Manage risk of sustainable product-service systems: a case-based operations research approach

Xiaojun Wang[1], Xu Chen[2]*, Christopher Durugbo[3], Ziming Cai[4]

1. School of Economics, Finance and Management, University of Bristol, Bristol, BS8 1TN, UK, Email:xiaojun.wang@bristol.ac.uk

2. School of Management and Economics, University of Electronic Science and Technology of China, Chengdu, 611731, China; Email: xchenxchen@263.net

3. Liverpool Management School, University of Liverpool, Liverpool L69 7ZH, UK, Email: christopher.durugbo@liverpool.ac.uk

4. Nottingham University Business School, University of Nottingham, Nottingham, NG8 1BB, UK, Email: ziming.cai@nottingham.ac.uk

Abstract: Sustainable product-service systems (SusPSSs) offer an innovation-driven approach to production based on providing results or functions with minimal material use and emissions. Networks of SusPSSs partners are central to the decision-making of sustainability policies. Evaluations and assessments of network-oriented risks sources are therefore crucial to informing an industrial firm's reorientation towards SusPSS. Traditionally, these risks beleaguer production and continue to grow in significance with complex production and innovation processes. This article presents a novel operations research application for evaluating network-oriented risks of industrial firms in pursuing SusPSSs. The model conceptualises a framework for network risk metrics and applies a fuzzy-based multi-criteria decision-making technique to evaluate levels of risk associated with reorientations to SusPSS approaches. It takes explicit account of multiple risk sources in aiding decision-making and assists in indicating strategies for improving business sustainability. In addition, it compares and ranks alternative SusPSSs as a system and on an indicator basis, which is a practical and effective decision support tool. A case study of an industrial firm is conducted to verify the effectiveness and applicability of the proposed approach in supporting firms' decision on SusPSSs.

Keywords: Sustainability, Product-service systems, Supply network risks, Multi-criteria decision-making

1. INTRODUCTION

Firms are increasingly acknowledging the importance of adopting sustainability policies and transforming these insights into operations that are environmentally and socially sound. For a start, directives such as the ISO 14000 series of standards have steadily gained acceptance and offered practical guidelines for environmental management systems to minimise negative environmental impacts and continuously improve sustainable production processes (Corbett and Kirsch, 2001; Gerbens-Leenes *et al.*, 2003). These standards draw upon interpretations of sustainability (e.g., Costanza and Patten, 1995) for policy level implementation and have spurred the development of sustainable systems of finance and exchange (Seyfang and Longhurst, 2013). Programmes such as Sustainable Product Development Network (SusProNet), the non-profit Global Reporting Initiative™ and the Environmental Sustainability Index have also offered reporting guidelines and provided data on sustainability performance for increased global awareness of the need for sustainable production. These schemes promote ideas that are based on cleaner production, designs for the environment and eco-design (Roy, 2000; Wang *et al.*, 2015). Nevertheless, global challenges including climate change, increasing population and pollution concerns about the planet Earth's ability of accept industrially generated wastes. As a result, research has intensified in recent years into exploring new ways of delivering quality products and services with efficient usage of resources and energy and minimal waste during production and consumption. A Sustainable Product-Service System (SusPSS) is one of the various sustainability initiatives designed to capture this development.

By definition, a SusPSS, also known as a 'sustainable service' (Heiskanen and Jalas, 2003; Halme *et al.*, 2004) or an 'eco-efficient product-service system' (Manzini and Vezzoli, 2003; Ceschin, 2013), is a Product-Service System (PSS), i.e., an innovation-driven approach to production that shifts business tenets from delivering physical products only to delivering integrated product-service offerings that meet the needs of clients and customers (Durugbo and Riedel, 2013; Rondini *et al.*, 2017). In contrast to other forms of PSSs such as technical PSSs or industrial PSSs (Aurich *et al.*, 2006), a SusPSS focuses on reorienting current unsustainable trends in production and consumption practices (Manzini and Vezzoli, 2003). The SusPSS approach pursues this target through outcomes in the form *stakeholder value*, which researchers often characterise as benefits for consumer/citizen, company and government groups in terms of the Triple Bottom Line, i.e., the environmental, economic and social dimensions of sustainability (Vogtländer *et al.*, 2002; Mont, 2002; Maxwell and Van der Vorst, 2003; Tukker, 2004; Vezzoli *et al.*, 2015). In the SusPSS approach, firms are encouraged to form partnerships with stakeholders to strategize the provision of results or functions and creatively generate ideas that reduce the environmental impact of companies by factors between 4 and 20 (Roy, 2000; Schmidt-Bleek, 2008). Scholars and practitioners widely acknowledged that risks associated with SusPSSs such as service offerings, service costs, eco-efficiency potentials, social factors, interaction strategies, capabilities and partnerships play a key role in how sustainability policies are adopted and how partners are chosen to deliver the sustainable product-service mix (see, for instance, Krucken and Meroni, 2006; Durugbo and Riedel, 2013; Choi *et al.*, 2016). Nevertheless, there has been little consideration in the SusPSS literature on approaches to manage risks of an industrial firm in a SusPSS.

This article proposes a real-case based operations research approach for evaluating network-oriented risk of industrial firms in SusPSSs. Risk is used in this context as "the chance, in quantitative terms, of a defined hazard occurring" (the Royal Society, 1992). Risks are highly random in nature and are caused by different forms of uncertainty existing in the SusPSSs. The research conceptualises a framework for risk evaluation metrics and applies a fuzzy-based operations research technique to evaluate levels of risks associated with reorientations to SusPSS approaches. The research focuses on SusPSS as an avenue for fostering sustainability and offers a multi-criteria decision-making (MCDM) approach to evaluate network-oriented risks for the supply chains of SusPSSs. MCDM approaches are often employed with case studies to provide insights into how the application of proposed approaches can support rational decisions for various business applications (Wang *et al.*, 2015; Kumar *et al.*, 2016; Viriyasitavat, 2016; Teixeira *et al.*, 2018). Apart from providing guidance for future SusPSS strategies, insights from the proposed model can be used to inform planning and control decisions and enhance the formulation of competitive business models that leverage communication and interactions in networks for SusPSS as discussed by authors such as Mont (2002), Briceno and Stagl (2006) and Krucken and Meroni (2006).

In the remainder of this article, we present the theoretical foundations for our research. We then describe our proposed model before applying it in a case study involving a manufacturing firm. We conclude with the theoretical and practical contributions of the research and potential future research directions.

2. THEORETICAL FOUNDATIONS

2.1 Sustainability and product-service systems

Citing international concern for increasing production and consumption patterns, SusPSS advocators have long argued that these value propositions offer a viable avenue for transforming service economics into functional economies (Mont, 2002). Service in this context "may refer to the role of the service sector in the economy, or to a company's offerings to its customers, or to the service (utility) provided by a product" (Heiskanen and Jalas, 2003). In most developed economies (e.g., United States, Germany, United Kingdom and Japan), the service sector contributes most of the employment of the total labour force. In these economies, services are used to reinforce products, and alternative strategies for product use are explored (Mont, 2002, Chen *et al.*, 2012). In contrast, functional economies optimise "the use (or function) of goods and services and thus the management of existing wealth (goods, knowledge, and nature)" (Stahel, 1997). Functional economies treat physical products as capital assets with a view to leveraging value-added services that efficiently use resources and enhance the life of physical products. Consequently, driven by the need to offer insights into how firms can functionally advance economies, SusPSS commentators have argued that the positioning of a SusPSS as a key contributor to sustainability offers a viable route for simultaneously enhancing the competitiveness of producers and minimising the environmental impact of production (Manzini and Vezzoli, 2003; Mont *et al.*, 2006).

Although several classifications for PSS offerings can be found in the literature (Roy, 2000; Mont, 2002; Heiskanen and Jalas, 2003; Halme *et al.*, 2004; Cavalieri and Pezzotta, 2012), the ternary of orientations for achieving PSS value propositions proposed in Tukker (2004) has been the most widely applied. This classification, discussed in Tukker and Tischner (2006) with regard to sustainability potentials, consists of product-, use- and result-orientations of firms. The feasibility of these value propositions is dependent on *business viability* with regard to competitiveness in the market place, *customer satisfaction* that is reliant on customer education and involvement during design processes, and *environmental soundness* that gauges environmentally based superiority over traditional business models (Mont, 2004).

SusPSSs have emphasised end-of-pipe attitudes and dematerialisation strategies to fulfil the needs of customers in more sustainable and life-cycle oriented ways. “End-of-pipe” attitudes focus on reducing post-production pollution and waste (Roy, 2000), and to “dematerialise” production means to reduce material flow in production processes (Mont, 2002) by implementing reuse and remanufacturing techniques and environmentally friendly technologies (Manzini and Vezzoli, 2003). In addition, physical products need to be optimised to lower their environmental impact through design processes such as life-cycle oriented product design, eco-design, Design for Disassembly, Design for Recycling, and the sustainable product and/or service development (SPSD) process (Maxwell and Van der Vorst, 2003; Aurich *et al.*, 2006). These optimised designs result in integrated (or cleaner production) technologies that ecological economists tend to contrast with end-of-pipe technologies (e.g., Belis-Bergouignan *et al.*, 2004).

However, researchers have critiqued the benefits of a SusPSS by highlighting *rebound effects* that offset SusPSS benefits (Manzini and Vezzoli, 2003; Halme *et al.*, 2004) and the awareness that eco-efficient services may not always be preferable compared to products (Mont, 2002). Furthermore, the “real strength” of value propositions is their relevance to customer needs (Tukker and Tischner, 2006), and these needs are shaped by the attitudes of customers and clients towards sustainable production and consumption (Mont, 2002; Briceno and Stagl, 2006). These factors reinforce how adopting a holistic view of sustainable consumption and production is required to evaluate and improve SusPSS characteristics and phenomena, such as environmental waste and systems innovation (Mont, 2004; Ness, 2008; Ceschin, 2013). In this article, current research is enhanced through the introduction of an approach for evaluating network risk.

2.2 Risk management for sustainable product-service systems

Driven by the potential for realising sustainable production and consumption, SusPSSs researchers have focused on evaluating service offerings (Roy, 2000; Mont, 2002; Anttonen, 2010; Hu *et al.*, 2012; Geum and Park, 2011), service costs (Vogtländer *et al.*, 2002), eco-efficiency potentials (Mont, 2002; Heiskanen and Jalas, 2003; Maxwell and Van der Vorst, 2003; Halme *et al.*, 2004; Maxwell *et al.*, 2006; Evans *et al.*, 2007; Lee *et al.*, 2012), social factors (Briceno and Stagl, 2006; Evans *et al.*, 2007; Hu *et al.*, 2012; Lee *et al.*, 2012; Chou *et al.*, 2015), interaction strategies (Mont, 2002; Briceno and Stagl, 2006; Krucken and Meroni, 2006; Evans *et al.*, 2007; Geum and Park, 2011; Rondini *et al.*, 2017), capabilities (Mont, 2004; Hu *et al.*, 2012) and partnerships (Vogtländer *et al.*, 2002; Krucken and Meroni, 2006; Evans *et al.*, 2007) for SusPSSs, as summarised in Table 1.

Table 1: Evaluations of sustainable product-service systems (SusPSSs)

Source	Description	*Approach	Risk factors for networks of SusPSS
Roy (2000)	Conceptualises and evaluates SusPSSs as made up of result services; shared utilisation services; product-life extension services; and demand side management	Conceptual and fundamental	Organisations collaborating to leverage levels of creativity
Mont (2002)	Idealises the motivation, elements and characteristics of SusPSSs	Conceptual and fundamental	Organisational involvement and close cooperation to implement environmental profiles
Vogtländer *et al.*, (2002)	Proposes the Eco-costs/Value Ratio (EVR) model, on the basis of the Life Cycle Analysis (LCA) methodology for assessing the eco-efficiency of SusPSSs	Conceptual and applied	Influence eco-efficiency decisions through stakeholders' participation
Heiskanen and Jalas (2003)	Discusses and evaluates the eco-efficiency of non-material services, result-oriented services, product-based services and service approach facilitated eco-design	Conceptual and applied	Stakeholders' influence on company activities
Manzini and Vezzoli (2003)	Conceptualises a working framework of elements and characteristics to describe the sustainable potentials of product-service systems	Empirical and fundamental	Involvement of stakeholders along value chains throughout product life cycles
Maxwell and Van der Vorst (2003), Maxwell *et al.*, (2006)	Proposes a method to aid in evaluating sustainable criteria during product and service development	Conceptual and applied	The level of control by companies over main life cycle stages
Halme *et al.*, (2004)	Proposes a set of indicators to evaluate sustainability of services directed to households	Conceptual and fundamental	Institutional arrangements of delivering services directed to households
Mont (2004)	Uses a SusPSS framework of products, service, infrastructure networks, business viability, customer satisfaction and environmental trustworthiness in case studies. Combines interviews, survey and literature sources to develop and assess the SusPSS evaluation framework	Empirical and applied	Business-to-consumer relationships to manage unsustainable consumption patterns
Tukker (2004)	Evaluates market and sustainability potentials for product-service offerings using value creation and sustainability models	Conceptual and fundamental	Improve customer loyalty through relationship development with clients
Briceno and Stagl (2006)	Evaluates social and humanistic factors within SusPSS	Conceptual and applied	Relationship building for new shared norms, attitudes and social frameworks that support transitions to more sustainable consumption patterns
Krucken and Meroni (2006)	Proposes a model of interaction and top-down /bottom-up strategies for communication to develop and deliver an SusPSS	Conceptual and applied	Communicative structure for business management and stakeholder empowerment
Evans *et al.*, (2007)	Evaluates environmental, economic and social performance of solution-oriented partnerships	Empirical and applied	Fundamental change in the relationship between stakeholders
Anttonen (2010)	Evaluates the value chains of service providers and uses insights from the evaluation to generate a typology of service profiles	Empirical and fundamental	Supplier-side opportunities in view of changing supplier-customer relationships
Geum and Park (2011)	Evaluates the benefits of the product-service blueprint as an approach to clarify the products and services relationship	Conceptual and applied	Behaviour of actors and spatial relationships within network

Hu *et al.*, (2012)	Proposes a framework for evaluating the economic, environmental and social aspects of SusPSSs for use in decision-making about suitable products and services	Conceptual and applied	Organisational and external factors relating to management capability
Lee *et al.*, (2012)	Evaluates environmental, economic and social dimensions of SusPSSs using systems dynamics	Conceptual and applied	Relationships and communication among stakeholders
Ceschin (2013)	Applies strategic niche management and transition management approaches in evaluating the implementation and diffusion of SusPSSs	Conceptual and applied	Economic, political, social, scientific and cultural linkages within the network of actors for achieving SusPSSs
Chou *et al.*, (2015)	Proposes a concept of sustainable product-service efficiency to explore the relationship between product-service value and the sustainability impact	Conceptual and fundamental	Socio-economic issues for the evaluation of SusPSSs
Mylan (2015)	Applies the sociology of consumption and practice theory to improve the understanding of processes that influence the diffusion and uptake of SPSS	Conceptual and fundamental	Demand-side view of the diffusion of SusPSS innovations
Rondini *et al.*, (2017)	Proposes a hybrid model integrating Discrete Event Simulation with Agent-Based Modelling	Conceptual and applied	Dynamic features of customer behaviours, process requirements and sustainability assessment

*Conceptual studies generate or re-interpret ideas, empirical studies use experience or observation data to draw conclusions, applied studies solve specific problems and fundamental studies generalise to build theories.

Although there is a common theme among scholars on the relevance of networks for SusPSSs, limited insight has been provided into what risks influence the reorientation of an industrial firm to more SusPSS approaches. This is because the majority of studies have focused on SusPSS evaluations to facilitate shifts towards dematerialisation of production and eco-efficiency mainly in terms of service thinking and the development new business models. These studies have also identified relationship and participation factors for creating awareness of sustainability potentials, overcoming barriers to SusPSS adoption and highlighting opportunities for leveraging innovation through SusPSSs. Yet, there is a need for industrial firms to apply a holistic evaluation that identifies network-oriented sources of SusPSS risk and prioritises the perceptions of these risks. Therefore, the current state of the literature necessitates an effective risk evaluation of SusPSSs with potentials for not only enhancing managerial decisions for a firm’s reorientation to more SusPSS approach but also for advancing the overall sustainability agenda.

2.3 A holistic framework for risk evaluation

To ensure a proper risk evaluation of SusPSSs, it is important to apply a holistic view of SusPSSs incorporating engineering characteristics, customer satisfaction and sustainability issues (Xu 2000; Lin *et al.*, 2012; Wang and Durugbo, 2013). Motivated by a holistic approach to evaluate risks of a SusPSS, literature was examined to formulate a framework detailing risk sources. It was for this purpose that a focus on supply chains was adopted. Modern supply chains represent network-oriented approaches to production that link suppliers (producers, processors, marketers and distributors) and customers for four main reasons: (a) to progressively add and accumulate value; (a) to retain competitive advantage; (b) to reduce costs of operations and (c) to improve collaboration and coordination among suppliers and between a supplier and a customer (Cooper *et* *al.*, 1997; Themistocleous *et al.*, 2004; Chen *et al.*, 2017). This is in contrast to traditional, sequential industrial supply chains that are characterised by material flow downstream (supplier to customer) and information flow upstream (customer to supplier), with each division receiving information in sequence. The management of a constant and dynamic flow of information, material, cash, product, process and product/service value is vital to the success of PSSs especially in light of the complexity of roles/relationships and life cycle challenges (Dimitriadis and Koh, 2005; Lockett *et al.*, 2011; Durugbo and Riedel, 2013; Xu, 2015).

Overall, five main network-oriented sources of risks were identified: demand, supply, manufacturing, control and technology, as illustrated in Table 2. Demand risk represents unpredictable variations in the quantity, quality and timing of demand that results in excessive product inventory or loss of opportunities (Davis, 1993; Wang and Durugbo, 2013). Supply risk is triggered by variability and inconsistency by suppliers that lead to delayed, deficient or defective deliveries (Davis, 1993; Wang and Durugbo, 2013). Manufacturing risk is caused by unreliable production processes that result in volatility in process performances (Davis, 1993; Chen and Paulraj, 2004). Control risk refers to unpredictable and unknown variations of system controls within supply networks (Childerhouse and Towill, 2004). Technology risk relates to technology changes within an industry sector and potential technology failures that disrupt business and service outages (Chen and Pulraj, 2004). These widely studied risk sources plague supply chains, business environments and industrial networks (e.g., Davis, 1993; Wang and Durugbo, 2013; Choi *et al.*, 2016), and they serve as a baseline in the framework for industrial partners to evaluate the network-oriented risks for the partner's reorientation to a more SusPSS approach.

Table 2: Measurement items of supply network-oriented risks

Risk sources	Tag	Descriptions	References
C_1 Demand risk	C_{11}	Rate of new product introduction	Davis, 1993; Hoyt and Huq 2000; Prater *et al.*, 2001; Van der Vorst and Beulens,2002; Fynes *et al.*, 2004; Chen and Paulraj, 2004; Ho *et al.*, 2005; Bhatnagar and Sohal, 2005; Paulraj and Chen, 2007; Wang and Durugbo 2013; Wang *et al.*, 2017
	C_{12}	Product demand predictability	
	C_{13}	Number of sales channels	
	C_{14}	Sharing demand forecast with customer	
	C_{15}	Channel heterogeneity	
	C_{16}	Channel replacement frequency	
	C_{17}	Product life cycle	
	C_{18}	Product variety	
	C_{19}	Frequency of change in order content	
C_2 Supply risk	C_{21}	Quality stability of critical material	Davis, 1993; Fynes *et al.*, 2004; Chen and Paulraj, 2004; Ho *et al.*, 2005; Bhatnagar and Sohal 2005; Paulraj and Chen, 2007; Wang and Durugbo 2013; Raddats *et al.*, 2017; Chen and Wang 2016; Wang *et al.*, 2017
	C_{22}	Replacement frequency of critical material supplier	
	C_{23}	Number of critical material suppliers	
	C_{24}	Variance of supply lead time	
	C_{25}	Complexity of critical material	
	C_{26}	Supplier ability to support delivery of new services	
	C_{27}	Time specificity of material procurement	
	C_{28}	Delivery frequency of critical material	
	C_{29}	Impact of on-time delivery	
	C_{20}	Delay of critical material delivery	
C_3 Manufacturing	C_{31}	Impact of pre-process change on post-process	Davis, 1993; Fynes *et al.*, 2004; Chen and Paulraj, 2004; Ho *et al.*, 2005; Bhatnagar and Sohal, 2005;
	C_{32}	Impact of pre-process output on post-process performance	

(and process) risk	C_{33}	Degree to which a product is decomposable to simpler components	Wang and Durugbo 2013; Wang *et al.*, 2017
	C_{34}	Degree of product modularization	
	C_{35}	Redesign frequency	
	C_{36}	Number of changes per redesign	
C_4 Control (and planning) risk	C_{41}	Information accuracy	Mason-Jones and Towill, 1998; Van der Vorst and Beulens, 2002; Childerhouse and Towill, 2004; Baines and Shi 2015; Choi *et al.*, 2016
	C_{42}	Information through-put time	
	C_{43}	Information availability and transparency	
	C_{44}	Organisational change through delivery of new services	
C_5 Technological risk	C_{51}	Rapidness of technology change in industry	Hoyt and Huq 2000; Fynes *et al.*, 2004; Chen and Paulraj, 2004; Koh and Tan, 2006; Paulraj and Chen, 2007; Ziaee Bigdeli, *et al.*, 2018
	C_{52}	Competitiveness by keeping up with technology changes	
	C_{53}	Rate of process obsolescence in industry	
	C_{54}	Complexity of procurement technology for critical materials	
	C_{55}	In-house technological knowledge	

Despite the increased attention on SusPSSs in the literature, few studies have focused on risk management of SusPSSs that support firms' strategic implementation of building a more sustainable product-service system. Furthermore, there is a lack of practical tools that help firms make appropriate decisions in the implementation of SusPSSs. Although various conceptual frameworks/models relating to SusPSSs have been provided, there is a lack of case-based operations research approaches supporting effective and sensible decisions on the adoption of SusPSSs. Therefore, this research aims to fill these gaps by developing a comprehensive framework for risk management of SusPSSs.

3. RESEARCH METHOD

In this study, a decision model made up of two parts, as shown in Figure 1, is proposed. The first part is a holistic framework that identifies network-oriented sources of risk as described in Section 2.3, and the second is a set of operations research approaches that analyses risk level and prioritises SusPSS strategies.

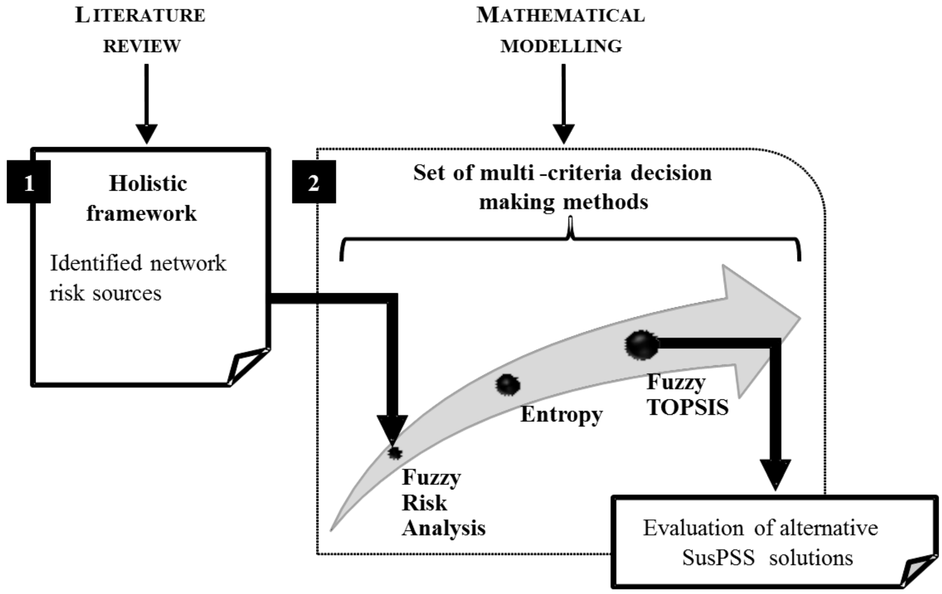

Figure 1 Proposed decision-making model

3.1 Set of operations research methods for risk analysis

Here, an integrated operations research approach combining fuzzy risk assessment, Fuzzy Technique for Order Performance by Similarity to Ideal Solution (Fuzzy TOPSIS), and information entropy is proposed to evaluate risks of SusPSSs. Fuzzy risk assessment is applied to rate the risk level of different items for alternative SusPSSs. Fuzzy set theory is often employed by operational research scholars to deal with uncertainties and subjectivities in risk assessment. Fuzzy risk assessment has the advantage of quantifying imprecise information and incorporating vagueness in the assessment. An increasing number of attempts to explore fuzzy set theory have been undertaken in the risk assessment domain in the last decade, including food safety risk (Davidson *et al.*, 2006), environmental risk (Pan and Chen 2012), and supply chain risk (Wang *et al.*, 2017). It is an effective way to deal with uncertainties inherent in the risk analysis of SusPSSs.

The weights of decision criteria estimated through the entropy theory are integrated with fuzzy TOPSIS to generate a decision index value to rank alternative solutions. Fuzzy TOPSIS evolved from the original TOPSIS technique (Hwang and Yoon, 1981) is then applied for risk evaluation of alternative SusPSSs. The main concept of TOPSIS is to define the positive ideal solution that has the lowest risk level of different risk sources and the negative ideal solution that has the highest risk level of different risk sources (Zhang *et al.*, 2011; Wang and Chan, 2013; Wang *et al.*, 2014). Fuzzy set theory is often incorporated with TOPSIS to deal with the uncertainty and imprecision inherent in the process of mapping the perceptions of experts (Krohling and Campanharo, 2011), and it has been employed in areas such as logistics provider selection (Singh *et al.*, 2018), green supplier selection and order allocation (Govindan and Sivakumar, 2016), and eco product design (Wang *et al.*, 2015). In relationship to this study, Wang and Durugbo (2013) applied fuzzy TOPSIS to evaluate alternative solutions through analysing network uncertainty for industrial product-service delivery. However, the main focus of their research is centred on evaluating the uncertainty of a service network that delivers an industrial product-service system. While focusing on risks management for sustainable product-service systems, this research proposes a more effective and objective weighting method for evaluation criteria.

For most MCDM problems, the weights of the decision criteria are crucial to evaluating alternative solutions. Often weights are determined by key decision-makers. This type of weight calculation methods, e.g., Analytical Hierarchical Process (AHP), is often regarded as subjective weighting (Xu *et al.*, 2003; Chen *et al.*, 2013). Here, a more objective weighting method, information entropy weighting, was employed. Information theory, developed by Shannon (1948), is a measure of how much information is associated with a given state of events. It is concerned with quantification of information, which is also known as entropy approach. This method is particularly useful for assigning a weight to each criterion because it does not require an individual decision-maker to rank the criteria, and the relative weight of each criterion can be obtained using rather simple calculations (Zou *et al.*, 2006; Erol *et al.*, 2011; Zhang *et al.*, 2011).

3.2 Steps for risk analysis

First, a panel of experts is organised for risk assessment of SusPSSs. For each SusPSS proposition, knowledge experts are asked to rate the probability of risk and severity of the consequence with respect to risk items using a range of linguistic expressions, as displayed in Table 3. A score is then denoted as P_{ik} and S_{ik} for the probability and severity ratings of risk item *i* rated by expert *k*, respectively.

Table 3 Linguistic classification of risk grades

Grade	**Linguistic expressions of risk probability (*P*)**	**Linguistic expressions of severity of the consequence (*S*)**
1	Very low	Very minor
2	Low	Minor
3	Medium	Medium
4	High	Severe
5	Very high	Very severe

Based on the risk ratings from the expert panel, a triangular fuzzy number (TFN) is assigned to the probability, $\widetilde{P_i} = (LP_i, MP_i, UP_i)$, and severity, $\widetilde{S_i} = (LS_i, MS_i, US_i)$, of risk items with respect to different SusPSSs. Using the TFN $\widetilde{P_i} = (LP_i, MP_i, UP_i)$ as an example, LP_i indicates the lower bound of probability rating as $LP_i = min(P_{ik})$; UP_i indicates the up bound of probability rating as $UP_i = max(P_{ik})$; and MP_i is the geometric mean of all the experts' risk probability rating for risk item *i*. It can be obtained as:

$$MP_i = (P_{i1}, P_{i2}, \dots, P_{ik})^{\frac{1}{k}} \tag{1}$$

In the same way, the lower bound (LS_i), geometric mean (MS_i), and the up bound (US_i) of TFN for the severity of risk item *i* can be obtained. The two risk factors are then multiplied to determine its risk level. To simplify the calculation, a standard approximation for fuzzy multiplication is used as:

$$\begin{aligned} &A \to \langle a_1, a_2, a_3 \rangle \\ &B \to \langle b_1, b_2, b_3 \rangle \\ &C = A \times B \\ &C \to \langle a_1 b_1, a_2 b_2, a_3 b_3 \rangle \end{aligned} \tag{2}$$

With the TFNs of the probability and severity ratings, the risk level of risk item *i* with respect to SusPSS solution *j* can be calculated individually as:

$$\tilde{R}_{ij} = \tilde{P}_{ij} \times \tilde{S}_{ij} \tag{3}$$

Following the sources of Zhang *et al.* (2011) and Wang *et al.* (2015a), the procedure of the fuzzy TOPSIS method can be described as follows: First, a fuzzy decision matrix, $\widetilde{D}$, is first constructed based on a given set of risk sources and their associated items.

$$\widetilde{D} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{bmatrix} \tilde{R}_{11} & \tilde{R}_{12} & \cdots & \tilde{R}_{1n} \\ \tilde{R}_{21} & \tilde{R}_{22} & \cdots & \tilde{R}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{R}_{m1} & \tilde{R}_{m2} & \cdots & \tilde{R}_{mn} \end{bmatrix} \end{matrix} \tag{4}$$

where $\tilde{R}_{ij}$ is the value of alterative *j* with respect to risk item *i*, which is further represented by TFNs. Then the normalized decision matrix is established, which allows comparison of the various risk items. An element of the normalized decision matrix is calculated as follows:

$$r_{ij} = \frac{\tilde{R}_{ij}}{\sqrt{\sum_{i=1}^{m} \tilde{R}_{ij}^2}} \quad (5)$$

where $1 \leq i \leq n$ for *n* risk items, and $1 \leq j \leq m$ for *m* SusPSS propositions.

In this research, entropy approach is used to calculate the weights of evaluation criteria. The calculation of the entropies is straightforward. According to the decision matrix, we calculated the information entropy of i^{th} criterion, defined as:

$$H_i = -K(\sum_{j=1}^{m} f_{ij} \ln f_{ij}) \quad (6)$$

in which $K = 1/\ln m$ and $i = 1, 2, \cdots, n$. *n* is the number evaluation items and *m* is the number of alternative SusPSS solutions considered in the evaluation. To avoid the insignificance of $\ln f_{ij}$, we stipulated:

$$f_{ij} = \frac{1+R_{ij}}{\sum_{j=1}^{m} R_{ij}} \quad (7)$$

Here, R_{ij} is the defuzzified risk value of $\tilde{R}_{ij}$ using the Centre of Area method given as:

$$R_{ij} = \left[\left(UR_{ij} - LR_{ij}\right) + \left(MR_{ij} - LR_{ij}\right)\right]/3 + LR_{ij} \quad (8)$$

The weight of entropy of i^{th} criterion can then be defined as:

$$w_i = \frac{1-H_i}{n-\sum_{i=1}^{n} H_i} \quad (9)$$

in which $0 \leq w_i \leq 1$, and $\sum_{i=1}^{n} w_i = 1$. This method is particularly useful for assigning a weight to each risk item because it uses rather simple calculations and does not require individual decision-makers to separately rank them for weighting purposes. In other words, decision-makers do not have to collect additional data to calculate the weights.

Now the weighted decision matrix is computed by multiplying the weighting derived from the entropy analysis to the normalized decision matrix as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{j \times j} \quad (10)$$

where $\tilde{v}_{ij} = \tilde{r}_{ij} \times w_i$. Then we calculate the distances from negative and positive ideal solutions. Let A^- and A^+ denote the fuzzy negative ideal solution (FNIS) and fuzzy positive ideal solution (FPIS), respectively. According to the weighted normalized fuzzy-decision matrix, we get:

$$A^+ = (\tilde{v}_1^+, \cdots, \tilde{v}_i^+, \cdots, \tilde{v}_n^+)$$

$$A^- = (\tilde{v}_1^-, \cdots, \tilde{v}_i^-, \cdots, \tilde{v}_n^-) \quad (11)$$

where $\tilde{v}_i^+$ and $\tilde{v}_i^-$ are the fuzzy numbers with the largest and smallest generalized means, respectively. For each column *i*, the largest generalized mean of $\tilde{v}_i^+$ and the smallest generalized mean of $\tilde{v}_i^-$ are derived, respectively. Consequently, the FPIS (A^+) and the FNIS (A^-) are obtained. Then the distances (d^+ and d^-) of each alternative SusPSS from A^+ and A^- can be calculated by the area compensation method as:

$$\tilde{d}_j^+ = \sum_{i=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^+\right)$$

$$\tilde{d}_j^- = \sum_{i=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^-\right) \quad (12)$$

$$d(\tilde{A},\tilde{B}) = \sqrt{\frac{1}{3}[(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2]} \quad (13)$$

Finally, the alternative SusPSSs can be ranked by their relative closeness indexes, which are determined by a combination of the difference distances d^+ and d^- as follows:

$$\theta_j = \frac{\tilde{d}_j^-}{\tilde{d}_j^+ + \tilde{d}_j^-} \quad (14)$$

The set of alternative SusPSSs can then be ranked from the most preferred to the least preferred feasible solutions according to the corresponding index values.

4. CASE STUDY

4.1 Case background

The case organisation is a manufacturing company in south-eastern China. The company produces stainless steel bands as well as stainless-steel consumer products such as kettles and kitchen sinks. The company mainly produces customised stainless steel bands and supplies them to external clients that use stainless steel bands as raw material. The company also manufactures consumer products (e.g., kettles and kitchen sinks) using its own stainless steel as the main raw material. Despite rapid business expansion in the past 10 years, both the stainless-steel production and consumer goods operations are facing tough challenges due to intense competition in both domestic and overseas markets, soaring prices of raw materials, energy and labour, and regulatory requirement of energy use and pollution control. These challenges pose a significant question mark about the sustainability of its business.

In response, the company has made great efforts in the last couple of years to deliver a more sustainable industrial system. For example, in 2012, the company invested over half million US dollars in technologies to replace its diesel-powered annealing furnaces with natural gas furnaces. The change not only reduced the energy bill by 20%, but also significantly decreased its unit carbon emissions. Moreover, the management team was keen to explore new income streams from servitization since such a movement may secure future growth and lead to a more sustainable business. Such a strategic move would require the company to develop new capabilities that offer new services and solutions and supplement their original product offerings. However, similar to the implementation of new changes, the servitization strategies may cause a variety of risks in the wide supply chain network along with their potential benefits. Therefore, it was critical to evaluate and manage the associated risks before any new value propositions are implemented. The proposed operations research enabled decision model was applied to the case company with a view to providing some strategic guidance for its move towards a more SusPSS.

4.2 Data collection

The data collection for the empirical inquiry was carried out in the two stages. An expert panel was assembled that included the managing director, finance director, marketing manager, procurement manager, and three factory managers for stainless-steel production, kettle production, and kitchen sink operation. This selection of panel members is to ensure good understanding of the firm’s overall strategic direction as well as the capabilities and challenges of its main operations. Furthermore, panel members have good knowledge and experience of its supply chain on both the demand and supply sides. A panel discussion was conducted to explore possible SusPSS value propositions. The discussion led to four SusPSS value propositions: intermediate services (e.g., breakdown, repair, and condition monitoring) (A1), shared utilisation services (A2), product-life extension services (A3), and demand-side management (A4) for risk evaluation. The panel members were then asked to rate the probability and severity of risk items with respect to four alternative SusPSSs. For each risk item, the panel members were required to give linguistic classification of the two risk factors. The collected data were used as input for risk evaluation, and the panel was then presented with analysis results. In the second stage, the managing director was interviewed two years after the initial SusPSS risk evaluation to find out what was eventually implemented and how the evaluation helped inform the organisation's decision-making for pursuing a SusPSS.

4.3 Case analysis

The proposed fuzzy methodology was applied to the case organisation to provide some strategic guidance for its transitions to a more SusPSS. First, linguistic risk ratings from expert panel members were used as raw data input for risk evaluation of four alternative SusPSS propositions considered in the case organisation. Through equations (1)-(3), the risk level for all the risk items with respect to alternative SusPSS propositions was derived. As displayed in Table 4, the levels of risks associated to different risk sources varied considerably between various SusPSSs considered in the study. For instance, for shared utilisation services (A_2), the risk level was low for items in the supply risk source, i.e., complexity of critical material (C_{25}) and delivery frequency of critical material (C_{28}), but high for items in the control risk source, i.e., information accuracy (C_{41}) and organisational change through delivery of new services (C_{44}).

The derived risk levels of SusPSS propositions were then used as input for entropy analysis. The normalized weightings for risk items from entropy analysis are also described in Table 4. The risk items with more substantive differences in risk level between alternative SusPSSs were assigned high weighting. In contrast, the risk items with small magnitudes of difference in risk level were assigned low weighting. For instance, rapidness of technology change in industry (C_{51}) was given a much higher weighting compared to complexity of procurement technology for critical material (C_{54}), although the two risk items derived from the same technological risk source. Following the fuzzy TOPSIS procedures outlined in Section 3, the distances from the positive and negative ideal solution (d^+ and d^-) and the relative closeness to the ideal solution (θ_j) were calculated through equations (4)-(14). Table 5 shows the final results.

Table 4 Fuzzy risk assessment and entropy analysis results

Risk sources	Risk items		A_1	A_2	A_3	A_4	Entropy Weighting
C_1 Demand risk	C_{11}	Rate of new product introduction	7.5	5.3	8.8	7.2	0.029
	C_{12}	Product demand predictability	7.5	6.0	8.0	5.1	0.025
	C_{13}	Number of sales channels	7.2	6.2	5.9	5.1	0.011

	C_{14}	Sharing demand forecast with customer	5.9	5.9	7.0	6.0	0.004
	C_{15}	Channel heterogeneity	7.2	4.9	7.7	7.7	0.025
	C_{16}	Channel replacement frequency	5.8	6.3	8.0	7.8	0.017
	C_{17}	Product life cycle	8.6	6.1	5.1	5.7	0.035
	C_{18}	Product variety	8.0	8.1	7.7	5.2	0.025
	C_{19}	Frequency of change in order content	6.9	9.9	6.0	5.9	0.047
C_2 Supply risk	C_{21}	Quality stability of critical material	7.8	4.6	6.7	6.5	0.027
	C_{22}	Replacement frequency of critical material supplier	5.6	5.3	5.2	6.6	0.006
	C_{23}	Number of critical material suppliers	6.7	5.3	5.9	6.9	0.008
	C_{24}	Variance of supply lead time	3.2	5.2	6.1	6.6	0.037
	C_{25}	Complexity of critical material	5.3	3.5	8.8	6.9	0.077
	C_{26}	Supplier ability to support delivery of new services	3.6	4.3	3.1	4.9	0.012
	C_{27}	Time specificity of material procurement	3.8	5.9	6.1	5.7	0.018
	C_{28}	Delivery frequency of critical material	3.3	4.1	5.9	3.6	0.025
	C_{29}	Impact of on-time delivery	7.4	7.1	5.2	7.8	0.019
	C_{20}	Delay of critical material delivery	7.2	5.4	6.2	6.0	0.009
C_3 Manufacturing (and process) risk	C_{31}	Impact of pre-process change on post-process	6.0	6.1	4.1	7.3	0.027
	C_{32}	Impact of pre-process output on post-process performance	6.2	5.3	5.3	8.9	0.043
	C_{33}	Degree of a product decomposable to simpler components	6.1	5.9	8.9	6.9	0.025
	C_{34}	Degree of product modularization	4.5	5.9	8.6	6.5	0.042
	C_{35}	Redesign frequency	6.6	7.3	5.1	6.1	0.013
	C_{36}	Number of changes per redesign	6.2	7.3	7.3	6.0	0.007
C_4 Control (and planning) risk	C_{41}	Information accuracy	6.7	8.7	6.6	11.7	0.069
	C_{42}	Information through-put time	6.6	5.6	7.5	4.1	0.033
	C_{43}	Information availability and transparency	5.9	6.2	4.9	6.0	0.006
	C_{44}	Organisational change through delivery of new services.	8.1	10.1	4.7	8.9	0.068
C_5 Technological risk	C_{51}	Rapidness of technology change in industry	7.8	3.2	6.0	8.7	0.088
	C_{52}	Competitiveness by keeping up with technology changes	5.9	5.0	5.9	8.9	0.042
	C_{53}	Rate of process obsolescence in industry	8.1	5.7	4.0	7.0	0.047
	C_{54}	Complexity of procurement technology for critical material	5.9	5.2	5.9	5.8	0.002
	C_{55}	In-house technological knowledge	8.1	7.1	4.8	7.8	0.031

Table 5 Holistic calculation results from entropy analysis and fuzzy TOPSIS

Propositions	d^+	d^-	**Θ**	**Rank**
A_1: intermediate services	0.066	0.081	0.553	2
A_2: shared utilisation services	0.040	0.104	0.722	1
A_3: product-life extension services	0.086	0.101	0.541	3
A_4: demand-side management	0.117	0.057	0.326	4

The findings in Table 5 give a clear indication of which SusPSS value propositions the company should focus on to deliver a sustainable product-service system. In this case, shared utilisation services (A_2) top the ranking list and should be recommended. Spare capacity in the key production processes usually results in enormous waste, which has a negative impact on the firm's economic and environmental dimensions Triple Bottom Line. Consequently, to maintain business viability, shared utilisation services appealed most to the management team. The indication from follow-up discussions with the participants was that this option had more potential but less network-oriented risks compared to other SusPSS propositions. It was also noticed that similar relative closeness indexes were obtained for SusPSS propositions such as intermediate services (A_1) and product-life extension services (A_3), although one proposition may be more exposed to specific network-oriented risks than the other. It is due to the fact that these indexes take into consideration all the sources and levels of risk that each SusPSS proposition was rated. Such analysis is useful for choosing the most suitable strategy for the organisation to improve sustainability performance and enhance supply chain resilience.

4.4 Follow-up interview

Two years after the initial risk evaluation of alternative SusPSSs, an interview was conducted with the managing director who was involved in the original risk evaluation. The main purpose for the interview was to find out what was eventually implemented since then and how the risk evaluation of SusPSS propositions helped the company make strategic decision on SusPSSs. The company did move ahead with shared utilisation services as that was regarded as the most viable SusPSS solution to generate new income streams through a service-oriented business model. The managing director also acknowledged that although the decision was not a direct response to the initial risk evaluation of the alternative SusPSSs, the evaluation exercise had certainly contributed to their decision. More importantly, from a practical point of view, the network-oriented risk metrics and the MCDM methods enabled them to understand the risks associated with SusPSSs in a systematic and holistic way. The evaluation helped them be proactive in mitigating and managing risks in the implementation of SusPSSs.

Furthermore, the implementation of any new business strategy requires firms to carefully assess the costs and benefits. The same rule applies to those manufacturing firms pursuing SusPSSs. The risk evaluation of SusPSSs was conducted in an effective and efficient manner that does not demand extensive resources and time. With the input from managers, who have good understanding and knowledge about the company's internal operations and external relationships with supply chain partners, the evaluation provided useful insights into the exposed risks with respect to various SusPSS options. Comparison of these options developed the firm's capability of foreseeing and responding to potential network risks and enabled managers to make important strategic and tactical decisions on SusPSSs.

5. DISCUSSION AND CONCLUSIONS

With the increasing emphasis on end-of-pipe attitudes, dematerialisation strategies and optimised designs, it is important that industrial firms have effective management tools for understanding and analysing risks associated with delivering sustainable product-service systems (SusPSSs). However, network-oriented risk is a complex subject involving vagueness and ambiguity in decision-making. With this in mind, this article presents a case based operations research approach that supports the reorientation of industrial firms towards more SusPSSs by performing a structured analysis of network-oriented risks and evaluating different SusPSS value propositions. The proposed decision model includes two elements: (1) an outline of a network-oriented risk matrix derived from the literature and (2) a set of operations research approaches that assess risks using fuzzy risk assessment, calculate the importance weights of risk items using entropy analysis, and evaluate alternative SusPSS solutions using Fuzzy TOPSIS technique. There are several reasons that the proposed methods can be employed by the industrial organisations that want to explore SusPSSs. First, it provides a critical assessment of a combination of operations research approaches to evaluate SusPSS value propositions. Second, it seeks to take explicit account of multiple risk sources in aiding decision-making and assists in identifying strategies for improving business sustainability. Third, it compares and ranks alternative SusPSS value propositions as a system and on an indicator basis, which is a practical and effective decision support tool. Finally, via a real case of an industrial firm, the research offers useful insights into how the application of the proposed methodology can support rational decision-making processes to adopt the SusPSS approach.

This research makes three key contributions. First, it provides a review of existing approaches to the evaluation of SusPSS and the main relationship/organisational factors that cause risks for a SusPSS. Generally, these risks plague decision-making associated with service offerings, service costs, eco-efficiency potentials, social factors, interaction strategies, capabilities and partnerships. Second, it delineates criteria for evaluating the network-oriented levels of risk associated with reorientations to SusPSS approaches based on a holistic network view of SusPSS as supply chains. The main innovation about the measurement items of supply network-oriented risks is that these risks beleaguer production and continue to grow in significance with complex production and innovation processes, and evaluations and assessments of network-oriented risks are therefore crucial to inform an industrial firm's reorientation towards SusPSS. In addition to conventional supply, demand, and process related risks used in supply chain risk management (Pan and Chen 2012; Wang et al. 2017), our case analysis also demonstrates the importance of incorporating other dimensions (e.g. control and technological risks) in the evaluation. Third, there is a lack of case-based operations research approaches supporting effective and sensible decisions on the adoption of SusPSSs (Wang and Durugbo 2013; Baines and Shi 2015). This research fills the gap by proposing an effective decision model that integrates a holistic risk evaluation framework and practical modelling approaches including fuzzy risk assessment, entropy and Fuzzy TOPSIS for evaluating network-oriented risks of reorientations to more SusPSS. The research demonstrates that a case-based operations research approach and specific insights derived from our findings contribute to the SusPSS debate, highlighting factors and mechanisms that can make SusPSSs successful.

This research also provides important managerial implications. Competing through services is a critically important for many industrial firms in the future competition. However, the uncertainties embedded in the complex and unpredictable wide economic environment will have a significant impact on how the services-oriented business model can be more effectively harnessed. Similar to the implementation of any new business strategies, industrial firms have to evaluate benefits and risks before committing investments to SusPSSs. Although SusPSSs are critical for many industrial firms to achieve sustainability objectives, firms have to cautiously assess potential benefits and risks involved in their strategic move on SusPSSs. Firms are more likely to invest in strategies that can bring economic growth and service improvement without compromising social and environmental performances. It is essential to foresee and respond to potential risks associated with wide supply networks. One main benefit of implementing the proposed case-based operations research approach is that it provides a more holistic view of risks associated with SusPSSs and enables firms to more pro-actively assess and manage the risks and support their strategic decisions on SusPSSs. Nevertheless, the expert panel members' knowledge of the company and wide supply network is important for the insights' reliability of the proposed operations research approaches. Therefore, it is vitally important to assemble an expert panel that has good knowledge and understanding of firms' operations and the wide supply network contexts. While ensuring effective communication in the decision making process and fully utilization of knowledge from the expert panel, such an evaluation could provide valuable insights into the exposed risks of available SusPSSs, leading to key strategic recommendations for achieving sustainability objectives.

