

Complexity Transfer in supplier-customer systems

This paper uses a multiple case-study methodology to investigate complexity transfer (CT) in manufacturing supplier-customer systems, leading to a new model of complexity transfer. An entropic-related complexity measure is applied to three supplier-customer systems, internally within each organisation and at their supplier-customer interface. The results are compared and integrated to provide cross-case analyses and insights. Although CT has been acknowledged in the literature to occur towards upstream supply chain (SC) partners, e.g. in the context of the bullwhip effect, this paper provides evidence that CT may also occur towards downstream SC partners. This study also highlights that complexity can be managed through significant and sustained operational interventions. Our new empirically-tested model of CT identifies four organisational types: Sink, Source, Equilibrium, and Boom or Bust, according to their transfer of internally-generated and externally-accepted complexity. This new model enables an in-depth representation of the transfer of complexity and of its impact on SC partnerships. Managers may use this CT model to develop complexity management insights and to identify structural and operational changes – at organisational level, and systemic SC changes that may reduce the costs associated with complexity.

Keywords: Complexity; supply chains; entropy; supplier-customer systems; case studies; manufacturing systems.

Introduction

A growing body of recent research on the complexity of manufacturing operations and supply chains (SCs) shows that complexity exists within manufacturing operations and SCs (de Leeuw et al., 2013; Roh et al., 2014; Blome et al., 2014; Bode and Wagner, 2015; Ge et al., 2016; Birkie and Trucco, 2016, Bai and Sarkis 2018, and Dittfeld et al. 2018) and that

complexity needs to be understood and measured in order to be properly managed (Bai and Sarkis 2018, Fernandez Campos et al., 2019). The prevalence of the problem of complexity management in industry is evident (KPMG, 2019) and the motivation for research on the complexity of manufacturing operations and SCs originates from the need of managers in industry to better understand and manage this complexity.

Complexity can be considered as static (structural) or dynamic (operational) (Serdarasan, 2013). Structural or static complexity is due to the static variety of the system (e.g. the number of different products, manufacturing routes etc.), and dynamic or operational complexity is due to the uncertainty of the system (Frizelle and Woodcock, 1995; Sivadasan et al. 2002). In a sense, structural or static complexity is related to known factors – the many items that are produced and the many stages or interconnections involved. On the other hand, dynamic or operational complexity is related to the (unscheduled) disruptions to production, delivery and despatch – and may occur because of internal problems, e.g. machine breakdown, or they may be due to exogenous factors, such as change requests from a customer, or problems with deliveries from a supplier (Sivadasan et al., 2004, 2006).

Although several studies have focused on complexity and complexity management within organisations, there is little research on complexity transfer (CT) between supplier and customer organisations within a SC. Where CT is sometimes referred to as “complexity propagation” (Hu et al., 2008; Zhu et al., 2008), the term “complexity transfer” was originally proposed by Sivadasan et al. (2004), who argued that complexity within organisations can be absorbed internally and/or transferred externally. Thus, in addition to generating or absorbing complexity internally, manufacturing organisations may transfer complexity from (by importing) and to (by exporting) their suppliers and customers. This paper will focus on complexity transfer (CT) which is defined here as “*the transfer of uncertainty and variety*

between SC partners due to variations between planned and actual production, delivery and despatch” (Sivadasan et al., 2004, 2006, 2010, 2013).

This paper addresses the research questions of (i) What are the response mechanisms of CT in supplier-customer systems? (ii) What is the impact of CT on the organisations within those supplier-customer systems? (iii) How could these organisations respond to manage CT effectively? The evidence is based on three case studies, which measured the internal complexity and complexity transfer at the supplier-customer interfaces. The results and insights of each case and the cross-case analyses is used to inform the proposed new model of complexity transfer (CT).

This proposed new model of CT identifies mechanisms of CT both upstream and downstream within a linear SC, with a focus on supplier-customer systems. This CT model identifies four organisational types - Sink, Source, Equilibrium, and Boom or Bust - according to the balance of internally generated or absorbed complexity and externally imported or exported complexity. The proposed CT model helps SC and production managers identify their organisation’s pattern of behaviour, so that they can better understand how complexity across supplier-customer interfaces affects their organisation’s internal production dynamics, and how it impacts on their SC partners. They may also look further up and down the SC to identify risky combinations of suppliers and customers that could destabilize the SC. Furthermore, insights from the proposed CT model may be used by organisations to make more informed decisions relating to SC configuration or SC design (Chopra and Meindl, 2012; Song et al., 2018); for example, in deciding on a single preferred supplier model or a multiple supplier model.

