoboken, New Jersey, USA.

Bulgrin, T.C. and T.H. Richards, 1995. Application of advanced control theory to enhance molding machine performance. IEEE T. Ind. Appl., 31(6): 1350-1357.

Caines, P.E., S.P. Sethi and T.W. Brotherton, 1977. Impulse response identification and causality detection for the Lydia-Pinkham data. Ann. Econ. Soc. Meas., 6:147-163.

Camargo, M.E., W.P. Filho, A.I. dos Santos Dullus and G.C. Malafaia, 2010. Transfer function and intervention models for the study of Brazilian inflationary process. Afr. J. Bus. Manag., 4(5): 578-582.

Carmichael, F., 2005. A Guide to Game Theory. Pearson Education Ltd., Hallow, England.

Chance, B.L., J.S. Leigh Jr, B.J. Clark, J. Maris, J. Kent, S. Nioka and D. Smith, 1985. Control of oxidative metabolism and oxygen delivery in human skeletal muscle: A steady-state analysis of the work/energy cost transfer function. P. Natl. Acad. Sci. USA, 82(24): 8384-8388.

Chang, R., S. Shen and C. Yu, 1992. Derivation of transfer function from relay feedback systems. Ind. Eng. Chem. Res., 31(3): 855-860.

Chatfield, C., 1993. Neural networks: Forecasting breakthrough or just a passing fad? Int. J. Forecasting, 9: 1-3.

Chatterjee, K. and W. Samuleson, 2002. Game Theory and Business Applications. Kluwer Academic Publishers, New York, New Jersey, USA.

Chen, W. and C. Liao, 2005. Scheduling with different maintenance policies in a textile company. J. Qual. Maintenance Eng., 11(1): 43-52.

Choudhury, A.H., 2007. Intervention impact of tax reform act on the business failure process. Acad. Account. Financ. Stud. J., 11(3): 57-68.

Cluckie, I.D., D.A. Harwood and R. Harpin, 1982. Three systems approaches to real time rainfall-runoff forecasting. Hydrological forecasting. Proceeding of the Oxford Symposium, April 1980, IAHS Publ. No. 129.

Cluckie, I.D., 1993. Real Time Flood Forecasting using Weather Radar. In: Young P.C. (Ed.), Concise Encyclopedia of Environmental Systems, Pergamon Press, Oxford, pp: 291-298.

Cooray, T., 2006. Analysis and evaluation of econometric time series models: Dynamic transfer function approach. Proceeding of the 62th Annual Session of the SLAAS (2006), pp: 96.

Cordon, O., F. Herrera and L. Sanchez, 1999. Solving electrical distribution problems using hybrid evolutionary data analysis techniques. Appl. Intell., 10(1): 5-24.

Coughanowr, D.R., 1991. Process Systems Analysis and Control. McGraw-Hill Inc., New York.

Czarski, A., 2008. Estimation of process capability indices in case of distribution unlike the normal one. Arch. Mater. Sci. Eng., 34(1): 39-42.

DeLurgio, S.A., 1998. Forecasting Principles and Applications. 3rd Edn., McGraw-Hill, New York, USA.

Dhillon, B.S., 2002. Engineering Maintenance: A Modern Approach. CRC Press, Boca Raton, FL, USA.

Dhillon, B.S. and Y. Liu, 2006. Human error in maintenance: A review. J. Qual. Maintenance Eng., 12(1): 21-36.

Disney, S.M. and D.R. Towill, 2002. A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain. Int. J. Prod. Res., 40(1): 179-204.

Edlund, P. and S. Karlsson, 1993. Int. J. Forecasting, 9(1): 61-76.

Enders, W., 1995. Applied Econometric Time Series. John Wiley and Sons, New York, USA.

Fagergren, A., Ö. Ekeberg and H. Forssberg, 2000. Precision grip force dynamics: A system identification approach. IEEE T. Bio-Med. Eng., 47(10): 1366-1375.

Fask, A. and P.B. Robinson, 1977. Identification of multivariate dynamic econometric models. Proceedings of the Business and Economic statistic section of the American Statistical Association.

Fearn, T. and P.I. Maris, 1991. An application of box-jenkins methodology to the control of gluten addition in a flour Mill. Appl. Statist., 40: 477-484.

Feron, E., M. Brenner, J. Paduano and A. Turevskiy§, 1998. Time-frequency analysis for transfer function estimation and application to flutter clearance. J. Guid. Control Dynam., 21(3): 375-382.

Flaig, J.J., 2009. A unifying process capability metric. J. Ind. Eng. Manage., 2(1): 48-59.

Forst, F.G., 2011. Forecasting restaurant sales using multiple regression and box-jenkins analysis. J. Appl. Bus. Res., 8(2): 15-19.

Gaetan, C., 2000. Subset ARMA model identification using genetic algorithms. J. Time Ser. Anal., 21(5): 559-570.

García-Martos, C., J. Rodriguez and M.J. Sanchez, 2007. Mixed models for short-run forecasting of electricity prices: Application for the Spanish market. IEEE T. Power Syst., 22(2).

Garg, A. and S.G. Deshmukh, 2006. Maintenance management: Literature review and directions. J. Qual. Maintenance Eng., 12(3): 205-238.

Gebel, R.K. and H.E. Fettis, 1974. Application of third-order transfer functions for edge enhancement of signals from scanned imaging systems. Ohio J. Sci., 74(4): 248-260.

Ghedamsi, K. and D. Aouzellag, 2010. Improvement of the performances for wind energy conversions systems. Int. J. Elec. Power, 32(6): 936-945.

Gibbons, R., 1992. Game Theory for Applied Economists. Princeton University Press, Princeton, New Jersey, USA.

Granger, C.W.J. and P. Newbold, 1977a. Identification of two-way causal models. In: Intriligator, M.D. (Ed.), Frontiers of Quantitative Economics. Amsterdam, Holland, Vol. IIIA.

Granger, C.W.J. and P. Newbold, 1977b. Time series approach to econometric model building. new methods in business cycle research, Proceeding of a Conference Sponsored by Federal Reserve Bank of Minneapolis, 1977.

Grant, E.L. and R.S. Leavenworth, 1996. Statistical Quality Control. 7th Edn., McGraw-Hill, New York, USA.

Guh, R. and Y. Hsieh, 1999. A neural network based model for abnormal pattern recognition of control charts. Comput. Ind. Eng., 36(1): 97-108.

Hatch, D. and D. Kazmer, 2001. Process transfer function for optical media manufacturing. Int. J. Adv. Manuf. Tech., 18(5): 357-365.

Haugh, L.D. and G.E.P. Box, 1977. Identification of dynamic regression (distributed lag) models connecting two time series. J. Am. Stat. Assoc., 72: 121-130.

Haupt, R.L and S.E. Haupt, 2004. Practical Genetic Algorithms. John Wiley and Sons, Inc., Hoboken, New Jersey, USA.

He, T., L. Hong, A. Kaufman and H. Pfister, 1996. Generation of transfer functions with stochastic search techniques. Proceeding of the 7th Conference on Visualization (VIS '96), San Fransisco, California, pp: 227-234.

Hernandez, W., 2008. Input-output transfer function analysis of a photometer circuit based on an operational amplifier. Sensors, 8: 35-50.

Hong, S.L., L. Ying and Q.C. Yang, 2010. A fractional order proportional and derivative (FOPD) motion controller: Tuning rule and experiments. IEEE T. Control Syst., 18(2): 516-520.

Huang, C. and C. Yu, 1989. Evaluation of the process transfer function using partial pulse response data. Ind. Eng. Chem. Res., 28(9): 1304-1308.

Igboanugo, A.C. and C.C. Nwobi-Okoye, 2011a. Production process capability measurement and quality control using transfer functions. J. Niger. Assoc. Math. Phys., 19: 453-464.

Igboanugo, A.C. and C.C. Nwobi-Okoye, 2011b. Optimisation of transfer function models using genetic algorithms. J. Niger. Assoc. Math. Phys., 19: 439-452.

Issarayangyun, T. and S. Greaves, 2006. Analysis of minute-by-minute pollution exposure inside a car-a time-series modelling approach. Proceeding of CAITR 2006.

Jeang, A. and C. Chung, 2009. Product design and process planning in using the process capability index. Eng. Lett., 16(3): 1-9.

Jeang, A., C. Chung, H.C. Li and M.H. Sung, 2008. Process capability index for off-line application of product life cycle. Proceeding of the World Congress on Engineering (WCE, 2008). London, U.K., Vol. II.

Jensen, M.C., 2010. The modern industrial revolution, exit and the failure of internal control systems. J. Appl. Corp. Financ., 22(1):43-58.

Johnson, G.K. and I.M. Turner, 1956. Use of transfer functions for company planning. Oper. Res., 4(6): 705-710.

Kazmer, D., 2008. Precision Process Control of Injection Molding. Mimeo, University of Massachusetts, Lowell, USA.

Kazmer, D. and D. Hatch, 2002. Investigation of variation and uncertainty in six sigma. Proceeding of DETC 7th Design for Manufacturing Conference.

Kelejian, H.H. and W.E. Oates, 1974. Introduction to Econometrics: Principles and Applications. Harper and Row, New York.

Kinney, W.R., 1978. ARIMA and regression in analytical review: An empirical test. Account. Rev., 53(1): 48-60.

Koomsap, P., N.I. Shaikh and W. Prabhu, 2005. Integrated process control and condition-based maintenance scheduler for distributed manufacturing control systems. Int. J. Prod. Res., 43(8): 1625-1641.

Kotz, S. and C.R. Lovelace, 1989. Process Capability Indices in Theory and Practice. Oxford University Press, New York, USA.

Kuligowski, R.J. and P.B. Ana, 1998. Experiments in short-term precipitation forecasting using artificial neural networks. Mon. Weather Rev., 126: 470-482.

Lai, P., 1979. Transfer function modelling relationship between time series variables. Concepts and Techniques in Modern Geography (CATMOG), No. 22.

Lees, M.J., 2000. Advances in Transfer Function based Flood Forecasting. In: Flood Forecasting: What does Current Research Offer the Practitioner? BHS Occasional Paper No. 12.

Leou, R., 2006. A new method for unit maintenance scheduling considering reliability and operation expense. Int. J. Elec. Power, 28(7): 471-481.

Leyton-Brown, K. and Y. Shoham, 2008. Essentials of Game Theory. Morgan and Claypool Publishers Ltd., USA.

Limanond, T., S. Jomnonkwao and A. Srikaew, 2011. Projection of future transport energy demand of Thailand. Energ. Policy, 39(5): 2754-2763.

Limbourg, P. and H.D. Kochs, 2005. Maintenance scheduling by variable dimension evolutionary algorithms. In: Kolowrocki, K. (Ed.) European Conference on Safety and Reliability-ESREL Balkema. Gdynia-Sopot-Gdansk, Poland, 2: 1267-1275.

Liu, L. and D.M. Hanssens, 1982. Identification of multi-input transfer function models. Commun. Stat. A-Theor., 11(3): 297-314.

Loha, E. and B. Lindtjørn, 2010. Model variations in predicting incidence of Plasmodium falciparum malaria using 1998-2007 morbidity and meteorological data from south Ethiopia. Malaria J., 9: 166.

Losenický, M., 2010a. Educating as the linear control process I. Mathematical model of pupils (Students) and teachers. Technológia Vzdelávania, 18(2): 2-7.

Losenický, M., 2010b. Educating as the linear control process II: mathematical model of pupils (Students) and teachers. Technológia Vzdelávania, 18(3): 2-6.

Maier, H.R. and G.C. Dandy, 2000. Neural networks for the prediction and forecasting of water resources variables: A review of modelling issues and applications. Environ. Modell. Softw., 15(2000): 101-124.

Mani, S.M., 1996. Financial forecasting using genetic algorithms. App. Artif. Intell., 10(6): 543-566.

Maxwell, J.C., 1867. On Governors. P. R. Soc. London, 16: 270-283.

Mayr, O., 1975. The Origins of Feedback Control. MIT Press, Boston, USA.

Min, S.H., J. Lee and I. Han, 2006. Hybrid genetic algorithms and support vector machines for bankruptcy prediction. Expert Syst. Appl., 31(3): 652-660.

Morari, M. and E. Zafiriou, 1989. Robust Process Control. Prentice Hall, New York, USA.

Mytakidis, T. and A. Vlachos, 2008. Maintenance scheduling by using the bi-criterion algorithm of preferential anti-pheromone. J. Sci., 12: 143-164.

Narahari, Y., D. Garg, R. Narayanam and H. Prakash, 2009. Game Theoretic Problems in Network Economics and Mechanism Design Solutions. Advanced Information and Knowledge Processing, Springer-Verlag, London Ltd., UK.

Nisan, N., 2007. Algorithmic Game Theory. Cambridge University Press, New York, NY 10013-2473, USA.

Nogales, F.J. and A.J. Conejo, 2006. Electricity price forecasting through transfer function models. J. Oper. Res. Soc., 57(4): 350-356.

Nwobi-Okoye, C.C., 2010. General theory of games with virtual strategies. Pac. J. Sci. Technol., 11(1): 317-327.

Nwobi-Okoye, C.C. and A.C. Igboanugo, 2011. Game theoretic aspect of production process transfer function. Res. J. Appl. Sci. Eng. Technol., 3(11): 1325-1330.

Nwobi-Okoye, C.C. and A.C. Igboanugo, 2012. Performance evaluation of hydropower generation system using transfer function modelling. Int. J. Elec. Power, 43(1): 245-254.

Nwobi-Okoye, C.C. and A.C. Igboanugo, 2015. Performance appraisal of gas based electric power generation system using transfer function modelling. Ain Shams Eng. J., 6(2): 541-551.

Nwobi-Okoye, C.C., S. Okiy and A.C. Igboanugo, 2015. Performance evaluation of Multi-Input-Single-Output (MISO) production process using transfer function and fuzzy logic: Case study of a Brewery. Ain Shams Eng. J., Retrieved from: http://dx.doi.org/10.1016/j.

Oakland, J.S., 2003. Statistical Process Control. 5th Edn., Butterworths-Heinemann, New York, USA.

Olason, T. and W.E. Watt, 1985. Multivariate transfer function-noise model of river flow for hydropower operation. Nord. Hydrol., 17: 185-202.

Ong, C.S., J.J. Huang and G.H. Tzeng, 2005. Model identification of ARIMA family using genetic algorithms. Appl. Math. Comput., 164(3): 885-912.

Osborne, M.J., 1998. A Course in Game Theory. MIT Press, Cambridge, MA, USA.

Otok, B.W., 2009. Development of rainfall forecasting model in Indonesia by using ASTAR, transfer function and ARIMA Methods. Eur. J. Sci. Res., 38(3): 386-395.

Owen, M., 1993. SPC and Business Improvement. IFS Publications, Bedford, UK.

Pardo, A., V. Meneu and E. Valor, 2002. Temperature and seasonality influences on Spanish electricity load. Energ. Econ., 24(1): 55-70.

Petcu, A. and B. Faltings, 2006. Distributed generator maintenance scheduling. Proceeding of the 1st International ICSC Symposium on Artificial Intelligence in Energy Systems and Power (AIESP'06). Madeira, Portugal.

Pindyck, R.S. and D.L. Rubinfeld, 1976. Econometric Models and Economic Forecasts. McGraw-Hill, New York.

Preciado, I., A. Punzon, J.L. Gallego and Y. Vila, 2006. Using time series methods for completing fisheries historical series. Bol. Inst. Esp. Oceanogr., 22(1-4): 83-90.

Priestly, M.B., 1969. Estimation of transfer functions in closed loop stochastic processes. Automatica, 5: 623-632.

Priestly, M.B., 1971. Fitting relationships between time series. B. Int. Statist. Inst., 34: 295-324.

Pyzdek, T., 1990. Pyzdek's Guide to SPC. Fundamentals, ASQC Quality Press, Milwaukee WI, USA, Vol. 1.

Razak, F.A., M. Shitan, A.H. Hashim and I.Z. Abidin, 2009. Load forecasting using time series models. Jurnal Kejuruteraan, 21(2009): 53-62.

Ritzberger, K., 2003. Foundations of Non-game Theory. Oxford University Press, Oxford, UK.

Rodriguez, P., A. Luna, I. Candela, R. Mujal, R. Teodorescu and F. Blaabjerg, 2011. Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions. IEEE T. Ind. Electron., 58(1):127-138.

Sadigh, A.N., N. Zulkifli, T.S. Hong and M. Abdolshah, 2009. Supplier evaluation and selection using revised Taguchi loss function. J. Appl. Sci., 9(24): 4240-4246.

Sample, A.P., D.A. Mayer and A.R. Smith, 2011. Analysis, experimental results and range adaptation of magnetically coupled resonators for wireless power transfer. IEEE T. Ind. Electron., 58(2): 544-554.

Schwartz, J.D. and D.E. Rivera, 2010. A process control approach to tactical inventory management in production-inventory systems. Int. J. Prod. Econ., 125(1): 111-124.

Schwartz, J.D., D.E. Rivera and K.G. Kempf, 2005. Towards control-relevant forecasting in supply chain management. Proceeding of the American Control Conference. Portland, OR, USA, June 8-10.

Sheta, A.F. and K. De Jong, 2001. Time-series forecasting using GA-tuned radial basis functions. Inform. Sciences, 133(3-4): 221-228.

Shumway, R.H. and D.S. Stoffer, 2006. Time Series Analysis and its Applications in R. Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA.

Stepanov, I.I., C.I. Abramson, O.T. Wolf and A. Convit, 2010. The application of the first order system transfer function for fitting the California verbal learning test learning curve. J. Int. Neuropsych. Soc., 16(3): 443-452.

Talmon, R., I. Cohen and S. Gannot, 2009. Relative transfer function identification using convolutive transfer function approximation. IEEE T. Audio Speech, 17(4): 546-555.

Tiao, G.C., G.E.P. Box, M.R. Grupe, G.B. Hudak and W.R. Bell, 1979. The Wisconsin Multiple Time Series (WMTS-1) program: A preliminary guide. Department of Statistics, Unversity of Wisconsisn, Madison, USA.

Toth, E., A. Brath and A. Montanari, 2000. Comparison of short-term rainfall prediction models for real-time flood forecasting. J. Hydrol., 239: 132-147.

Tsai, C. and C. Lu, 1998. Multivariable self-tuning temperature control for plastic injection molding process. IEEE T. Ind. Appl., 34(2): 310-318.

Versace, M., R. Bhatt, O. Hinds and M. Shiffer, 2004. Predicting the exchange traded fund DIA with a combination of genetic algorithms and neural networks. Expert Syst. Appl., 27(3): 417-425.

Von Stengel, B. and T. Turocy, 2008. Game theory. CDAM Research Report LSE-CDAM-2001-09.

Von Stengel, B., 2008. Game Theory Basics. Lecture Notes, Department of Mathematics, London School of Economics, Houghton St, London WC2A 2AE, United Kingdom.

Vossa, M.S. and X. Feng, 2002. Arma model selection using particle swarm optimization and AIC criteria. Proceeding of the 15th Triennial World Congress, IFAC, Barcelona, Spain.

Webb, R.D. and D.E. Hardt, 1991. Transfer function description of sheet metal forming for process control. Trans. ASME, 113: 44-52.

Wheeler, D.J. and D.S. Chambers, 1992. Understanding Statistical Process Control. 2nd Edn., SPC Press, Knoxville TN, USA.

Wilson, N., G. Sertsou, R. Edwards, Thomson, M. Grigg and J. Li, 2007. A new national smokefree law increased calls to a national quitline. BMC Public Health, 7: 75.

Winker, P. and M. Gilli, 2004. Applications of optimization heuristics to estimation and modelling problems. Comput. Stat. Data An., 47(2): 211-223.

Wolpert, D.H. and W.G. Macready, 1997. No free lunch theorems for optimization. IEEE T. Evolut. Comput., 1(1): 67-82.

Wu, B. and C. Chang, 2002. Using genetic algorithms to parameters (d,r) estimation for threshold autoregressive models. Comput. Stat. Data An., 38(3): 315-330.

Yingthawornsuk, T., 2003. Identification of open-loop transfer functions in closed loop baroreflex system using random breathing in humans. Comput. Cardiol., 29: 461-464.

Young, P.C., 2004 Identification and estimation of continuous-time hydrological models from discrete time data. Proceeding of the Submitted British Hydrological Society Conference, London.

Zalewski, J., 2001. Real-time software architectures and design patterns: Fundamental concepts and their consequences. Annu. Rev. Control, 25(2001): 133-146.

Zareipour, H., C.A. Canizares, K. Bhattacharya and J. Thomson, 2006. Application of public-domain market information to forecast ontario's wholesale electricity prices. IEEE T. Power Syst., 21(4): 1707-1717.

Zhang, R., J.H. Zuckerman, C.A. Giller and B.D. Levine, 1998. Transfer function analysis of dynamic cerebral autoregulation in humans. Am. J. Physiol-Heart C., 274(1): H233-H241.

Zhang, Y., Z. Wang, J. Zhang and J. Ma, 2011. Fault localization in electrical power systems: A pattern recognition approach. Int. J. Elec. Power, 33(3): 791-798.

Zhao, Y., V. Volovoi and M. Waters, 2006. A sequential approach for gas turbine power plant preventive maintenance scheduling. Eng. Gas Turbine Power, 128(4): 796-895.

Zhou, X., 2006. Reliability-centred predictive maintenance scheduling for a continuously monitored system subject to degradation. Reliab. Eng. Syst. Safe., 92(4): 530-534.

Zvirblis, A., 2003. The principle of analysis of competitiveness and control schemes in transport services. Transport, 18(2): 57-60.