

# Measuring the Resilience of Supply Chain Systems Using a Survival Model

Ratan Raj, J. W. Wang, Ashutosh Nayak, M. K. Tiwari, B. Han, C. L. Liu, and W. J. Zhang

**Abstract**—Disruptions at any stage of a supply chain system can cause mammoth operational and financial losses to a firm. When there is a disruption with a supply chain system, it is highly desired that the system quickly recover. The ability of recovery is, in short, called resilience. This paper proposes a new measure of the resilience of a supply chain system based on the concept of survival and, subsequently, a survival model [Cox proportional hazard (Cox-PH) model]. The survival model represents a time interval or period from the time the system failed to function to the time the system gets back with its function (i.e., recovery). The input to the model is, thus, a failure event; the output from the model is the recovery time. This model has been implemented. There is a case study to illustrate how the model is used to give a quantitative measurement of resilience, in terms of recovery time.

**Index Terms**—Cox proportional hazard (Cox-PH) model, supply chain, supply chain resilience, survival analysis.

## I. INTRODUCTION

**R**ESILIENCE has been an important concept in engineering recently. A summary of resilience for general systems and information systems can be found in [1]–[3]. The concept

of resilient manufacturing systems can be found in [4]. Supply chain resilience addresses the supply chain's ability to cope with the consequences of unavoidable risk events or disruptions, such as the loss of a critical supplier, a major fire at a manufacturing plant, or an act of terrorism, in order to return to its original operations or move to a new and more desirable state after being disturbed [5]–[8]. These events can take many forms, as highlighted in many recent highly publicized events, including the 2004 Indian Ocean Tsunami, the 2010 Haiti and Chile Earthquakes, the recent global financial crisis, and the 2010 eruption of Icelandic Volcano Eyjafjallajökull [9]. Natural disasters, pandemic disease, terrorist attacks, economic recession, equipment failure, and human error can all pose both a potentially unpredictable and severe threat to the continuity of an organization's operation.

Resilience is a function of both vulnerability of a system and its adaptive capacity [10]–[12]. Fiksel identifies four major system characteristics that contribute to resilience [13]. These are diversity, adaptability, efficiency, and cohesion. To date, many definitions have been proposed by researchers for supply chain resilience, but theoretical justifications are still in their infancy.

For resilience with respect to ecological systems, the Canadian ecologist Holling was one of the first researchers to note resilience in an ecological perspective [14]. According to him, any system has two distinct properties: resilience and stability. Resilience determines the ability of systems to absorb changes, and stability is the capacity of systems to return to an equilibrium state after a temporary disturbance. The faster a system returns to equilibrium, the greater its stability [14]. Gunderson and Holling defined resilience as the capacity of a system to experience disturbance and maintain its functions and controls [15]. Carpenter *et al.* [16] extended the research by examining the magnitude of disturbance that a system could tolerate before it fundamentally changes into a different region with a different set of controls. The psychological perspective on resilience is well studied and widely represented in the literature. It has its roots in developmental theory that deals with the examination of people's behavior across the life span, and encompasses an understanding of biopsychological factors as well as the spiritual realm [17]. From an economics perspective, static economic resilience refers to the ability or capacity of a system to absorb or cushion against damage or loss [14], [18]. From an organizational perspective, supply chain resilience is the capacity to adjust and maintain desirable functions under challenging or straining conditions [19]–[21]. Hamel and Valikangas [22] stress that resilience is not just concerned with recovery, flexibility, or crisis preparedness but

Manuscript received June 26, 2012; revised December 3, 2013. Date of publication August 12, 2014; date of current version May 22, 2015. The work of W. J. Zhang was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through a strategic project. The work of C. L. Liu was supported by the East China University of Science and Technology through a program of the Fundamental Research Funds for the Central Universities. The work of J. W. Wang was supported by the State Key Laboratory of Synthetical Automation for Process Industries. (Corresponding author: W. J. Zhang.)

R. Raj was with the Department of Industrial Engineering and Management, Indian Institute of Technology, Kharagpur 721302, India, and also with the Advanced Engineering Design Laboratory, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada. He is now with the Complex Systems Research Center, East China University of Science and Technology, Shanghai 200237, China, and also with the Department of Mechanical Engineering, University of Alberta, Edmonton, AB T6G 2G8, Canada (e-mail: rar200@mail.usask.ca).

J. W. Wang is with the Complex Systems Research Center, East China University of Science and Technology, Shanghai 200237, China, and also with the Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Kowloon, Hong Kong (e-mail: wangjw1979@gmail.com).

A. Nayak and M. K. Tiwari are with the Department of Industrial Engineering and Management, Indian Institute of Technology, Kharagpur 721302, India (e-mail: mktiwari9@iem.iitkgp.ernet.in).

B. Han is with the Advanced Engineering Design Laboratory, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada (e-mail: hanbinking1987@gmail.com).

C. L. Liu is with the Complex Systems Research Center, East China University of Science and Technology, Shanghai 200237, China (e-mail: cliu@ecust.edu.cn).

W. J. Zhang is with the Complex Systems Research Center, East China University of Science and Technology, Shanghai 200237, China, and also with the Advanced Engineering Design Laboratory, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada (e-mail: Chris.Zhang@Usask.ca).

Digital Object Identifier 10.1109/JSYST.2014.2339552

also a distinct source of sustainable competitive advantage. In the area of supply chain systems, Ponomarov and Holcomb [23] defined supply chain resilience as “the adaptive capability of a supply chain to prepare for unexpected events, respond to disruptions and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.” In this paper, this definition is taken for studying the problem of measuring supply chain resilience.

Very limited research work has been done on resilience measurement until now [24]–[27]. Mauro *et al.* [28] built a decision-making model based on supply chain density, complexity, and the number of key nodes from the qualitative point of view. Zhu and Su [29] built a mathematical model based on Hooke’s law. At present, studies on the measuring method of supply chain resilience are limited, and quantitative studies are scarce, which is not enough to provide an accurate theoretical basis for practical applications. Rosenkrantz *et al.* [24] measured the resilience through the number of node failures and edge failures while the network can remain its function. Wang and Ip [26] proposed an approach to evaluate the logistics network resilience based on the redundant resource and reliability of nodes and edges. Ash and Newth [25] used an evolutionary algorithm to evolve the complex systems that are resilient to cascading failure. In the work of Shuai *et al.* [30], a quantitative method, referring to stress relaxation time of material mechanics, was proposed based on the biological cell elasticity theory, and furthermore, a supply chain system was modeled as a biological cell system so that the measurement method for the latter can be applied to the former. The aforementioned studies were focused on qualitative measures, and furthermore, they measured the resilience of a system through the resource redundancy or structure redundancy but not explicitly the recovery of a supply chain system.

In this paper, we present a new measure for the resilience of a system, including a supply chain system, from the perspective of recovery of a system’s function or service and by taking an entire system as a black box. Note that the structure of the black-box system in responding failure is determined based on the historical data, and as such, the proposed measure is applicable to any system. In particular, the present measure is based on the so-called Cox proportional hazard (Cox-PH) model [31], [32].

The Cox-PH model is a model that describes the survival of a system. The model relates events to times with the so-called resource variables, representing the sources of failures, when the Cox-PH model is applied to survival analysis. The event-time historical data are assumed to be available, and these data are used to determine or train the coefficients of the resource variables or resources. If the event is a failure of the system, the time represents the period from a time before the failure to the time the failure occurs.

The remainder of this paper is organized as follows. In Section II, the procedure to construct a Cox-PH model is presented. The effectiveness of the proposed model has been confirmed through simulation in Section III. Conclusions are drawn and insights in need of further research are discussed in Section IV.

## II. BUILDING THE COX-PH MODEL

In the Cox-PH model, the hazard function, which is also called the conditional failure rate function, is defined as follows:

$$h(t) = \lim_{\Delta t \rightarrow 0} \Pr(t \leq T \leq t + \Delta t | T \geq t) = \frac{f(t)}{S(t)} \quad (1)$$

where

$T$  time the hazard function is estimated;

$h(t)$  hazard function;

$f(t)$  probability density function of  $T$ ;

$S(t)$   $\Pr(T > t)$ , the survival function of  $T$ .

**Notations**

$\mu = [\mu_1, \mu_2, \mu_3, \dots, \mu_n]$  set of coefficients of the covariates in the model;

$z = [z_1(t), z_2(t), z_3(t), \dots, z_n(t)]$  set of decision variables for the model ( $z_i(t) = 1$  if  $t \leq T$  and  $= 0$  otherwise);

$t'$  time at which the estimation is made;

$P_q$  residual survival function of the system;

$S(t|z(t'))$  survival probability of a system at time  $t$ , given that the system has survived until time  $t'$ ;

$S_o(t)$  base survival function;

$h_o(t)$  base hazard function.

The failure rate is described as follows:

$$f(t) = \frac{d[1 - S(t)]}{dt}. \quad (2)$$

From (2), we obtain

$$f(t) = -S'(t). \quad (3)$$

The Cox-PH model is used to describe the relationship between the system hazard function and covariates, as shown in the following equation:

$$h(t|z(t)) = h_o(t)e^{\mu^t z(t)} = h_o(t) \prod_{i=1}^n \mu_a z_a(t). \quad (4)$$

From (1) and (3), we obtain

$$h(t) = \frac{-S'(t)}{S(t)}. \quad (5)$$

By solving (5) and simplifying it, we obtain

$$S(t|z(t)) = \exp \left( \int_0^t h_o(t) \exp \left( \sum_{i=1}^n \mu_a z_a(t) \right) dt \right). \quad (6)$$

The conditional probability of the survival of a system  $\Pr(T > t|t'z(t'))$ , which is the probability that the system survives for a time  $T$  given that it has survived until time  $t'$ , is given by

$$\frac{S(t|z(t))}{S(t'|z(t'))} = S(t|z(t')). \quad (7)$$

Using (6), (7) can be simplified as

$$S(t|z(t')) = \left( \frac{S_o(t)}{S_o(t')} \right)^{\exp[\mu^t z(t)]}. \quad (8)$$

The failure point of the system is predicted when the survival probability (residual life of the system) estimated at  $t'$  is  $P_q$ . Therefore, the estimated failure time  $t$  can be obtained from the following equation:

$$\left( \frac{S_o(t)}{S_o(t')} \right)^{\exp[\mu^t z(t)]} \leq (1 - P_q). \quad (9)$$

From (9) and assuming that the survival function is continuous and invertible, the failure time can be estimated by

$$t = S_o^{-1} (S_o(t)(1 - P_q)^{\exp(\mu^t z(t))}) \quad (10)$$

To estimate the recovery time from the failure events, it can be assumed that no failure event has occurred; the value of the decision variables is 0 in this case, i.e.,

$$z_1 = z_2 = z_3 \dots = z_n = 0. \quad (11)$$

Equation (11) corresponds to the no failure event. Thus, by modifying (10), we can get the recovery time as follows:

$$T_{rc} = T_{nf} - T_f \quad (12)$$

where

$T_{rc}$  recovery time;

$T_{nf}$  estimated time for the system to have  $P_q$  residual life but with no source of disruption;

$T_f$  estimated time for system to have  $P_q$  residual life with sources of disruption.

From (10), the following equations can be obtained:

$$T_f = S_o^{-1} (S_o(t)(1 - P_q)^{\exp(\mu^t z(t))}) \quad (13)$$

$$T_{nf} = S_o^{-1} (S_o(t)(1 - P_q)). \quad (14)$$

Equation (12) can be used to estimate the recovery time of the system from a failure event. From the coefficients obtained and the recovery time estimated from each failure event, the influence of the various sources of disruptions on the health of a supply chain system can then be analyzed as well.

### III. SIMULATION MODEL

As an illustration, a simulation model of the supply chain is developed based on the aforementioned theory to estimate the recovery time of a supply chain after disruption. In particular, the 12 different sources of disruptions have been considered. The 12 sources include both external and internal factors. The examples of external sources are fire, extreme weather, strikes, high-cost labors, and epidemics. The examples of internal sources are shortage of qualified labors, inflexible production capacity, long setup and lead time, overly leaned inventory, and process issues.

In the simulation model, 2000 general events have been generated randomly. The inability of the supply chain of the firm to meet at least 95% of the demand has been considered as a failure event for the purpose of this study. In the 2000 events, 142 failure events with the different sources responsible for the failures have been identified.