Organisations with poor strategies and practices for managing and understanding complexity transfer might find themselves suffering from cascading propagation of complexity, leading to the well-known Bullwhip effect (Disney and Towill, 2003a; 2003b;

2003c; 2006; Geary et al., 2006; Zhou and Disney, 2006; Towill et al., 2007). The CT model will help supply chain managers select complexity management strategies, as well as identify the strategies to adopt for particular supply chain partners.

The remainder of this paper is organised as follows. The next section sets out the theoretical background on complexity management in SCs. Next, the case study methodology for measuring complexity at supplier-customer interfaces is presented, followed by the qualitative and entropic-related complexity measurement from the three case studies. Then, the new model of CT in supplier-customer systems is provided. Finally, the paper concludes with a discussion of how the research questions were addressed, recommendations for SC managers, limitations and further research opportunities.

Complexity Management in supply chains

It is argued that complexity is the outcome of operations that involve many products, many components, multiple-stage processes, buffer stocks and unscheduled disruptions, and that complexity can make manufacturing and other repetitive processes difficult to schedule and manage (Sivadasan et al., 2004). This is further exacerbated by the increasing number of connections and the unpredictability of operational behaviours between supplier and customer organisations in a SC. To capture this, complexity is conceptualized as a performance measure that integrates and jointly quantifies the results of managerial choices on business processes, the dynamics of the supplier-customer systems that make up the supply network, and the uncertainty associated with information and/or material flows (Sivadasan et al., 2013). This conceptualisation aligns with Manuj and Sahin (2011) who proposed a comprehensive model of SC and SC decision-making complexity based on a grounded theory methodology.

It is acknowledged both by academics and practitioners that complexity is inherent in SCs, and many studies have focused on guiding organisations in the management of complexity (e.g. Frizelle and Woodcock, 1995; Frizelle, 1998; ElMaraghy et al., 2013). For some authors, SC complexity is a feature characterizing the supply network context rather than internal operations and is something managers can address by modifying business processes (e.g. Birkie and Trucco, 2016) or supply network structure (e.g. Inman and Blumenfeld, 2014). For example, Choi and Hong (2002) define supply network complexity in terms of vertical, horizontal and spatial complexity. In addition, they recognize that there may be other intangible measures of complexity, such as the level of coupling between organisations in the supply network, as evidenced in the closeness of the working relationships. However, in this paper, and as presented by Sivadasan et al. (2004, 2006, 2010, 2013), we posit that complexity is akin to a performance measure using information-theoretic entropy, which can help compare the dynamic or operational complexity of different elements of the supply chain, e.g. supplier-customer dyads as basic components of the supply network.

Bozarth et al. (2009) consider dynamic complexity across different SC positions (upstream, internal and downstream). This particular classification is helpful to this paper, as existing literature has focused on the effects of complexity affecting upstream organisations, but there is scarcity on research that show how complexity also affects downstream organisations (Sivadasan et al. 2010, Rong et al., 2017).

The management of complexity has been addressed by previous research in terms of strategies, practices and mechanisms. First, complexity management strategies are used by organisations to mitigate, reduce or eliminate complexity (e.g. Bozarth et al., 2009, Perona and Miragliota, 2004, Aitken et al., 2016). This can be achieved via increased IT capabilities, hiring more staff, rationalizing operations and processes, increasing inventory and improving

decision-making (Sivadasan et al., 2004). Second, complexity management practices refer to those specific managerial techniques, systems and designs adopted by organisations in order to manage complexity (Fernandez Campos et al., 2017). In their work, they propose three clusters of complexity management practices derived from qualitative interviews with SC managers: i) design out structural complexity (e.g. reduction of product portfolio), ii) decision-support and knowledge generation practices (e.g. multi-echelon ERPs and optimization tools) for both structural and dynamic complexity reduction, and iii) coordination and collaboration practices to reduce dynamic complexity. Aitken et al. (2016) propose complexity reducing or absorbing mechanisms with a focus on business units. They suggest that complexity-reducing mechanisms are effective at reducing dysfunctional (non-value adding) complexity and that complexity-absorbing mechanisms are effective at moderating the relationship between strategic SC complexity and operational performance.

In relation to previous literature, this paper proposes a new CT model to help organisations better understand and manage their internal complexity (whether generated or absorbed) and external complexity (whether imported from or exported to their SC partners, whether customers or suppliers). It is argued that this model can help organisations to identify suitable supply chain partners, and to assess the potential benefits and risks of alternative supply chain strategies (such as whether to invest in integration or buffer stocks).

Methodology for measuring complexity of supplier-customer systems

A multi-case study methodology was used to measure complexity and to observe the phenomena of CT within supplier-customer systems – both internally and at the supplier-customer interface. This case study methodology approach (i) allowed for an entropic complexity measurement methodology to be applied to different types of supplier-customer systems; (ii) provided opportunities for an in-depth investigation and detailed observation of CT in each of the cases; (iii) allowed for different CT characteristics to be identified; and (iv)

facilitated and informed a more general analysis and classification of CT. More generally, case study methodology allows one or more of the following “theory generation, theory testing, and theory elaboration” (Ketokivi and Choi, 2014: 232)”, as “data are inextricably fused with theory” (Alvesson and Kärreman, 2007: 1265). For this study, the case study methodology allowed for the theoretical development (theory elaboration) of CT in SCs, whereby a new model of CT is proposed, having previously identified and applied the entropy-based measure of complexity and analysed empirical results from several case studies across individual organisations and their supplier-customer interfaces (Sivadasan et al. 2004, 2006, 2010, 2013). These quantitative and qualitative analytical processes in turn provide insights towards developing a new theory on complexity transfer (CT) in supplier-customer systems.

A protocol (Voss et al., 2002; Pettigrew, 1990; Yin, 2013) was followed for each case study, consisting of the following phases as detailed in Sivadasan et al. (2002): preparation, familiarization, design factors, data collection, and single-case and cross-case analysis and presentation of findings. Below is the summary of the phases:

- The preparation phase consisted of establishing contact with a project champion at each organisation within the supplier-customer system to facilitate access and arrangements of interviews. This phase also included presentations to the organisations establishing the research project objectives, needs in terms of data collection, communication roles between researchers and organisation, and expectations in terms of feedback. In each case, the supplier-customer interface is isolated, i.e. interactions between one customer and one supplier are investigated (based on the selected key/critical supplier as perceived by the customer company), and the research and analysis focused only on product lines relevant to both

organisations. This is based on the assumption that the simplified supplier-customer system forms the basic unit of all SCs and supply networks (Sivadasan et al., 2004).

- The familiarization phase included visits to the organisation to interview key personnel, observe the manufacturing facilities, and map material and information flows. During this phase, several participants were interviewed, with typically between five and eight semi-structured interviews with key personnel e.g. Production Managers, SC Managers, Managing Directors, Purchasing staff, Product Designers and Sales Representatives. Appendix A shows the list of interviewees for each of the case studies presented in this paper. The semi-structured interview questions were refined following the pilot stages of the study (Calinescu et al., 1998). Systematic observations were also carried out across the three main departments of investigation: Purchasing, Production and Despatch. The observations included mapping of actual information and material flows.
- The design factors such as the specific material and information flows to be monitored, the frequency of observations, the dimensions to measure (e.g. variations in time or quantity) and states of interest (e.g. early, on-time, late) were determined following the familiarization phase.
- The data collection phase included real-time monitoring of the manufacturing system, to record actual vs. expected variations in relevant information and material flows, scrutiny of documents/spreadsheets relating to purchasing, production and despatch, and on-going discussions with key managers to validate any perceived discrepancies in data, and to provide qualitative insights. Typically, this phase would cover two to three weeks of live on-site data collection and a few weeks of historical data.
- The analysis phase included the calculation of the information-theoretic complexity indices, supported and complemented by the analysis of documents/spreadsheets and

interview responses. The internal analysis of both supplier and customer organisations were extended to include a Joint Data Analysis phase of their interface. Further validation of the quantitative results and qualitative insights and recommendations was ensured through discussions with key personnel and managers at the participating organisations, following data collection and after the presentation of the findings of the individual and cross-case studies.

The focus of each case study was the measurement of entropic-related complexity within the manufacturing organisation and at the supplier-customer interface. Data collection for complexity calculations consisted of electronic and/or paper-based data on dates and times of: actual versus expected deliveries from suppliers; actual versus expected internal production; and actual versus expected despatches to customers. As the entropic measure of complexity is systemic and integrative, it allows for comparison across case studies and at different times (Calinescu et al., 1998).

The Entropic-related complexity

The entropic-related complexity measure used in this paper (complexity index) is derived from information theory, as “the amount of information required to monitor the state of the system, in order to manage it” (Sivadasan et al., 2002: 81). This measure has been used in previous research to investigate complexity in supplier-customer systems, including uncertainty and variety of products and flows, in terms of variations in delivery time and quantity (Sivadasan et al., 2006, 2010, 2013; Huaccho Huatuco et al., 2010). These earlier papers present specific aspects of case studies; for example, the focus in Huaccho Huatuco et al. (2010) was on measuring the effects of *before* and *after* a managerial intervention, such as lean implementation or BPR. By analysing and abstracting generic themes across several case studies in the context of state of the art related literature, the novel contribution of this paper

is in developing the theoretical understanding and model of CT, as set out in the proposed new model of CT.

This complexity measure is based on Shannon's (Shannon, 1948, 1949) information-theoretic entropy as follows. Given a set of n states $E = \{e_1, e_2, \dots, e_n\}$ and their

respective a priori probabilities of occurrence, $P = \{p_1, p_2, \dots, p_n\}$, where $p_i \geq 0$ and

$\sum_{i=1}^n p_i = 1$, entropy, H , can be calculated using Equation 1.

$$H = -K \sum_{i=1}^n p_i \log_2 p_i \quad (1)$$

In Equation 1, H is entropy, K is a positive constant ($K = 1$ throughout this paper), n is the number of states, and p_i is the probability of occurrence of state i . Entropy measures information rate and its units are bits per state (bps), i.e. this unit reflects the average amount of information required to define each state. Further details on the properties of entropy as a method for measuring complexity in manufacturing systems can be found in Smart et al. (2013), Lukáš and Plevný (2015) and Chryssolouris et al. (2013).

Complexity can be measured at different SC positions, e.g. internally, within the manufacturing organisation, and at the supplier-customer interface. The measured entropy represents the complexity index considered in this paper.

This paper presents findings relating to complexity due to variations in the timing of deliveries from suppliers, production and despatch to customers. These time-based variations were identified by the case study organisations as being one of the most important variations affecting their SC performance. The importance of compression of lead times and on-time delivery is widely mentioned in the literature, e.g. regarding quick response as competitive advantage (Suri, 2010). Also, considering variations in time allows for an objective comparison of variations across different interfaces and supplier-customer systems. We

focused on variations in time, between planned and actual, in terms of deliveries from suppliers, internal production and despatch to customers.

For deliveries from suppliers, internal production and despatch to customers, the number of states of variations in timings was simplified and standardized to three: “Early”, “On time” and “Late”. These states were meaningful to all decision makers, e.g.: late deliveries from suppliers have a knock-on effect on production and costs associated with delayed production; and early deliveries from suppliers lead to stock holding costs. These three states were used in the case studies (i.e. at the internal production and at supplier-customer interface), enabling comparison within and across the cases.

Calculation of the complexity index

The complexity index was calculated on each side of an interface, i.e. where goods are transferred across either an internal or an external SC interface. Since all calculations were carried out using three states, the complexity indices are comparable across case studies. For any system with three states (here, “Early”, “On time” and “Late”), the Maximum Entropy is $\log_2(3)$ or 1.58 bits per state (bps). As an example of the complexity index calculation, suppose that for a particular case, the “observed” probabilities of occurrence for the “Early”, “On time” and “Late” states were: 0.2, 0.4 and 0.4, respectively, then the complexity index calculation is: $-0.2 \log_2(0.2) - 0.4 \log_2(0.4) - 0.4 \log_2(0.4) = 1.52$ bps.

We categorised the possible range of the complexity indices into seven categories, in order to (i) obtain sufficiently informative and relevant quantitative results and insights, (ii) ensure results are meaningful to decision-makers and (iii) facilitate comparison. Typically, around seven states are used in complexity index calculations following the recommendation by Miller (1956) that the human mind is expected to receive, process and remember around seven categories of information. So, in this paper, seven categories of complexity ranges were

chosen, as follows: $[0, 0.4]$ bps = “Extremely Low”, $(0.4, 0.6]$ = “Very Low”, $(0.6, 0.8]$ = “Low”, $(0.8, 1.0]$ = “Medium”, $(1.0, 1.2]$ = “High”, $(1.2, 1.4]$ = “Very High”, and $(1.4, 1.58]$ = “Extremely High”.

Case studies selection

The case studies were conducted in UK manufacturing organisations, both internally and at the supplier-customer interface. All the participating organisations were actively seeking strategies for managing, mitigating or reducing their complexity. The criteria for companies’ selection in the sample were to include UK-based manufacturing companies working together in a supplier-customer system, providing access to both supplier and customer organisations’ data within a similar period of data collection. The case study organisations are described in Table 1.

Table 1: Fact file summary of case studies

Case study	What do they manufacture?	Product Complexity	Process Complexity	What are their key performance indicators?	Which Market do they operate in?
A. FMCG	Supplier: Plastic bottles. Customer: Cleaning liquids.	Relatively low: standardized.	Relatively low: production line.	Supplier: efficiency, cost. Customer: responsiveness, flexibility.	Competitive

B. Co-located FMCG	As above	Relatively low: standardized.	Relatively low: production line.	Supplier: same as customer: responsiveness and flexibility.	Competitive
C. Aerospace	Supplier: Printed Circuit Boards. Customer: Aircraft manufacturer.	Relatively high: high precision required for aerospace products.	Medium: cell production.	Quality and flexibility.	Niche

Validity and reliability

The case study protocol (Voss et al., 2002; Pettigrew, 1990; Yin, 2013) adopted in this study included the following phases: familiarization, data collection, presentation of results, and report. Triangulation methods were used to ensure internal validity of the findings, in such that interview responses from key personnel were used to corroborate live data collection and historical data. Frequent regular live observations were made of material and information flows, and significant periods of historical data were collected. Where inconsistencies were noted in the data or in observations, this was checked with relevant personnel prior to the complexity analysis. To further validate the findings, preliminary results were presented to the managers of the participating organisations at the beginning, during and after each case study, to check whether the researchers' understanding, interpretation and use of data, as well as the quantitative results and qualitative insights, fully and accurately reflected reality. In terms of reliability, the researchers were able to apply and replicate the same case study methodology across all the case studies in this paper, which were carried over a period of time spanning several years. The complexity measurement methodology has been applied in

different settings and by different teams led by different researchers (e.g. Calinescu et al., 1998; Sivadasan et al., 2013) demonstrating that the methodology is generic and transferable.

Case studies – descriptions and qualitative analysis

B. Fast Moving Consumer Goods (FMCG) supplier-customer system

This case study involved two large organisations in a supplier-customer relationship in the Fast-Moving Consumer Goods (FMCG) sector. The supplier's production facility was located about 40 km from the customer, with delivery by lorry every few hours. Since the supplier was producing to and delivering from stock (with no apparent issues of storage space), it was not really considering the updates of the demand forecasts that the customer was sending regularly, as the supplier knew that these forecasts were likely to change substantially up until the last minute.

The key performance measures for the supplier were machine efficiency (100% target) and cost reduction, whereas for the customer they were flexibility and responsiveness, i.e. being able to deliver according to the latest request by the end customer. For the suppliers' interface 258 data points were recorded during the five-week period.

Complexity was transferred from the customer to the supplier in the form of changes in requests up until the last minute. Complexity was transferred from the supplier to the customer in the form of early deliveries which had to be held at the customer's premises (which could be easily absorbed by their excess storage capacity), or late deliveries, impacting on the customer's production schedule (which could lead to not satisfying the end customer). The case study analysis found that the customer generated and exported complexity to the supplier, while the supplier absorbed this imported complexity by using stock as a buffer.

B. Co-located FMCG supplier-customer system

This case study involved the same two organisations from the FMCG case study A above. The purpose of this case study was to assess the complexity after the supplier had moved a small, dedicated production facility onto their customer's premises.

The supplier's production facility was now located next door to the customer's production facility, with deliveries from supplier to customer being made, literally, through a hole in the wall. The supplier was now constrained by limited physical storage space, so it could no longer produce to stock, at least not in the quantities they were accustomed to before integration. The demand forecasts sent by the customer needed to be taken into account more accurately than before, since having machines making the wrong product, in terms of excess or too early production, could no longer be afforded, as there was limited storage space. This implied a lot of coordination between production managers and the SC manager, at both supplier and customer. This coordination meant an increase in the number of information flows and in the amount of information transferred in the form of more frequent meetings (on a shift-by-shift basis) and more documents being exchanged. New joint key performance indicators were responsiveness and flexibility. For the customers' interface 313 data points were recorded during the eight-week period.

Complexity was transferred from supplier to customer by not being able to fulfil their latest requests as there was no longer any spare storage capacity. Complexity was transferred from customer to supplier by continuing to change requests up until the last minute. The case study analysis found that the customer continued to generate and export complexity to the supplier while the supplier absorbed the imported complexity by closely synchronising its production with that of the customer, rather than through using excess inventory holdings as buffer stock, as before.

C. Aerospace supplier-customer system

This case study consisted of a supplier which was a SME supplying to a much larger organisation. The supplier provided specialized parts for a highly customised and complex product produced by the customer. At the time of the case study, normal delivery times were adhered to by the supplier. Furthermore, the supplier was able to capitalize on the relatively frequent last-minute requests made by the customer by charging a premium for fast turnaround deliveries. The key performance indicators were quality and flexibility. As a customized production case, the transactions were less frequent than Cases A and B, overall 185 data points were recorded during the six-month period.

Complexity was transferred from customer to supplier by placing orders at the last minute, however the supplier organisation was able to charge and accommodate for this and therefore no complexity was transferred back to the customer organisation, since deliveries were made according to the agreed schedule. Internally, the large customer organisation was generating complexity due to its complex products, and the supplier was absorbing complexity and exporting charges for managing complexity. The case study analysis found that the customer was generating and exporting complexity to the supplier, whilst the supplier capitalised on this by charging a premium for fast-turn-around delivery.

A summary of complexity-related findings across case studies is presented in Table 2.

Table 2: Summary of CT behaviour for each case study

Supplier-customer system case study	What complexity situation were they in?	Variation in Demand	Implications for suppliers' interface	Implications for customers' interface	How they managed that complexity?
A. FMCG	Customer frequently	Relatively high	Supplier ignored	Customer trying	Supplier

	<p>changed their order.</p> <p>Large amount of stock was held at both the supplier and customer sites.</p>	<p>due to end customer, e.g. retailers' promotions.</p>	<p>customer's forecast since it was known they would be highly inaccurate.</p> <p>Supplier able to deliver from stock.</p>	<p>to achieve higher responsiveness to its own customers, however operating leanly at the same time, e.g. zero inventory, transport costs.</p>	<p>delivered from stock.</p>
<p>B. Co-located FMCG</p>	<p>Supplier was handling more complexity with limited stock.</p>	<p>Relatively high due to end customer, e.g. retailers' promotions.</p>	<p>Supplier found it difficult to make the right product at the right time, since last minute changes made by customer.</p> <p>Production normally planned in long runs, however no space for final stock.</p> <p>Needed to cancel batches not required any more.</p>	<p>Frustration in the lack of responsiveness by supplier, which was now next door.</p> <p>More information exchange needed than in stock-driven case.</p>	<p>Co-location, leading to frequent exchange of information.</p>
<p>C. Aerospace</p>	<p>Understand complexity as how to improve the processes.</p>	<p>Low to medium: some ability to predict.</p>	<p>Supplier was long-term (established) and able to capitalise on the customers' last-</p>	<p>Customer was dependent on supplier of specialized part.</p> <p>Normally</p>	<p>Customer charged a Premium for Fast Turn Around products.</p>

			minute requests, by charging a premium for Fast Turn Around (FTA) products.	reliable.	
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Complexity indices for cross-case analysis

The complexity indices were calculated using Equation 1 to enable cross-case analysis with direct comparison of the complexity levels for the diverse case study organisations introduced above.

Each complexity calculation was based on a large number of data points, e.g. 258 for suppliers' interface in case study A (FMCG). The number of data points per case study interface varied because of the format of data recording (electronic or on paper) and the number of transactions (date and time of deliveries from suppliers and despatches to customers) that occurred across the particular interface during the observation period. The entropy measure assumes that the system is stationary (Frizelle and Woodcock, 1995), so enough data points were obtained to give a consistent estimate of the system's behaviour, even if that behaviour is variable.

Table 3 presents the findings from the supplier-customer systems and identifies the complexity internally and at the supplier-customer interface. It can be seen that for the supplier-customer interface, similar levels of complexity are observed as the supplier's internal complexity, whereas the customer's internal complexity is higher than both the supplier-customer interface and the supplier's internal complexity. In doing so, some mechanisms by which CT may also occur towards downstream SC partners is presented next by analysing both the quantitative and qualitative results.

Table 3: Measured internal complexities of customer supplier-customer systems with qualitative assessment of level of complexity and identification of organisational type

Supplier-customer system Case study	Supplier (Internal) (bps)	Supplier-Customer interface (bps)	Customer (Internal) (bps)
A. FMCG	1.07 High	1.16 High	1.27 Very High
B. Co-located FMCG	1.00 Medium	1.00 Medium	1.30 Very High
C. Aerospace	1.36 Very High	1.37 Very High	1.48 Extremely High

Next, some key points from Table 3 can be further explained as follows:

- a. Most of the complexity levels range from “Medium” to “Very High”. This is not surprising, since the organisations involved in this study shared the common desire to manage, mitigate or reduce their perceived high levels of complexity.
- b. The “Extremely High” value relates to the internal complexity measures of the customer in the Aerospace supplier-customer system (Case C). This is supported by the qualitative analysis of these three organisations; the evidence from interviews and observations was that complexity was “out of control”.

- c. Organisations in the sample which had undergone a managerial intervention, e.g. co-location (Case B), were controlling their complexity more effectively than those organisations that had not undertaken an intervention (Case C). More frequent communication and fewer product lines had enabled the organisations to reduce the impact of variations and disruptions to their processes.
- d. The small organisation supplier in the Aerospace supplier-customer system (Case C) manages complexity by charging their large customer for accepting complexity from
- e. them. This response mechanism allows them to survive, succeed and manage their relationship with a much larger customer, who might be accustomed to higher levels of complexity.

To summarize the findings of this work, we have shown that companies' interventions to managing complexity can have a measurable impact on their complexity levels and overall performance. The interventions involved significant changes to their SC structure or internal operations, such as removing a stage in the SC, or charging customers for last-minute changes. Theoretically, these efforts were consistent with the reduction in complexity index. Practically, these findings confirm that operational complexity is systemic, and that it requires committed managerial effort to be reduced.

We show in the following section how manufacturing organisations can understand their own CT behaviour and the CT behaviour of their SC partners in order to take a deliberate and meaningful approach to CT in their SC.

A new model of Complexity Transfer (CT) in supplier-customer systems

This section presents a new model of CT in supplier-customer systems, by building on Sivadasan et al. (2004)'s earlier conceptual CT framework. Sivadasan et al (2004) proposed that organisations have the capacity to internally generate and absorb complexity and to

externally import and export complexity; and identified those that generate and export complexity as ‘sources’ and those that absorb and import complexity as ‘sinks’. They also proposed that organisations can export complexity downstream to its suppliers through unreliable deliveries and upstream to its customers through change requests. When CT takes place from customers to suppliers, this can also have implications for the internal complexity of the customers, as the supplier may rebound complexity back on to their customer (Sivadasan et al., 2010). This phenomenon was referred to as complexity rebound, since the complexity that a supplier or customer imposes on an organisation may be reflected back to the originator, because of the limited capacity of a company to cope with the additional complexity the complexity originator is imposing upon them (Sivadasan et al., 2010).

The new CT model also extends, encapsulates and frames key ideas from other researchers (Boisot and Child, 1999, Ashmos et al., 2000 and Aitken et al., 2016). Findings from Boisot and Child (1999) that individual organisations adopt complexity reduction and complexity absorption strategies to adapt to their complex contexts (environments) may be framed by the new CT model. