Int. J. Production Economics 145 (2013) 253–262

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Reducing schedule instability by identifying and omitting complexity-adding information flows at the supplier–customer interface ☆

Suja Sivadasan [a], Janet Smart [b], Luisa Huaccho Huatuco [c,*], Anisoara Calinescu [d]

[a] Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK
[b] Saïd Business School, University of Oxford, Park End Street, Oxford OX1 1HP, UK
[c] Leeds University Business School, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK
[d] Department of Computer Science, University of Oxford, Wolfson Building, Parks Road, Oxford OX1 3QD, UK

ARTICLE INFO

Article history:
Received 1 July 2011
Accepted 26 April 2013
Available online 15 May 2013

Keywords:
Schedule instability
Supplier–customer interface
Information flows
Entropy
Operational complexity
Case studies

ABSTRACT

Within the supply chain context, schedule instability is caused by revisions to forecast demand from customers, problems with scheduled deliveries from suppliers, and disruptions to internal production. Supply chain partners attempt to address schedule instability by regular exchanges of information flows on current demand and delivery forecasts. However, if these updating information flows are unreliable and likely to be over-ridden by subsequent updated schedules, then the problem of schedule instability at the supplier–customer interface is not being solved. The research hypothesis investigated in this paper is whether supply chain partners may reduce schedule instability at the supplier–customer interface by identifying and omitting complexity-adding information flows. To this aim, previous work by the authors on an information-theoretic methodology for measuring complexity is extended and applied in this paper for identifying complexity-adding information flows. The application consists of comparing the complexity index of actual exchanged information flows with the complexity index of scenarios that omit one or more of these information flows. Using empirical results, it is shown that supply chain partners may reduce schedule instability at the supplier–customer interface by identifying and omitting complexity-adding information flows. The applied methodology is independent of the information systems used by the supplier and customer, and it provides an objective, integrative measure of schedule instability at the supplier–customer interface. Two case studies are presented, one in the commodity production environment of fast-moving consumer goods, and another in the customised production environment of electronic products sector. By applying the measurement and analysis methodology, relevant schedule instability-related insights about the specific case-studies are obtained. In light of the findings from these case studies, areas for further research and validation of the conditions in which the proposed research hypothesis holds are also proposed.

1. Introduction

The purpose of this paper is to present a novel application of an information-theoretic methodology to assess to what extent schedule instability at the supplier–customer interface can be reduced by identifying and omitting complexity-adding information flows. Complexity-adding information flows in this paper refer to the draft schedules that are not accurate predictors of the actual final production schedules. Therefore, to keep up with the changes the draft schedules recommend would add unnecessary (i.e. non-value-adding) complexity to an organisation's operations.

The contribution of this paper is three-fold. First, the paper considers the research hypothesis, "by omitting some intermediate versions of the schedule (information flows), supply chain partners can reduce their schedule instability". Second, to investigate this hypothesis, we extend and apply an information-theoretic, information system-independent methodology to identifying complexity-adding information flows at the supplier–customer interface, across two case-studies. Having identified complexity-adding information flows, this paper shows that schedule instability in the supplier–customer interface may be reduced by omitting complexity-adding information flows. This novel application provides quantifiable guidance on the effects of removing information

* Corresponding author. Tel.: +44 113 343 6821; fax: +44 113 343 4885.
E-mail addresses: suja_sivadasan@yahoo.co.uk (S. Sivadasan), Janet.Smart@sbs.ox.ac.uk (J. Smart), lh2@lubs.leeds.ac.uk (L. Huaccho Huatuco), Ani.Calinescu@comlab.ox.ac.uk (A. Calinescu).

0925-5273/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ijpe.2013.04.043

flows across the supplier–customer interface. Third, this paper presents empirical case study data from real-world manufacturing supplier–customer interfaces, within the schedule instability context. So, the application of this methodology is grounded in practice and the insights and recommendations emanating from the analysis are directly relevant to the participating organisations. Two case studies are presented in this paper, one in the commodity production environment and another in the customised production environment. By using real-world industrial case studies, this research contributes to the currently limited body of empirical research that exists in the study of supplier–customer information exchange and schedule instability. As Huang et al. (2003, page 1510) stated: "the empirical approach has not been widely used in the literature to find out the perceived benefits and difficulties [of supplier–customer sharing information] from the point of view of industrialists". More recently, Pujawan and Smart (2012) concluded that the main perceived causes of schedule instability are external to the manufacturing organisation (at the supplier–customer interface), and called for more empirical studies on schedule instability to be carried out within the supply chain context.

Typical research methodologies used to investigate schedule instability as evidenced in the literature (Mula et al., 2006) are computer simulations (e.g. Rodriguez-Verjan and Montoya-Torres, 2009; Narayanan and Robinson, 2010; van Donselaar and Gubbels, 2002; Sahin and Robinson, 2005) and analytical models (e.g. Cachon and Fisher, 2000; Lee et al., 2000; van der Sluis, 1993). The use of real-world empirical case study data in this research is a valuable contribution to investigating schedule instability and supplier–customer information exchange.

The structure of the paper is as follows. Section 2 presents the background and literature review of the research, Section 3 outlines the operational complexity methodology, Section 4 applies the methodology to measuring schedule instability at the supplier–customer interface, Section 5 presents two case studies, Section 6 discusses the results and Section 7 ends the paper with some concluding remarks, limitations and future research.

2. Background and literature review

Organisations seek to integrate their supply chains by frequent information exchanges with their supply chain partners, so that each party is aware of changes and revisions to the planned delivery of products, in terms of scheduled due date and quantity. However, although this open and honest exchange of information may lead to greater transparency, awareness and coordination between suppliers and customers (Arshinder and Deshmukh, 2008; Lamming et al., 2001; Martinez-Olvera, 2008), it also carries costs. These costs include the information management costs of gathering, formatting, recording, maintaining and transmitting the information, and the installation and running costs of the IT system that supports these activities (Sahin and Robinson, 2002; Gattiker and Goodhue, 2004; Kelle and Akbulut, 2005; Wu et al., 2007; Bartezzaghi and Verganti, 1995; Ackoff, 1967). The organisation that receives these information flows must also decide how to react to them (giving rise to more costs associated with recording, possibly re-formatting the information, and revising production and, possibly, delivery schedules for other customers) in order to accommodate the changes that have been requested.

It is worth mentioning that the information flows discussed in this paper are those that are formally agreed to be exchanged between the customer and the supplier *a priori* (e.g. Purchase Order). Therefore, other forms of information flows, such as informal communications, are not covered in this research.

The organisation that receives several versions of these formal information flows could be either the supplier or the customer, and the product to be delivered could be a commodity item (mass produced good), or a specialised product (customised product). Regardless of whether they are the supplier or customer, the receiving organisation has to decide whether and how to respond to the revised plan or schedule.

Many authors have considered the problem of schedule instability and system nervousness (e.g. Pujawan, 2004; Pujawan and Smart, 2012; Koh, 2004; van Donselaar and Gubbels, 2002; van der Sluis, 1993; Blackburn et al., 1985). Here an application of an information-theoretic methodology for assessing the schedule instability is presented, by identifying information flows which can be complexity-adding at supplier–customer interfaces. Thus, this paper extends the authors' previous work on the operational complexity of manufacturing systems (Calinescu et al., 2001; Sivadasan et al., 2002, 2004, 2006, 2010) to assess and provide insights into the measurement and management of schedule instability at supplier–customer interfaces.

2.1. Supplier–customer interface

All supply chains consist of organisations that are linked by information and material flows. However, these links define the dependencies between individual organisations vs. overall supply chain constraints and objectives. Decision-making, i.e. acting on information and material flows (Calinescu et al., 2001; Huchzermeier and Loch, 2001; Sahin and Robinson, 2002) plays a key role here.

Organisational units may be modelled as material and information processing units with three basic characteristics of supply, transformation and demand (Christopher, 2005; Davis, 1993). The primary links between the organisational units include the one-way flow of material from the supplier to the customer and the two-way exchange of information between them. Secondary links may include the reverse flow of material and the consequent two-way flow of money. A supplier–customer interface in this paper consists of the information flows between the supplier and customer as given in Fig. 1.

2.2. Schedule instability and schedule nervousness

There is a difference between "schedule instability" and "schedule nervousness" (also referred in the literature as "system nervousness"). Schedule instability is defined as the frequent changes to production schedules (Pujawan and Smart, 2012; Sridharan and LaForge, 1989). "Schedule instability" is considered the cause of "schedule nervousness". The reported causes of schedule nervousness include problems related to the mismatch between external and internal supply and demand, which affect changes in the lot-sizing decisions within MRP systems (Ho, 2002; Narayanan and Robinson, 2010) which can compound into knock-on effects to other components within the same bill of materials (BOM), and to other products that use the same production facilities (Koh, 2004). Manufacturers respond to mismatch between supply and demand problems by holding extra stock as a buffer against delays and shortfalls by suppliers (Koh et al., 2002), which seems to be more effective than building in safety lead time. However, the extra inventory leads to extra costs, and

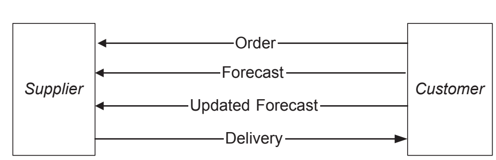

Fig. 1. Information flows at a supplier–customer interface (commodity production environment).

not necessarily to improvements in customer deliveries (de Kok and Inderfurth, 1997; Childerhouse et al., 2008; Huaccho Huatuco and Calinescu, 2011). The consequences of schedule nervousness include loss of management trust in the MRP system (Blackburn et al., 1985, 1986) or ERP system (Koh and Saad, 2006), fluctuation in capacity utilisation, rescheduling costs and confusion in delivery schedules (Ho, 1989, 1992, 2002; Ho and Ireland, 1998), increased costs in record keeping and dissemination of schedules, increased material handling costs and management interventions (Inman and Gonsalvez, 1997). Although mitigation strategies, such as improved forecasting (Blackburn et al., 1985, 1986; van Donselaar and Gubbels, 2002), can help to alleviate the problem of schedule nervousness, several authors recommend uncovering the underlying causes of schedule nervousness and addressing those in the first place. Many authors (e.g. Blackburn et al., 1985, 1986; Koh, 2004; Koh and Saad, 2006; Stadtler, 2005) call for a greater understanding of the reasons for schedule nervousness, but current measures of systems nervousness do not have the precision or focus to pinpoint its underlying causes.

2.3. Quality of information

Information flows can be regarded as the controlling factors in the supplier–customer interfaces. The manner in which information is transmitted and used across organisational interfaces has been identified as a critical factor for the success of entire supply chains (Mason-Jones and Towill, 1999; Al-Mudimigh et al., 2004). Extending the definition of 'information quality' given in the literature (Kehoe and Boughton, 2001; Kahn et al., 2002; Huang et al., 2003) a responsive and flexible supplier–customer interface would ensure that the *relevant* information on all flows is *accurate* and *comprehensive*, being made *accessible*, to the *right place,* at the *right time* in the correct *format.* McGuffog and Wadsley (1999) stated the issues surrounding the quality of information, where poor quality definitions of products, orders, payments and general logistics can amplify the levels of uncertainty and unreliability across organisational boundaries. These were confirmed by Childerhouse et al. (2008) whose studies of the European automotive industry showed the impact of the delivery process as well as demand forecasts. Poor quality information transfer between organisations can be amplified and become more uncertain as information undergoes transformations, delays and losses as it travels through the supply chain (Forrester, 1958, 1961; Childerhouse et al., 2008). To improve the overall performance of organisations there needs to be a reduction in information uncertainty (Wilding, 1998) and improvements in the quality of the information (van der Vorst and Buelens, 1998) transmitted across organisational interfaces.

2.4. Materials vs. information flows

However, regardless of the criticality of information flows, organisations often focus on material flows when addressing supplier–customer interface issues (van Donselaar et al., 2000). This approach is often motivated by the tangible nature of material flows, and driven by the dominance of customers and the prevalence of contractual agreements on material delivery adherence. There is a balance to be struck between tracking every information flow, which may be revoked or modified later, and selectively ignoring or omitting complexity-adding information flows. The scarcity of tools that provide effective guidance on the effects of adding or removing information flows on supply chain issues will be addressed in this paper.

Often, this lack of attention to information flows can impede organisational performance, as uncertainties and variations are carried and amplified across organisations through information transfers. A study of Hewlett-Packard's supply chains (Davis, 1993) considers orders as the primary information communication between businesses. The study estimated that 60% of its inventory was used as protection against irregular and unpredictable customer orders, whilst only 5% was against material supply variance such as late deliveries and poor quality products. Childerhouse et al. (2008) found significant real-word correlations between customer schedule volatility and poor supplier deliveries performance. These industrial examples support the proposition that unpredictability and variability of information flows are at least as important as material flows.

2.5. Timing and frequency of information updates

Across the dynamic supplier–customer interface, one way to improve performance is to provide (and manage effectively) information updates. The addition or removal of information flows can affect the performance of the supplier–customer interface, but doing this involves cost in generating, transmitting, receiving, recording, interpreting and acting upon information updates (Sahin and Robinson, 2002; Ackoff, 1967). Apart from the overheads involved in managing information flow exchange, organisations need to be aware of the impact that reacting to each information update may have on their operations.

Often, the lack of attention to managing cross-organisational information flows arises primarily because organisations have little knowledge of the impact that schedule instability has on their performance. Through a novel application of an information-theoretic methodology, this paper presents two empirical case studies for reducing schedule instability by identifying and omitting complexity-adding information flows in supply chains.

3. Measuring operational complexity

Information theory provides a measure of the amount of information required to describe the state of the system (Shannon, 1948; Shannon and Weaver, 1949). Shannon's seminal work was originally intended for communication channels, but Frizelle (e.g. Frizelle and Woodcock, 1995; Frizelle and Suhov, 2008) and Efstathiou and co-workers (e.g. Calinescu et al., 1998, 2000) adapted and applied these ideas to manufacturing systems.

From an information-theoretic perspective, the operational complexity at a supplier–customer interface can be defined as the amount of information required to monitor the state of the system in order to manage it (Sivadasan et al., 2002, 2006, 2010). The operational complexity measure is relative to the level of control, and the detail and frequency of monitoring required at the interface. The proposed information-theoretic expression for measuring the operational complexity across supplier–customer interfaces, $H_o(SC)$, is given in Eq. (1). The derivation of this equation, its data requirements and calculation detail of the operational complexity measure are given in Sivadasan et al. (2006), and a practical data collection methodology for conducting this analysis is outlined in Sivadasan et al. (2002), which includes: (a) direct observations of the production shopfloor at the supplier and the customer production premises, (b) interviews with production and supply chain managers and (c) collection of recent and historical production related records both on paper or in electronic formats.

$$H_o(SC) = -\sum_{i=1}^{F} c_i \sum_{j=1}^{U} (1-P_{ij}) \sum_{K=1}^{R} \sum_{l=1}^{NS} p_{ijld} \log_2 p_{ijld} \quad (1)$$

where

$H_o(SC)$: operational complexity index for a supplier–customer interface.

F: number of Flow Variations, a flow variation is the arithmetic difference between two information flows, e.g. Forecast–Order,
c_i: number of observations required during a particular time interval for which the Flow Variation i is monitored by the Controller,
U: number of products,
R: number of reasons,
p_{ij}: probability of product j across Flow Variation i being in the scheduled (in-control) state,
NS: number of non-scheduled (out-of-control) states across flow i for product j and reason k, and
p_{ijkl}: probability of product j across flow i being in non-scheduled (out-of-control) state l due to reason k.

Consider the supplier–customer interface in Fig. 1. The Customer sends an Order with an expected delivery date to the Supplier. The Customer follows this later with a revised version of the order, Forecast, based on forecast orders from their downstream customers. As the scheduled due date approaches, a further version of the order is sent, the Updated Forecast. Then, ideally, the actual delivery occurs according to the quantity stated in the latest forecast.

The variables to be considered in measuring the operational complexity, $H_o(SC)$, in bits per week are briefly outlined below.

- The number of Flow Variations monitored at the interface (F) is related to the information flows used, e.g. two flow variations are (Forecast–Order) and (Updated Forecast–Forecast). Where $i=1$ corresponds to (Forecast–Order), $i=2$ corresponds to (Updated Forecast–Forecast), hence $F=2$.
- The number of observations (c_i) is the frequency by which Flow Variation i is monitored. For example, if the Updated Forecast and Forecast are both sent once a week and the Order is sent once a day, 5 days a week, then the variation between (Forecast–Order) would be monitored 5 times per week, and that between (Updated Forecast–Forecast) would only be monitored once per week. In this case $c_1=5$ and $c_2=1$ per week.
- The number of products (U) represents the number of products chosen (for the research) to be monitored in the case studies, which could be for example those products perceived by the supply chain managers as the most difficult to manage.
- The number of different reasons (R) relates to the causes for production going 'out of control' (i.e. differing from the schedule).
- The probability (P_{ij}) is calculated using the collected case study data in terms of both current and historical data for the 'in-control' state.
- Where variations are recorded, each variation is assigned to one of the out-of-control states or non-scheduled states (NS) which are defined by the Controller (e.g. the Production Manager) according to the level of detail he/she decides to monitor.
- p_{ijkl} is calculated using the collected case study data in terms of both current and historical production data for the 'out of control' states.

An example of the operational complexity calculation is given in Table 1 below. Assume there are three information flows, which result in two Flow Variations, i.e.: (Updated Forecast–Forecast) and (Order–Updated Forecast). These flow variations are monitored as indicated by $i=1$ and $i=2$. For given probability distributions across this interface, where $j=k=1$, $P_{ij}=0$ and $c_i=1$ per week, the operational complexity associated with monitoring these two flow variations is given as 1.97 bits per week.

Table 1
Operational complexity across two flow variations (bits per week).

i	j	k	l	p_{ijkl}	$p_{ijkl}\log_2 p_{ijkl}$
1	1	1	1	0.6	0.44
			2	0.4	0.53
			3	0	0.00
			4	0	0.00
			5	0	0.00
2	1	1	1	0	0.00
			2	0	0.00
			3	0.5	0.50
			4	0.5	0.50
			5	0	0.00
$H_o(SC)$, where $c_i=1$, $P_{ij}=0$					1.97

Note: $i=1$ corresponds to flow variation 1: Forecast–Order and $i=2$ corresponds to flow variation 2: Updated Forecast–Forecast.

The operational complexity between information flows is associated with variations in quantity or time between the expected and actual information flows. With respect to information flows, operational complexity refers to the variations in quantity or time that appear across successive information flows. For example, across the interface, the delivery quantity or delivery time requests may differ, for any product, from the Order to Delivery. The problem investigated here is the uncertainty of not knowing how many more (or fewer) units of a product are required than previously specified and how much earlier (or later) that product is required than previously informed.

4. Applying the methodology for assessing schedule instability

This methodology has been applied in an earlier paper (Sivadasan et al., 2010) to investigate the operational complexity associated with supplier–customer integration. In this paper we extend the application of this methodology to assess and reduce schedule instability at the supplier–customer interface by identifying and omitting complexity-adding information flows. The steps to applying the information-theoretic methodology for assessing schedule instability are briefly outlined here, with reference to Fig. 1.

1. The 'AS IS' information flows exchanged between the customer and the supplier are identified, and the operational complexity of each flow variation (Forecast–Order; Updated Forecast–Forecast; and Delivery–Updated Forecast) is calculated, using Eq. (1). This is referred to as the Base scenario or Scenario (i).
2. Information flows are systematically omitted from the pattern of information exchange between the two organisations, generating a new scenario each time. For example, for the supplier–customer interface in Fig. 1, Scenario (ii) could be to omit the Forecast. Scenario (iii) could be to omit Updated Forecast; Scenario (iv) could be to omit both Forecast and Updated Forecast; and so on. It is assumed that when an information flow is omitted, all the other information flows remain unchanged.
3. The operational complexity is re-calculated for the information flows in each of the generated scenarios. For example, for Scenario (ii) above, the operational complexity of each new flow variation (Updated Forecast–Order; and Delivery–Forecast) is then calculated, using Eq. (1). This calculation measures the information-theoretic difference between two versions of the schedule, giving an indication of schedule instability.

4. The complexity measures of the generated scenarios are analysed and compared against the Base scenario complexity measure. When a generated scenario is found to have a lower complexity measure than the Base scenario, then the omitted information flow in that scenario can be identified as a complexity-adding information flow. In such a case, the schedule instability at the supplier–customer interface reduces when a complexity-adding information flow is removed. The scenario with the least complexity is considered to be the least schedule instability scenario. The complexity is zero when the facility is always under control or as previously scheduled.

The advantage of the methodology is that it is simple to apply and can be done off-line (i.e. after the data collection). The novel application of this methodology provides a tool for manufacturing organisations to assess whether the information flows they are using for managing and controlling their production are complexity-adding or complexity-reducing at the supplier–customer interface. If some information flows are found to be complexity-adding and non-value adding, these could be eliminated to reduce the overall complexity at the interface without affecting the overall performance of the facility.

The limitations of the methodology are that the results are case-dependant. Therefore, it is difficult to generalise the findings. Other approaches such as computer simulations and analytical solutions could be used for generalisation of results, but they would lack the individual data-rich 'in depth' findings of this case study methodology.

5. Case studies

5.1. Commodity production: the Company A–Company B interface

5.1.1. Case study background and data acquisition

The first interface investigated is of a supplier–customer interface within the FMCG (Fast-Moving Consumer Goods) sector. Company B is a bottle-filling plant and its principal bottle supplier is Company A. With reference to Fisher (1997), the Company A–Company B interface belongs to functional products operating in an efficient supply chain.

Information flows were monitored at the Company A–Company B interface (Fig. 2) to capture the operational complexity associated with Company B's demand forecasts for bottles. These information flows are described below.

- Customer Delivery Instruction Forecast (CDI Forecast): This information flow contains the quantity required by Company B, per bottle type, *per week*, over a 13-week rolling period. The CDI Forecast was sent from the Material Planner at Company B to the Bottle Planner at Company A.
- Customer Delivery Instruction 1 Week (CDI 1 Week): This information flow contains the quantity per bottle variant required by Company B, *per week*, for the following week's delivery. This was an updated and isolated week version of the CDI Forecast for the following week's delivery. The CDI 1 Week was sent from the Material Planner at Company B to the Bottle Planner at Company A.
- Weekly Material Requirements (WMR): This information flow contained the quantity per bottle variant required by Company B, *per day*, for the following week's delivery. This was an updated and more detailed version of the CDI 1 Week. The WMR was sent from the Material Planner at Company B to the Bottle Planner at Company A.
- Daily Material Requirements (DMR): This information flow contained the quantity per bottle variant required and the times of delivery, for the following day's delivery. This was an updated and more detailed version of the CDI 1 Week. The DMR was sent from the Material Planner at Company B to the Bottle Planner at Company A, *each day*, on the day before delivery.
- Delivery: Actual delivery of products from Supplier A to Customer B. Please note that this flow was not analysed in this interface due to the units being different from the other flows and the difficulty in matching specific orders with deliveries within the same data collection period.

Within each organisation, 2 weeks were dedicated to current data collection, which was supported by 3 weeks' historical data. This provided 5 weeks' data from each organisation (supplier and customer) at two different periods in time. Combining the interface data from both organisations, 10 weeks' data were available for analysis at the Company A–Company B interface, which involved eight products, between 60 and 334 data points, depending on the scenario analysed.

5.1.2. Data analysis

The Company A–Company B interface operated with four distinct information flows, from which three Flow Variations were identified. It is reasonable to assume that each information flow contributed differently to the operational complexity at the interface. The operational complexity associated with the Flow Variations was calculated with respect to variations in quantities delivered (Table 2).

Four scenarios were analysed, as follows:

- Base scenario or Scenario (i): the four information flows as they appeared in Fig. 2 (except for Delivery);
- Scenario (ii): three information flows, omitting the CDI 1 Week;
- Scenario (iii): three information flows, omitting the WMR; and
- Scenario (iv): the initial and final information flows only, omitting the WMR and CDI 1 Week.

The operational complexity calculations are based on the assumption that when an information flow is omitted, all the other information flows remain unchanged.

The analysis is carried out at product level, from which the amount of information monitored per week is calculated. The state boundaries (an 'in control' state and five 'out of control' states) were defined according to the level of action needed to be taken by the decision maker, e.g. the production scheduler. For a discussion on definition of

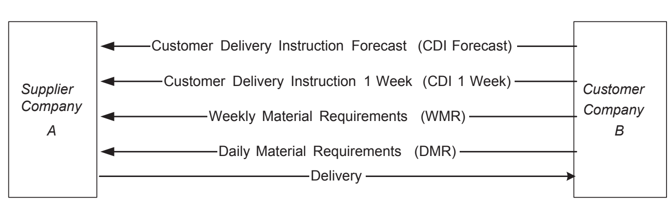

Fig. 2. Information flows monitored at the Company A–Company B interface.

Table 2
Data requirements for measuring the operational complexity at the Company A–Company B interface.

Analysis	Flow Variation i	Monitoring frequency c_i (information flows per week)
Base scenario: Scenario (i) All Flows	CDI 1 Week−CDI Forecast	1
	WMR−CDI 1 Week	1
	DMR−WMR	5
Scenario (ii) Omit CDI 1 Week	WMR−CDI Forecast	1
	DMR−WMR	5
Scenario (iii) Omit WMR	CDI 1 Week−CDI Forecast	1
	DMR−CDI 1 Week	5
Scenario (iv) Omit CDI 1 Week and WMR	DMR−CDI Forecast	5

Note: "−" denotes arithmetic difference.

states, see Sivadasan et al. (2001). The results obtained for the Company A–Company B interface are presented next.

5.1.3. Results and discussion

The results of the analysis are given in Fig. 3, where the operational complexity across the different Flow Variations is presented for the four scenarios listed above. Note the direction of all the arrows flow from Customer to Supplier in this commodity production environment. Fig. 3 shows that the operational complexity of the system decreases from Scenario (i) to Scenario (ii), and then increases from Scenario (i) to Scenario (iii) and from Scenario (i) to Scenario (iv). The Base scenario, i.e. Scenario (i) presents the interface system 'AS IS', with three information flows. In this scenario, the Controller needed to manage these information flows with an operational complexity of 1.93 bits per week, which results from the addition of the operational complexity indices calculated using Eq. 1 for each of the three flow variations, i.e.: (CDI 1 Week−CDI Forecast)=0.46, (WMR−CDI 1 Week)=1.21 and (DMR−WMR)=0.26. The same method of calculation is applied to the remaining scenarios.

In the second and third scenarios, it is assumed that Company B does not provide Company A with the CDI 1 Week and WMR, respectively. Scenario (ii) has the least complexity of the four scenarios, at 1.68 bits per week. This represents a reduction of 13% from the Base scenario (Scenario i), which is calculated as: (new −base)/base × 100. This suggests that the best strategy for the two companies would be for the customer to send the CDI Forecast, and then follow up with the WMR and DMR because this scenario has the least operational complexity. Comparing with Scenario (i), this analysis would suggest that the CDI 1 Week is actually contributing to schedule instability, by introducing information that is uncertain and variable, and which is later overridden. Scenario (iii), removing the WMR, greatly increases complexity (285%), since there are large discrepancies between CDI 1 week and DMR, which would cause many changes to the scheduling and set-up for final production. Similarly, Scenario (iv) has a high level of operational complexity (299% over Base level, 7.70 vs. 1.93 bits), suggesting that substantial late changes would be required if CDI 1 Week and WMR had not been provided.

This analysis shows that WMR is a good predictor of DMR, since it generates a low operational complexity (0.26 bits per week). Perhaps surprisingly, CDI 1 Week and CDI Forecast show similar levels of operational complexity with respect to DMR (6.98 and 7.70 bits per week, respectively). Therefore, it is suggested that it is probably not necessary for the Customer to issue both information flows to the Supplier. They are very similar in content, and are likely to be over-ridden by the WMR, which is much closer to the DMR. In particular CDI 1 Week seems to increase schedule instability. In the light of these findings, our recommendation was that the companies A and B should consider whether to continue with the preparation, distribution and processing of CDI 1 Week. So, managers should consider adopting Scenario (ii) with the sequence of information flows: {CDI Forecast, WMR, DMR}. The organisations in this interface later carried out an 'integration' exercise which consisted on the supplier 'co-locating' dedicated facilities for the customer. This implied the omission of the CDI Forecast and the CDI 1 Week, which greatly increased the complexity after integration (Sivadasan et al., 2010).

5.2. Customised production: the Company C–Company D interface

5.2.1. Case study background

The second supplier–customer interface investigated belongs to the Customised Production environment, involving Company D, a large manufacturing company final assembly area and Company C, its key bare Printed Circuit Boards (PCB) supplier. With reference to Fisher (1997), the Company C–Company D interface belongs to the class of innovative products operating in a responsive supply chain. In this case, the Supplier was more proactive than in the Company A–Company B interface, and provided regular updates on its progress according to the schedules that the Customer provided. The Customer was subject to high levels of operational complexity, due to production difficulties and downstream fluctuations.

The flows monitored at the Company C–Company D interface are identified in Fig. 4. The supplier (Company C) would send a Quote (Q) to which the customer (Company D) could agree and then place the Purchase Order (PO). Next, the supplier (Company C) would respond with an Order Acknowledgement (OA), which confirmed the receipt of the Purchase Order (PO). Each Purchase Order and Order Acknowledgement contained information on only one product. Each week, a Progress Report (PR) was sent from Company C to Company D to provide an update of Company C's production. This was then followed by the Delivery of the PCBs. These information flows were monitored for variations in quantity, as described below.

- Quote (Q): This information flow contained the specifications of the requested PCB in terms of price according to the requested lead time, which could be either standard delivery or fast turn around (FTA).
- Purchase Order (PO): This information flow contained the description of the PCB required, along with the quantity and required delivery date. This information flow was sent by the Purchaser at Company D to the Sales Contact at Company C. Company C received on average five orders per week from Company D.
- Order Acknowledgement (OA): This information flow confirmed the receipt of the purchase orders. It contained the product code, quantity required and the date to be delivered. The OA was sent by the Sales Contact at Company C to the Purchaser at Company D to follow every Purchase Order.
- Progress Report (PR): This information flow contained information on all outstanding deliveries from Company C to Company D. The PR was sent once per week by the Sales Contact at Company C indicating the products that were outstanding, their expected delivery date and delivery quantity. This provided Company D with early notice of possible delays or shortages of deliveries from Company C.

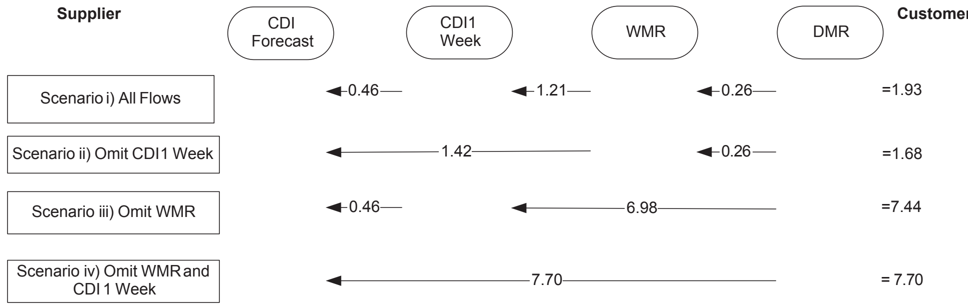

Fig. 3. Results of the four information exchange scenarios for the Supplier (Company A) and the Customer (Company B) interface (bits per week).

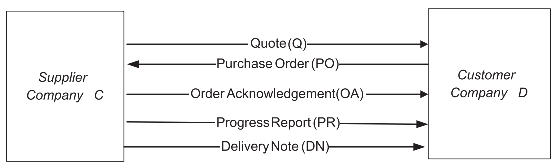

Fig. 4. Information flows monitored at the Company C–Company D interface.

Table 3
Data requirements for measuring the operational complexity at the Company C–Company D interface.

Analysis	Flow Variation *i*	Monitoring frequency c_i (information flows per week)
Base scenario: Scenario (i) All flows	PO−Q	5
	OA−PO	5
	PR−OA	1
	DN−PR	5
Scenario (ii) Omit PO or OA (PO=OA)	PR−PO or PR−OA or PR−Q	1
Scenario (iii) Omit PR	DN−OA or DN−PO or DN−Q	5
Scenario (iv) Omit OA and PR	PO−Q and DN−PO	5
Scenario (v) Omit PO, OA and PR	DN−Q	5

Note: "−" denotes arithmetic difference.

- Delivery Note (DN): This information flow contained information on the actual dispatch of the PCBs from the supplier to the customer.

Within each organisation, 2 weeks were dedicated to current production data collection, which was supported by historical data: 1 month from Company D and 6 months from Company C, which involved two products and between 70 and 179 data points, depending on the scenario.

5.2.2. *Data analysis*

At the Company C–Company D interface, the operational complexity associated with Flow Variations was calculated with respect to the quantity of PCB's variations (Table 3).

Five scenarios were analysed, as follows:

- Base Scenario: Scenario (i): the five information flows as they appeared in Fig. 4;
- Scenario (ii): four information flows, omitting either PO or OA (Omit PO or OA, since PO=OA in this case);
- Scenario (iii): four information flows, omitting the information flow PR (Omit PR);
- Scenario (iv): three information flows, omitting the information flows of OA and PR (Omit OA and PR); and
- Scenario (v): two information flows, omitting the information flows of PO, OA and PR.

As with Company A–Company B's interface, it was assumed that when an information flow is omitted, all the other information flows remain unchanged.

The calculations considered the Standard and Fast-Turnaround (FTA) product types, and operational complexity units were calculated in bits per week.

5.2.3. *Results and discussion*

The results of the scenarios are shown in Fig. 5 below. Note the direction of the arrows flow mostly from Supplier to Customer in this customised production environment, which is in contrast to the flow from Customer to Supplier as seen in the commodity production environment.

This case shows lower operational complexity than the previous case (Company A–Company B interface). The Base Scenario's operational complexity is 0.32 bits per week, which results from the addition of the operational complexity indices calculated using Eq. 1 for each of the four flow variations, i.e.: (PO−Q)=0, (OA−PO)=0, (PR−OA)=0.03 and (DN−PR)=0.29. The same method of calculation is applied to the remaining scenarios.

The complexity is lower than the previous case study at 1.33 bits per week in the highest complexity scenarios. In this case, it can be seen that the supplier–customer interface is more stable with little variation seen between the exchanged information flows.

The least complex scenario (apart from the Base scenario) is Scenario (ii) which omits PO or OA, with 0.32 bits per week. This means that the effect of omitting either of these information flows is neutral (0%) in terms of contributing to schedule instability. It is clear that information flows PO or OA are not contributing to the planning process, except by confirming that nothing has changed. Therefore, a new information flow exchange plan could be {PO, PR, DN}. Alternatively, {Q, PR, DN} could be used with the same level of complexity, but providing a longer planning horizon. The exchange of only two information flows, either {Q, DN} or {PO, DN} would increase complexity to 1.33 bits per week or 316% increase, which is calculated as: (new−base)/base × 100. The supply chain partners would be advised in this case to consider these two options, leave the exchanges as they are, or a three-information flow exchange, since their ordering and supply relationship is very stable, as can be seen from the complexity measurements shown in Fig. 5. Customised, innovative products rely heavily on customer service levels, with one element of the relationship of trust being the 'updates' sent by the supplier. These suggestions should be seen in the light of the objectives set and agreed by the supply chain partners. The organisations involved in this interface (as far as the authors know) continued using the same information flows as stated in the Base

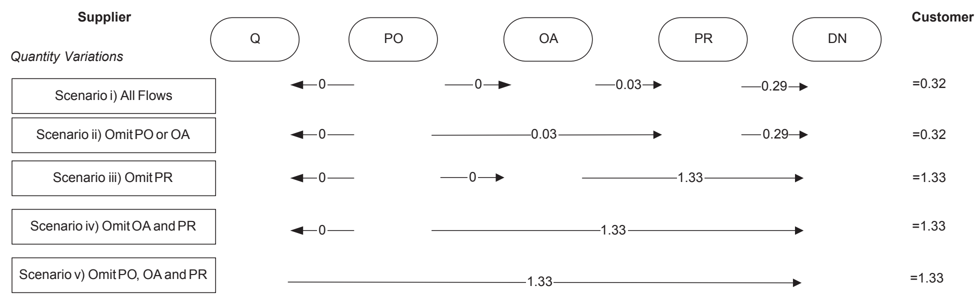

Fig. 5. Results of the five information exchange scenarios for the Supplier (Company C) and the Customer (Company D) interface (bits per week).

scenario, as they had already a system which minimised the schedule instability at the customer–supplier interface.

6. Discussion of results

It is argued in this paper that complexity-adding information flows between supply chain partners can contribute to schedule instability by causing changes to supply and delivery schedules, which can be later withdrawn or overridden. The analysis presented in this paper shows how complexity-adding information flows can be identified and the extent to which they can contribute to schedule instability. This information-theoretic methodology has been applied to measuring the information-flow complexity of two very different supplier–customer interfaces (i.e. commodity vs. customised production), under different scenarios.

The case study in the commodity production environment showed that the customer generated most of the complexity by providing different versions of the demand forecast, which the supplier ignored and ultimately delivered from stock, when the final requirements were fixed. In the customised production environment case study, the supplier provided information flows which did not add much valuable information, but helped to keep the customer reassured that the agreed deliveries were still valid. Recommendations were made to the managers at the companies involved, as how to deal with schedule instability within their particular production environment. The proposed application of the information-theoretic methodology can help the participating companies detect situations where too-frequent information flow exchanges contribute to schedule instability, since these flows would often lead to schedule updates or production changes which are later withdrawn or over-ruled. This method can help supply chain partners to identify new, effective strategies for information exchange that could damp down schedule instability and thus reduce the costs associated with exchanging information and responding to it unnecessarily. This is in agreement with results found by Wu et al. (2007), where less complexity in commodity production environments is equivalent to lower costs.

In the case of the customised production environment, the proposed application of the information-theoretic methodology can help the participating companies detect unnecessary information flows. In an objective sense (i.e. using operational complexity) these duplicate information flows are neutral in their contribution to schedule instability at the supplier–customer interface, but do provide reassurance that the original delivery agreements remains under control. This finding is in contrast with the findings by Sahin and Robinson (2002) who reported a much higher benefit (47.58% cost savings) in terms of sharing information in customised production.

7. Conclusions

This paper presents a novel application of an information-theoretic methodology for identifying complexity-adding information flows. Furthermore, this paper presents empirical case study data to show that *schedule instability at supplier–customer interfaces can be reduced by identifying and omitting complexity-adding information flows*.

The proposed research hypothesis that "by omitting some intermediate versions of the schedule (information flows), supply chain partners can reduce their schedule instability" is accepted for the case study of commodity products, since omission of an information flow leads to a reduction in complexity (lower schedule instability). However, the hypothesis is rejected for the case study of customised products, since omission of information flows in this production environment leads to higher complexity (higher schedule instability). The hypothesis holds true only when 'complexity-adding' information flows are omitted.

This study provides further evidence to support recent findings (Huaccho Huatuco and Calinescu, 2011) that, perhaps counter-intuitively, commodity production can exhibit higher operational complexity than customised production. The case study in the commodity production environment showed that the customer is the main source of complexity-adding information flows, whereas the case study in the customised production environment showed that it is the supplier that is the main source of complexity-reducing information flows.

Based on the findings of this paper, schedule instability may be reduced by omitting only information flows that are identified as being complexity-adding. Removing complexity-reducing information flows can lead to increased schedule instability at the supplier–customer interface. Having a tool to identify and measure complexity-reducing information flows can empower organisations to make informed decisions that reduce schedule instability at their supplier–customer interface.

7.1. Limitations and recommendations for future research

The limitations of this research include the fact that only two case studies have been used to derive generic conclusions on the contrasting commodity and customised production environments. The authors acknowledge that the application of this methodology across additional case studies would provide further evidence to evaluate the more general conclusions outlined in this paper. Additionally, this case study methodology could be supported by computer simulations to investigate whether the empirical results presented in this paper are consistent across different scenarios and production environments (commodity vs. customised).

Recommendations for further work include:

1. Extending the application of this information-theoretic methodology to identify the reasons for schedule instability. In previous work, the authors have used changes in production schedules to elicit the reasons from the personnel who were involved in preparing revisions to information flows (Sivadasan et al., 2004). The frequency of occurrence of these reasons can help pinpoint those aspects, both internally in manufacturing organisations or

externally at their supplier–customer interface, that are driving schedule instability and schedule nervousness as a consequence.

2. Extending this analysis further along the supply chain to detect whether supplier–customer interfaces with upstream or downstream partners are affected by schedule instability. What happens at the supplier–customer interface may or may not affect the internal production schedule within the organisation, which could cause schedule instability. So, further work will require the usage of a more complex model than the dyadic relationship (i.e. supplier–customer) presented and used in this paper.
3. Conducting further case studies to specifically contrast organisations operating with relatively stable demand patterns with those with uncertain demand patterns. Such a study would help to understand whether the differences in schedule instability are due to sector or organisational characteristics rather than just uncertainty and variety in demand.

Overall, this paper has reinforced the finding that, although a company is transmitting many information flows to their customers or suppliers with the aim of improving the overall performance and customer satisfaction, this behaviour may in fact cause a complexity rebound (Sivadasan et al., 2010). In other words, too frequent schedule updates and revisions may give rise to schedule instability in the receiving organisation, which may then have to revise its own production schedules. These schedules will then need to be transmitted back to the organisation that originated the schedule change, thus potentially amplifying schedule instability. This novel, information-theoretic perspective on identifying, quantifying and reducing schedule instability could help manufacturing organisations make informed, analytically-based decisions when they redesign their business processes (Burgess, 1998; Clark and Hammond, 1997; Huaccho Huatuco et al., 2010).

Acknowledgements

The authors would like to thank the industrial collaborators and their suppliers, for supporting the EPSRC-funded Complexity in the Supply Chain Project (Grant no. GR/M57842). The authors gratefully acknowledge EPSRC support including Grants GR/M52458 and 98316556.

References

Ackoff, R.L., 1967. Management Misinformation Systems. Management Science 14 (4), B147–B156.
Al-Mudimigh, A.S., Zairi, M., Ahmed, A.M.M., 2004. Extending the concept of supply chain: the effective management of value chains. International Journal of Production Economics 87 (3), 309–320.
Arshinder, K.A., Deshmukh, S.G., 2008. Supply chain coordination: perspectives, empirical studies and research directions—institutional perspectives on supply chain management. International Journal of Production Economics 115 (2), 316–335.
Blackburn, J.D., Kropp, D.H., Millen, R.A., 1985. System nervousness: causes and cures. Engineering Costs and Production Economics 9 (1–3), 141–146.
Blackburn, J.D., Kropp, D.H., Millen, R.A., 1986. A comparison of strategies to dampen nervousness in MRP Systems. Management Science 32 (4), 413–429.
Bartezzaghi, E., Verganti, R., 1995. Managing demand uncertainty through order overplanning. International Journal of Production Economics 40 (2–3), 107–120.
Burgess, R., 1998. Avoiding supply chain management failure: lessons from business process reengineering. International Journal of Logistics Management 9 (1), 15–23.
Cachon, G.P., Fisher, M., 2000. Supply chain inventory management and the value of shared information. Management Science 46 (8), 1032–1048.
Calinescu, A., Efstathiou, J., Schirn, J., Bermejo, J., 1998. Applying and assessing two methods for measuring complexity in manufacturing. Journal of the Operational Research Society 49 (7), 723–733.
Calinescu, A., Efstathiou, J., Sivadasan, S., Schirn, J., Huaccho Huatuco, L., 2000. Complexity in manufacturing: an information theoretic approach. In: Proceedings of the International Conference on Complexity and Complex Systems in Industry, 19th–20th September 2000. The University of Warwick, UK, pp. 30–44.
Calinescu, A., Efstathiou, J., Sivadasan, S., Huaccho Huatuco, L., 2001. Information-theoretic measures for decision-making complexity in manufacturing. In: Proceedings of the 5th World Multi-Conference on Systemics, Cybernetics and Informatics (SCI 2001), 22nd–25th July 2001. Orlando, Florida, USA. vol. X, pp. 73–8. SCI 2001/ISAS 2001 best paper in the "Conceptual Infrastructure of SCI" session. Organised by The International Institute of Informatics and Systemics.
Childerhouse, P., Disney, S.M., Towill, D.R., 2008. On the impact of order volatility in the European automotive sector. International Journal of Production Economics 114 (1), 2–13.
Christopher, M., 2005. Logistics and Supply Chain Management: Creating Value-Added Networks. Pearson Education, UK.
Clark, T.H., Hammond, J.H., 1997. Reengineering channel reordering processes to improve total supply chain performance. Production and Operations Management 6 (3), 248–265.
Davis, T., 1993. Effective supply chain management. Sloan Management Review 34 (4), 35–46.
de Kok, T., Inderfurth, K., 1997. Nervousness in inventory management: comparison of basic control rules. European Journal of Operational Research 103 (1), 55–82.
Fisher, M.L., 1997. What is the right supply chain for your product? Harvard Business Review 75 (2), 105–116.
Forrester, J.W., 1958. Industrial dynamics. Harvard Business Review 36 (4), 37–66.
Forrester, J.W., 1961. Industrial Dynamics: A Major Breakthrough for Decision Makers. MIT Press, Cambridge, MA.
Frizelle, G., Woodcock, E., 1995. Measuring complexity as an aid to developing operational strategy. International Journal of Operations & Production Management 1 (5), 26–39.
Frizelle, G., Suhov, Y., 2008. The measurement of complexity in production and other commercial systems. Proceedings of the Royal Society A Mathematical Physical and Engineering Sciences 464 (2098), 2649–2668.
Gattiker, T.F., Goodhue, D.L., 2004. Understanding the local-level costs and benefits of ERP through organizational information processing theory. Information & Management 41 (4), 431–443.
Ho, C.J., 1989. Evaluating the impact of operating environments on MRP system nervousness. International Journal of Production Research 27 (7), 1115–1135.
Ho, C.J., 1992. An examination of a distribution resource planning problem: DRP system nervousness. Journal of Business Logistics 13 (2), 125–152.
Ho, C.J., Ireland, T.C., 1998. Correlating MRP system nervousness with forecast errors. International Journal of Production Research 36 (8), 2285–2299.
Ho, C.J., 2002. Evaluating dampening effects of alternative lot-sizing rules to reduce MRP system nervousness. International Journal of Production Research 40 (11), 2633–2652.
Huaccho Huatuco, L., Burgess, T.F., Shaw, N.E., 2010. Entropic-related complexity for reengineering a robust supply chain: a case study. Production Planning and Control 21 (8), 724–735.
Huaccho Huatuco, L., Calinescu, A., 2011. Hybrid algorithms for manufacturing rescheduling: customised vs. commodity production. In: Montoya-Torres, J. R., Juan, A.A., Huaccho Huatuco, L., Faulin, J., Rodriguez-Verjan, G. (Eds.), Hybrid Algorithms for Service, Computing and Manufacturing Systems: Routing, Scheduling and Availability Solutions. IGI Global, Hershey, PA, USA 58 p.
Huang, G.Q., Lau, J.S.K., Mak, K.L., 2003. The impacts of sharing production information on supply chain dynamics: a review of the literature. International Journal of Production Research 41 (7), 1483–1517.
Huchzermeier, A., Loch, C.H., 2001. Project management under risk: using the real options approach to evaluate flexibility in R&D. Management Science 47 (1), 85–101.
Inman, R.R., Gonsalvez, D.J.A., 1997. Measuring and analysis supply chain stability: a case study in the automotive industry. Production Planning & Control 8 (2), 194–204.
Kahn, B.K., Strong, D.M., Wang, R.Y., 2002. Information quality benchmarks: product and service performance. Communications of the ACM—Supporting Community and Building Social Capital 45 (4), 184–192.
Kehoe, D.F., Boughton, N.J., 2001. New paradigms in planning and control across manufacturing supply chains—the utilisation of Internet technologies. International Journal of Operations & Production Management 21 (5–6), 582–593.
Kelle, P., Akbulut, A., 2005. The role of ERP tools in supply chain information sharing, cooperation, and cost optimization. International Journal of Production Economics 93–94, 41–52.
Koh, S.C.L., 2004. MRP-controlled batch-manufacturing environment under uncertainty. Journal of the Operational Research Society 55 (3), 219–232.
Koh, S.C.L., Saad, S.M., Jones, M.H., 2002. Uncertainty under MRP-planned manufacture: review and categorization. International Journal of Production Research 40 (10), 2399–2421.
Koh, S.C.L., Saad, S.M., 2006. Managing uncertainty in ERP-controlled manufacturing environments in SMEs. International Journal of Production Economics 101 (1), 109–127.
Lamming, R.C., Caldwell, N.D., Harrison, D.A., Phillips, W., 2001. Transparency in supply relationships: concept and practice. Journal of Supply Chain Management 37 (4), 4–10.
Lee, H.L., So, K.C., Tang, C.S., 2000. The value of information sharing in a two-level supply chain. Management Science 46 (5), 626–643.
Martinez-Olvera, C., 2008. Entropy as an assessment tool of supply chain information sharing. European Journal of Operational Research 185 (1), 405–417.
Mason-Jones, R., Towill, D.R., 1999. Total cycle time to compression and the agile supply chain. International Journal of Production Economics 62 (1), 61–73.

McGuffog, T., Wadsley, N., 1999. The general principles of value chain management. Supply Chain Management: An International Journal 4 (5), 218–225.
Mula, J., Poler, R., Garcia-Sabater, J.P., Lario, F.C., 2006. Models for production planning under uncertainty: a review. International Journal of Production Economics 103 (1), 271–285.
Narayanan, A., Robinson, P., 2010. Evaluation of joint replenishment lot-sizing procedures in rolling horizon planning systems. International Journal of Production Economics 127 (1), 85–94.
Pujawan, I.N., 2004. Schedule nervousness in a manufacturing system: a case study. Production Planning and Control 15 (5), 514–524.
Pujawan, N., Smart, A.U., 2012. Factors affecting schedule instability in manufacturing companies. International Journal of Production Research 50 (8), 2252–2266.
Rodriguez-Verjan, G., Montoya-Torres, J.R., 2009. Measuring the impact of supplier–customer information sharing on production scheduling. International Journal of Information Systems and Supply Chain Management 2 (2), 47–60.
Sahin, F., Robinson, E.P., 2002. Flow coordination and information sharing in supply chains: Review, implications, and directions for future research. Decision Sciences 33 (4), 505–536.
Sahin, F., Robinson, E.P., 2005. Information sharing and coordination in make-to-order supply chains. Journal of Operations Management 23 (6), 579–598.
Shannon, C.E., 1948. A mathematical theory of communication. Bell System Technical Journal 27, 379–423.
Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, USA.
Sivadasan, S., Efstathiou, J., Calinescu, A., Huaccho Huatuco, L., 2001. A discussion of the issues of state definition in the entropy-based measure of operational complexity across supplier-customer systems. In: Proceedings of the 5th World Multi-Conference on Systemics, Cybernetics and Informatics (SCI 2001), 22nd–25th July 2001. Orlando, Florida, USA, vol. II, pp. 227–232.
Sivadasan, S., Efstathiou, J., Frizelle, G., Shirazi, R., Calinescu, A., 2002. An information-theoretic methodology for measuring the operational complexity of supplier–customer systems. International Journal of Operations & Production Management 22 (1), 80–102.
Sivadasan, S., Efstathiou, J., Calinescu, A., Huaccho Huatuco, L., 2004. Supply chain complexity. In: New, S, Westbrook, R. (Eds.), Understanding Supply Chains. Oxford University Press, Oxford, UK, pp. 133–163.
Sivadasan, S., Efstathiou, J., Calinescu, A., Huaccho Huatuco, L., 2006. Advances on measuring the operational complexity of supplier–customer systems. European Journal of Operational Research 171 (1), 208–226.
Sivadasan, S., Smart, J., Huaccho Huatuco, L., Calinescu, A., 2010. Operational complexity and supplier–customer integration: case studies insights and complexity rebound. Journal of Operational Research Society 61 (12), 1709–1718.
Sridharan, V., LaForge, R.L., 1989. The impact of safety stock on schedule instability, cost and service. Journal of Operations Management 8 (4), 327–347.
Stadtler, H., 2005. Supply chain management and advanced planning—basics, overview and challenges. European Journal of Operational Research 163 (3), 575–588.
van der Sluis, E., 1993. Reducing system nervousness in multi-product inventory systems. International Journal of Production Economics 30–31, 551–562.
van der Vorst, J.G.A.J., Buelens, A.J.M., 1998. Supply chain management in food chains: improving performance by reducing uncertainty. International Transactions in Operational Research 5 (6), 487–499.
van Donselaar, K.H., Gubbels, B.J., 2002. How to release orders in order to minimise system inventory and system nervousness? International Journal of Production Economics 78 (3), 335–343.
van Donselaar, K., van den Nieuwenhof, J., Visschers, J., 2000. The impact of material coordination concepts on planning stability in supply chains. International Journal of Production Economics 68 (2), 169–176.
Wilding, R., 1998. The supply chain complexity triangle: Uncertainty generation in the supply chain. International Journal of Physical Distribution and Logistics Management 28 (8), 599–616.
Wu, Y., Frizelle, G., Efstathiou., J., 2007. A study on the cost of operational complexity in customer–supplier systems. International Journal of Production Economics 106 (1), 217–229.