Cox-PH model fitting has been developed on these 12 sources of disruptions. After that, it has been observed that sources 3 and 6 are statistically insignificant. Thus, sources 3

TABLE I  
COEFFICIENTS OF RESOURCES

Source	Coef	EXP (COEF)	SE (COEF)	z	P
1	3.57651	35.75	0.36424	9.819	0.00E+00
2	3.66263	38.96	0.37083	9.877	0.00E+00
4	1.98346	7.27	0.35058	5.658	1.50E-08
5	4.16312	64.27	0.34864	11.941	0.00E+00
7	3.78612	44.08	0.23695	15.979	0.00E+00
8	3.80748	45.04	0.22587	16.857	0.00E+00
9	0.02992	1.03	0.00814	3.677	2.40E-04
10	0.03348	1.03	0.01629	2.056	4.00E-02
11	0.00946	1.01	0.03347	0.283	7.80E-01
12	0.1937	1.21	0.02031	9.537	0.00E+00

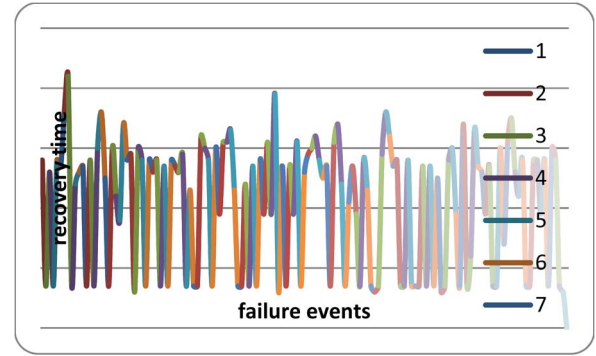


Fig. 1. Recovery time at different failure events.

and 6 are ignored, and a refitting to the model has been performed. The coefficient of the resources of the different sources after the refitting is shown in Table I.

The exponential coefficients of the variables in the Cox-PH model are interpretable as the multiplicative effects of the variable. Thus, for example, holding other covariates (sources in the model) constant, an additional occurrence of source 1 increases the chances of failure of the system and, in this case, disruption in the supply chain by the factor of  $e^{3.576} = 35.75$ . Thus, the coefficients of the sources, after encoding into the Cox-PH model, relatively estimate the significance of the different sources responsible for disruption. The recovery time of the supply chain from the disruption for all the 142 events can be estimated, as shown in Fig. 1.

In the simulation model, estimation of the recovery period has been done on the basis of 10% residual life. This means that the estimation of the recovery period is done when the supply chain health is 10% only. At the health of 1, the supply chain is considered to be perfectly fit. For all the different 142 failure events, different combinations of sources are recognized imbibing different recovery times of the supply chain. The average number of days taken by the system to recover from the disruption due to a particular source is given in Table II. It is noted that the procedure for calculating the recovery time has been thoroughly explained in Section II, in (14).



TABLE II  
SOURCES OF DISRUPTION AND RECOVERY TIME

Source	Frequency of sources	Recovery time
1	10	26.3
2	10	29.1
4	10	22.6
5	10	30.6
7	30	28.86
8	30	27.3
9	4	6
10	6	25.16
11	6	25.5
12	43	8.37

TABLE III  
SOURCES OF DISRUPTION AND RECOVERY TIME

Average recovery time	20.89 observation time
Maximum recovery time	42 observation time (Sources 5,1 and 7)
Minimum recovery time	6 observation time (Source 10)

The recovery time after failure event due to different sources is indicative of the estimated recovery time since some interaction pattern may also be present between the sources affecting the recovery time. The observations from the model developed can be summarized as in Table III.

The Cox-PH model has been developed using the R-software run in Windows 7 environment. The R-square value obtained in the simulation model is 0.25 (the details for the R-value have already been provided using the R-software run in Windows environment).

#### IV. CONCLUSION AND DIRECTIONS FOR FURTHER RESEARCH

This paper focused on the measurement of supply chain resilience. The definition of the resilience of supply chain taken in this paper was described as follows: it is the ability of the supply chain to bounce back to its normal operating status following a disruption. The paper proposed a new measure of resilience, in terms of recovery time. The new measure is based on the Cox-PH model, which is a semiparametric model. In the Cox-PH model, the variables represent various sources of disruptions, the input variable represents an event (failure event for survival or resilience analysis), and the output variable is the time. It is remarkable that the model can capture the multiple sources of failures, as this is the more accurate case in real-world systems.

However, the mathematical model presented in this paper is just one of the possible views. As such, it has some limitations, which leads to some potential future works. First, further conceptualization using different research perspectives would be highly recommended. For instance, increasing the number of variables for representing disruption in a supply chain could help to develop a broader perspective of supply chain resilience measurement. Second, different risk assessment paradigms, such as probabilistic choice, systems theory, and the theory

of constraints, could also be applied to the problem. Third, the present model is based on the assumption that the survival function of a system depicting the health of the supply chain follows the Cox-PH model exactly, which seems to be a highly strong condition. Fourth, the number of sources of disruptions is limited for Cox-PH model fitting. Fifth, the model is based on the assumption that the sources are independent of each other; however, in real life, one source might have impact on the other source.

#### REFERENCES

- [1] W. J. Zhang, "Guest editor's foreword," *Enterprise Inf. Syst.*, vol. 4, no. 2, pp. 95–97, May 2010.
- [2] W. J. Zhang and Y. Lin, "On the principle of design of resilient systems—Application to enterprise information systems," *Enterprise Inf. Syst.*, vol. 4, no. 2, pp. 99–110, May 2010.
- [3] J. W. Wang, "Towards a resilient networked service system," Ph.D. dissertation, Dept. Mech. Eng., Univ. Saskatchewan, Saskatoon, SK, Canada, 2013.
- [4] W. J. Zhang and C. A. van Luttervelt, "Toward a resilient manufacturing system," *CIRP Ann.-Manuf. Technol.*, vol. 60, no. 1, pp. 469–472, 2011.
- [5] M. Christopher and H. Peck, "Building the resilient supply chain," *Int. J. Logist. Manag.*, vol. 15, no. 2, pp. 1–14, 2004.
- [6] H. Peck, "Drivers of supply chain vulnerability: An integrated framework," *Int. J. Phys. Distrib. Logist. Manag.*, vol. 35, no. 4, pp. 210–232, Jan. 2005.
- [7] J. W. Wang *et al.*, "On domain modeling of the service system with its application to enterprise information systems," *Enterprise Inf. Syst.*, DOI: 10.1080/17517575.2013.810784.
- [8] J. W. Wang, H. F. Wang, W. J. Zhang, W. H. Ip, and K. Furuta, "On a unified definition of the service system: What is its identity?" *IEEE Syst. J.*, DOI: 10.1109/JSYST.2013.2260623.
- [9] R. Bhamra, S. Dani, and K. Burnard, "Resilience: The concept, a literature review and future directions," *Int. J. Prod. Res.*, vol. 49, no. 18, pp. 5375–5393, Sep. 2011.
- [10] E. P. Dalziel and S. T. McManus, "Resilience, vulnerability, adaptive capacity: Implications for system performance," in *Proc. 1st IFED*, St. Gallen, Switzerland, Dec. 5–8, 2004, pp. 1–17.
- [11] J. W. Wang, W. H. Ip, R. R. Muddada, J. L. Huang, and W. J. Zhang, "On Petri net implementation of proactive resilient holistic supply chain networks," *Int. J. Adv. Manuf. Technol.*, vol. 69, no. 1–4, pp. 427–437, Oct. 2013.
- [12] J. W. Wang, H. F. Wang, W. J. Zhang, W. H. Ip, and K. Furuta, "Evacuation planning based on the contraflow technique with consideration of evacuation priorities and traffic setup time," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 480–485, Mar. 2013.
- [13] J. Fiksel, "Designing resilient, sustainable systems," *Environ. Sci. Technol.*, vol. 37, no. 23, pp. 5330–5339, Dec. 2003.
- [14] C. S. Holling, "Resilience and stability of ecological systems," *Ann. Rev. Ecology Syst.*, vol. 4, pp. 1–23, Nov. 1973.
- [15] L. Gunderson and C. S. Holling, *Panarchy: Understanding Transformation in Human and Natural Systems*. Washington, DC, USA: Island Press, 2001, pp. 25–62.
- [16] S. Carpenter, B. Walker, M. Anderies, and N. Abel, "From metaphor to measurement: Resilience of what to what?" *Ecosystems*, vol. 4, no. 8, pp. 765–781, Dec. 2001.
- [17] A. P. Conra, *Professional Tools for Social Work Practice, Human Behaviour Theory and Social Work Practice*, 2nd ed. New York, NY, USA: Aldine, 1999, pp. 63–72.
- [18] C. Perrings, "Ecological resilience in the sustainability of economic development," in *Proc. Int. Symp. Models Sustain. Develop.*, Paris, France, 1994, vol. 2, pp. 27–41.
- [19] K. E. Weick, K. M. Sutcliffe, and D. Obstfeld, "Organizing for high reliability: Processes of collective mindfulness," *Res. Org. Behav.*, vol. 21, pp. 81–123, 1999.
- [20] J. S. Bunderson and K. M. Sutcliffe, "Comparing alternative conceptualizations of functional diversity in management teams: Process and performance effects," *Acad. Manag. J.*, vol. 45, no. 5, pp. 875–93, Oct. 2002.
- [21] A. C. Edmondson, "Psychological safety and learning behavior in work teams," *Admin. Sci. Quart.*, vol. 44, no. 2, pp. 350–83, Jun. 1999.
- [22] G. Hamel and L. Valikangas, "The quest for resilience," *Harv. Bus. Rev.*, vol. 81, no. 9, pp. 52–63, Sep. 2003.

- [23] S. Y. Ponomarov and M. C. Holcomb, "Understanding the concept of supply chain resilience," *Int. J. Logist. Manag.*, vol. 20, no. 1, pp. 124–143, 2009.
- [24] D. J. Rosenkrantz, S. Goel, S. S. Ravi, and J. Gangolly, "Structure-based resilience metrics for service-oriented networks," in *Lecture Notes in Computer Science*, vol. 3463. Berlin, Germany: Springer-Verlag, 2005, pp. 345–362.
- [25] J. Ash and D. Newth, "Optimizing complex network for resilience against cascading failure," *Phys. A*, vol. 380, pp. 673–683, Jul. 2007.
- [26] D. W. Wang and W. H. Ip, "Evaluation and analysis of logistic network resilience with application to aircraft serving," *IEEE Syst. J.*, vol. 3, no. 2, pp. 166–173, Jun. 2009.
- [27] J. W. Wang, F. Gao, and W. H. Ip, "Measurement of resilience and its application to enterprise information systems," *Enterprise Inf. Syst.*, vol. 4, no. 2, pp. 215–223, May 2010.
- [28] F. Mauro, W. Z. Christopher, and C. Deborah, "A decision support framework to assess supply chain resilience," in *Proc. 5th Int. ISCRAM Conf.*, Washington DC, USA, 2008, pp. 596–605.
- [29] X. Q. Zhu and C. Su, "Study on supply chain elasticity based on Hooke Law," (in Chinese), *Logist. Technol.*, vol. 29, no. 11, pp. 102–105, 2010.
- [30] Y. Shuai, X. Wang, and L. Zhao, "Research on measuring method of supply chain resilience based on biological cell elasticity theory," in *Proc. IEEE IEEM*, 2011, pp. 264–268.
- [31] D. R. Cox, "Regression models and life-tables," *J. R. Stat. Soc. Ser. B-Stat. Methodol.*, vol. 34, no. 2, pp. 187–220, 1972.
- [32] J. P. Klein and M. L. Moeschberger, *Survival Analysis: Techniques for Censored and Truncated Data*, 2nd ed. New York, NY, USA: Springer-Verlag, 2003, pp. 21–62.



**Ratan Raj** received the B.E. degree in industrial engineering from the Indian Institute of Technology, Kharagpur, India, in 2013. He is currently working toward the M.S. degree in the Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada.

From May 2012 to July 2012, he was a Research Student with the Department of Mechanical Engineering, University of Saskatchewan, Saskatoon, Canada, where he was a Research Assistant from September 2013 to November 2013. He is currently

with the Complex Systems Research Center, East China University of Science and Technology, Shanghai, China. His research interest includes energy supply chain systems.



**J. W. Wang** received the first Ph.D. degree in systems engineering on the topic of optimization from the Northeastern University, Shenyang, China, in 2006 and the second Ph.D. degree in mechanical engineering on the topic of resilience engineering from the University of Saskatchewan, Saskatoon, Canada, in 2013.

From 2011 to 2013, he was a Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellow with the Department of Systems Innovation, The University of Tokyo, Tokyo, Japan. Since February

2014, he has been an Assistant Professor with the Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Kowloon, Hong Kong. He is also with the Complex Systems Research Center, East China University of Science and Technology, Shanghai, China. He has published 18 refereed technical papers and refereed conference papers, and he also coauthored a book on optimization algorithms. His current research interests are modeling and optimization for resilience engineering of complex networked systems.



**Ashutosh Nayak** received the B.E. degree in industrial engineering from the Indian Institute of Technology, Kharagpur, India, in 2013.

He is currently with the Department of Industrial Engineering and Management, Indian Institute of Technology. His research interest includes supply chain systems.



**M. K. Tiwari** received the B.E. degree from the Visvesvaraya Regional College of Engineering, Nagpur, India; the M.E. degree from the Motilal Nehru Regional Engineering College, Allahabad, India; and the Ph.D. degree from the Jadavpur University, Kolkata, India.

He was a Senior Lecturer with the Department of Mechanical Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli, India, for eight years. In 1998, he joined the Department of Forge Technology, National Institute of Foundry

and Forge Technology, Ranchi, India, where he was an Assistant Professor and then a Professor. He is currently an Associate Professor with the Department of Industrial Engineering and Management, Indian Institute of Technology, Kharagpur, India. He has been working toward collaborative research with several faculty members, working in various universities such as Loughborough University, University of Wisconsin at Madison, University of Missouri–Rolla, Rutgers University, Kansas State University, Bath University, Caledonian Business School, University of Windsor, and The University of Hong Kong. He has been well known for training undergraduate students in several research areas and involving them in meaningful research. Some of his students are working toward doctoral and postdoctoral work in at least ten reputed universities. He has contributed more than 100 articles in various leading international journals of repute and international conferences, including the *European Journal of Operation Research*, the *International Journal of Production Research*, and the *Journal of Engineering Manufacture—Part B*.

Dr. Tiwari is currently the Associate Editor of one international journal and serves as the Editorial Board Member for four other international journals.



**B. Han** received the M.S. degree in biomedical engineering in 2013 from the University of Saskatchewan, Saskatoon, Canada, where he is currently working toward the Ph.D. degree in biomedical engineering.

His research interest includes supply chain scheduling and algorithm design.



**C. L. Liu** received the Ph.D. degree in mechanical engineering from the Northeastern University, Shenyang, China, in 2004.

He is currently an Associate Professor with the Department of Mechanical Engineering, East China University of Science and Technology, Shanghai, China. He has published several refereed technical papers and refereed conference papers. His current research interests include modeling of nonlinear dynamic systems as well as condition monitoring and fault diagnosis of turbine machines.



**W. J. Zhang** received the Ph.D. degree from the Delft University of Technology, Delft, The Netherlands, in 1994.

He is currently a Professor of mechanical engineering with the University of Saskatchewan, Saskatoon, Canada. He is also with the Complex Systems Research Center, East China University of Science and Technology, Shanghai, China. He has published over 320 refereed technical publications, among which 193 papers in refereed journals and over 130 papers in refereed conference proceedings,

in a broad scope of fields, including design and mechatronics, manufacturing, informatics, and human-machine systems. His *h*-index (SCI) is 22 as of November 2013.

Dr. Zhang is a member of the American Society of Mechanical Engineers (ASME), a Senior Member of the Society of Manufacturing Engineers (SME), and a member of The International Society for Optical Engineers (SPIE). He has served as a Technical Editor for IEEE/ASME TRANSACTIONS ON MECHATRONICS and as an Associate Editor for the *International Journal of Systems Science* and *International Journal of Enterprise Information Systems*. He was a recipient of the Outstanding Researcher Award from the College of Engineering, University of Saskatchewan, in 2011 and the Distinguished Graduate Supervisor Award in 2012 from the University of Saskatchewan.