Despite the contribution outlined above, the present approach has its own limitations with potential directions for future research. For example, all the network-oriented risk sources and their associated items have to be accounted for and accumulated in the evaluation. In addition, users have to rate different risk items using linguistic expressions. The functionality of the methodology also depends highly on the knowledge, expertise and communication skills of the users. One future research option could be to consider data-driven techniques that use available transactional data from firms (Wang *et al.*, 2015b). In addition, the SusPSS approach, with its focus on end-of-pipe attitudes and dematerialisation strategies driven by a sustainability agenda, is geared towards the realisation of functional economies. This agenda offers potential for the realisation of functional economies that fosters energy efficiencies and minimal waste as well as nature and environmentally friendly policies. There is therefore a need for studies that leverage a holistic view of production to shed light on sustainable values that are progressively created or destroyed and potential variations in the sources, levels and perceptions of risks during this process of resource acquisition. Such studies may enhance strategic decision-making of firms for sustainability policies. Potential future research could also examine the formation and evolution of partnerships for SusPSS based on themes such as value systems, co-creation and leadership.

ACKNOWLEDGMENTS

This research is partially supported by the National Natural Science Foundation of China (Nos. 71272128, 71432003, 91646109).

REFERENCES

Anttonen, M. (2010). Greening from the front to the back door? A typology of chemical and resource management services. *Business Strategy and the Environment*, 19 (3), 199-215.

Aurich, J. C., Fuchs, C., & Wagenknecht, C. (2006). Life cycle oriented design of technical Product-Service Systems. *Journal of Cleaner Production*, 14 (17), 1480-1494.

Baines, T., & Shi, V.G. (2015). A Delphi study to explore the adoption of servitization in UK companies. *Production Planning & Control*, 26(14-15), 1171-1187.

Belis-Bergouignan, M. C., Oltra, V., & Saint Jean, M. (2004). Trajectories towards clean technology: example of volatile organic compound emission reductions. *Ecological Economics*, 48(2), 201-220.

Bhatnagar, R., & Sohal, A.S. (2005). Supply chain competitiveness: Measuring the impact of location factors, uncertainty and manufacturing practices. *Technovation*, 25(5), 443-456.

Briceno, T., & Stagl, S. (2006). The role of social processes for sustainable consumption. *Journal of Cleaner Production*, 14 (17), 1541-1551.

Cavalieri, S., & Pezzotta, G. (2012). Product–Service Systems Engineering: State of the art and research challenges. *Computers in Industry*, 63(4), 278-288.

Ceschin, F. (2013). Critical factors for implementing and diffusing sustainable product-Service systems: insights from innovation studies and companies' experiences. *Journal of Cleaner Production*, 45, 74-88.

Chan, H.K., Wang, X, White, G., & Yip. N. (2013) An extent fuzzy-AHP approach for the evaluation of green products design, *IEEE Transactions on Engineering management*, 60(2), 327-339

Chen, I.J., & Paulraj, A. (2004). Towards a theory of supply chain management: the constructs and measurements. *Journal of Operations Management*, 22(2), 119-150.

Chen X., Li, L., & Zhou, M. (2012). Manufacturer's pricing strategy for supply chain with warranty period-dependent demand. *OMEGA-International Journal of Management Science*, 40(12): 807-816.

Chen, X., & Wang, X. (2016). Effects of carbon emission reduction policies on transportation mode selections with stochastic demand. *Transportation Research Part E: Logistics and Transportation Review*, 90, 196-205.

Chen, X., Wang, X., & Chan, H.K. (2017). Manufacturer and retailer coordination for environmental and economic competitiveness: A power perspective. *Transportation Research Part E: Logistics and Transportation Review*, 97, 268-281.

Childerhouse, P., & Towill, D.R. (2004). Reducing uncertainty in European supply chains. *Journal of Manufacturing Technology Management*, 15(7), 585-598.

Choi, T.M., Wang, M., & Yue, X. (2016). Emerging production optimization issues in supply chain systems. *Annals of operations research*, 240(2), 381-393.

Chou, C.J., Chen, C.W., & Conley, C. (2015). An approach to assessing sustainable product-service systems. Journal of Cleaner Production, 86, 277-284.

Cooper, M. C., Lambert, D. M., & Pagh, J. D. (1997). Supply chain management: more than a new name for logistics. *International Journal of Logistics Management*, 8(1), 1-14.

Corbett, C.J., & Kirsch, D.A. (2001). International dispersion of ISO 14000 certifications. *Production and Operations Management*, 10 (3), 327-342.

Costanza, R., & Patten, B. C. (1995). Defining and predicting sustainability. *Ecological Economics*, 15(3), 193-196.

Davis, T. (1993). Effective supply chain management. *Sloan Management Review*, 34(4), 35-46.

Davidson, V.J., Ryks, J., & Fazil, A. (2006). Fuzzy risk assessment tool for microbial hazards in food system, *Fuzzy Sets and Systems*, 157, 1201-1210.

Dimitriadis, N. I., & Koh, S. C. L. (2005). Information flow and supply chain management in local production networks: the role of people and information systems. *Production Planning and Control*, 16 (6), 545-554.

Durugbo C., & Riedel J. (2013). Readiness assessment of collaborative networked organisations for integrated product and service delivery. *International Journal of Production Research*, 51 (2), 598-613

Erol, I., Sencer, S., & Sari, R. (2011) A new fuzzy multi-criteria framework for measuring sustainability performance of a supply chain, *Ecological Economics*, 70, 1088-1100.

Evans, S., Partidário, P.J., & Lambert, J. (2007). Industrialization as a key element of sustainable product-service solutions. *International Journal of Production Research*, 45 (18-19), 4225-4246.

Fynes, B., de Búrca, S., & Marshall, D. (2004). Environmental uncertainty, supply chain relationship quality and performance. *Journal of Purchasing and Supply Management*, 10 (4-5), 179-190.

Gerbens-Leenes, P. W., Moll, H. C., & Schoot Uiterkamp, A. J. M. (2003). Design and development of a measuring method for environmental sustainability in food production systems. *Ecological Economics*, 46(2), 231-248.

Geum, Y., & Park, Y. (2011). Designing the sustainable product-service integration: A product-service blueprint approach. *Journal of Cleaner Production*, 19 (14), 1601-1614.

Govindan, K., & Sivakumar, R. (2016). Green supplier selection and order allocation in a low-carbon paper industry: integrated multi-criteria heterogeneous decision-making and multi-objective linear programming approaches. *Annals of Operations Research*, 238(1-2), 243-276.

Halme, M., Jasch, C., & Scharp, M. (2004). Sustainable homeservices? Toward household services that enhance ecological, social and economic sustainability. *Ecological Economics*, 51 (1-2), 125-138.

Heiskanen, E., & Jalas, M. (2003). Can services lead to radical eco-efficiency improvements? - A review of the debate and evidence. *Corporate Social Responsibility and Environmental Management*, 10 (4), 186-198.

Ho, C.F., Chi, Y.P., & Tai, Y.M. (2005). A structural approach to measuring uncertainty in supply chains. *International Journal of Electronic Commerce*, 9 (3), 91-114.

Hoyt, J., & Huq, F. (2000). From arm's-length to collaborative relationships in the supply chain. *International Journal of Physical Distribution & Logistics Management*, 30(9), 750-764.

Hu, H.A., Chen, S.H., Hsu, C.W., Wang, C., & Wu, C.L. (2012). Development of sustainability evaluation model for implementing product service systems. *International Journal of Environmental Science and Technology*, 9 (2), 343-354.

Hwang, C. L., & Yoon, K. (1981). Multiple attributes decision making methods and applications. Berlin: Springer.

Krohling, R. A., & Campanharo, V. C. (2011). Fuzzy TOPSIS for group decision making: A case study for accidents with oil spill in the sea. *Expert Systems with Applications*, 38(4), 4190-4197.

Krucken, L., & Meroni, A. (2006). Building stakeholder networks to develop and deliver product-service-systems: practical experiences on elaborating pro-active materials for communication. *Journal of Cleaner Production*, 14 (17), 1502-1508.

Kumar, P., Singh, R.K., & Sinha, P. (2016). Optimal site selection for a hospital using a fuzzy extended ELECTRE approach. *Journal of Management Analytics*, 3(2), 115-135.

Lee, S., Geum, Y., Lee, H., & Park, Y. (2012). Dynamic and multidimensional measurement of product-service system (PSS) sustainability: A triple bottom line (TBL)-based system dynamics approach. *Journal of Cleaner Production*, 32, 173-182.

Lin, Y., Duan, X., Zhao, C., & Xu, L. (2012). Systems science: methodological approaches. Boca Raton, FL, USA: CRC Press, 2012.

Lockett, H., Johnson, M., Evans, S., & Bastl, M. (2011). Product Service Systems and supply network relationships: An exploratory case study. *Journal of Manufacturing Technology Management*, 22 (3), 293-313.

Manzini, E., & Vezzoli, C. (2003). A strategic design approach to develop sustainable product service systems: Examples taken from the 'environmentally friendly innovation' Italian prize. *Journal of Cleaner Production*, 11, 851-857.

Mason-Jones, R., & Towill, D.R. (1998). Shrinking the supply chain uncertainty circle. Control, 24(7), 17-22.

Maxwell, D., & Van der Vorst, R. (2003). Developing sustainable products and services. *Journal of Cleaner Production*, 11, 883-895.

Maxwell, D., Sheate, W., & Van der Vorst, R. (2006). Functional and systems aspects of the sustainable product and service development approach for industry. *Journal of Cleaner Production*, 14 (17), 1466-1479.

Mont, O. (2002). Clarifying the concept of product-service system. *Journal of Cleaner Production*, 10 (3), 237-245.

Mont, O. (2004). Institutionalisation of sustainable consumption patterns based on shared use. *Ecological Economics*, 50 (1-2), 135-153.

Mylan, J. (2015). Understanding the diffusion of Sustainable Product-Service Systems: Insights from the sociology of consumption and practice theory. *Journal of Cleaner Production*, 97, 13-20.

Ness, D. (2008). Sustainable urban infrastructure in China: Towards a Factor 10 improvement in resource productivity through integrated infrastructure systems. *International Journal of Sustainable Development and World Ecology*, 15 (4), 288-301.

Pan, J. N., & Chen, S. C. (2012). A new approach for assessing the correlated risk. *Industrial Management & Data Systems*, 112(9), 1348-1365.

Paulraj, A., & Chen, I. J. (2007). Environmental uncertainty and strategic supply management: A resource dependence perspective and performance implications. *Journal of Supply Chain Management*, 43(3), 29-42.

Prater, E., Biehl, M., & Smith, M. A. (2001). International supply chain agility: tradeoffs between flexibility and uncertainty. *International Journal of Operations and Production Management*, 21(5-6), 823-839.

Raddats, C., Zolkiewski, J., Story, V.M., Burton, J., Baines, T., & Ziaee Bigdeli, A. (2017). Interactively developed capabilities: evidence from dyadic servitization relationships. *International Journal of Operations & Production Management*, 37(3), 382-400.

Roy, R. (2000). Sustainable product-service systems. *Futures*, 32 (3-4), 289-299.

Rondini, A., Tornese, F., Gnoni, M.G., Pezzotta, G., & Pinto, R. (2017). Hybrid simulation modelling as a supporting tool for sustainable product service systems: a critical analysis. *International Journal of Production Research*, 55(23), 6932-6945.

Schmidt-Bleek, F. (2008). Factor 10: The future of stuff. *Sustainability: Science, Practice, & Policy*, 4(1), 1-4.

Seyfang, G., & Longhurst, N. (2013). Growing green money? Mapping community currencies for sustainable development. *Ecological Economics*, 86, 65-77.

Shannon, C.E. (1948). A mathematical theory of communication. Bell System Technical Journal, 27, 379-423

Singh, R.K., Gunasekaran, A., & Kumar, P. (2018). Third party logistics (3PL) selection for cold chain management: a fuzzy AHP and fuzzy TOPSIS approach. *Annals of Operations Research*, 267(1-2), 531-553.

Stahel, W.R. (1997). The functional economy: cultural and organisational change. From the industrial green game: implications for environmental design and management. Washington (DC): National Academy Press, 91-100

Teixeira, C., Lopes, I., & Figueiredo, M. (2018). Classification methodology for spare parts management combining maintenance and logistics perspectives. *Journal of Management Analytics*, 5(2), 116-135.

The Royal Society. (1992). Analysis, Perception and Management. London: The Royal Society.

Themistocleous, M., Irani, Z., & Love, P. E. D. (2004). Evaluating the integration of supply chain information systems: A case study. *European Journal of Operational Research*, 159, 393-405.

Tukker, A. (2004). Eight types of product-service system: Eight ways to sustainability? Experiences from suspronet. *Business Strategy and the Environment*, 13 (4), 246-260.

Tukker, A., & Tischner, U. (2006). Product-services as a research field: past, present and future. Reflections from a decade of research. *Journal of Cleaner Production*, 14 (17), 1552-1556.

Van der Vorst, J. G.A.J., Beulens, A.J., Wit, W.D., & Beek, P.V. (1998). Supply chain management in food chains: improving performance by reducing uncertainty. *International Transactions in Operational Research*, 5(6), 487-499.

Van der Vorst, J., & Beulens, A. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies. *International Journal of Physical Distribution & Logistics Management*, 32(6), 409-30.

Vezzoli, C., Ceschin, F., Diehl, J. C., & Kohtala, C. (2015). New design challenges to widely implement 'Sustainable Product–Service Systems'. *Journal of Cleaner Production*, 97, 1-12.

Viriyasitavat, W. (2016). Multi-criteria selection for services selection in service workflow. *Journal of Industrial Information Integration*, 1, 20-25.

Vogtländer, J. G., Bijma, A., & Brezet, H. C. (2002). Communicating the eco-efficiency of products and services by means of the eco-costs/value model. *Journal of Cleaner Production*, 10 (1), 57-67.

Wang, X., & Chan, H. K. (2013). A hierarchical fuzzy TOPSIS approach to assess improvement areas when implementing green supply chain initiatives. *International Journal of Production Research*, 51(10), 3117-3130.

Wang, X., & Durugbo, C. (2013). Analysing network uncertainty for industrial product-service delivery: A hybrid fuzzy approach. *Expert Systems with Applications*, 40(11), 4621-4636.

Wang, X, Chan, H.K., & Li, D. (2015). A case study of integrated fuzzy methodology for green product development. *European Journal of Operational Research*, 241, 212-223

Wang, X., White, L., & Chen, X. (2015). Big data research for the knowledge economy: past, present, and future. *Industrial Management & Data Systems*, 115(9): 1566-1576.

Wang, X., Tiwari, P., & Chen, X. (2017). Communicating supply chain risks and mitigation strategies: a comprehensive framework. *Production Planning & Control*, 28(13), 1023-1036.

Wang, Y., Ji, W., & Chaudhry, S. S. (2014). A hybrid approach for the evaluation of supermarket food safety. *Journal of Management Analytics*, 1(2), 156-167.

Xu, L. (2000). The contribution of systems science to information systems research. *Systems Research and Behavioural Science*, 17(2), 105-116.

Xu, L. (2015). Enterprise integration and information architecture: a systems perspective on industrial information integration. CRC Press, Taylor & Francis Group, New York

Xu, S., Xu, L., & Chen, X. (2003). Determining optimum edible films for kiwifruits using an analytical hierarchy process. *Computers & Operations Research*, 30(6), 877-886.

Zhang, H., Gu, C. L., Gu, L. W., & Zhang, Y. (2011). The evaluation of tourism destination competitiveness by TOPSIS & information entropy–A case in the Yangtze River Delta of China. *Tourism Management*, 32(2), 443-451.

Ziaee Bigdeli, A., Bustinza, O.F., Vendrell-Herrero, F., & Baines, T. (2018). Network positioning and risk perception in servitization: evidence from the UK road transport industry. *International Journal of Production Research*, 56(6), 2169-2183.

Zou, Z., Yun, Y., & Sun, J. (2006). Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. *Journal of Environmental Sciences*, 18(5), 1020-1023.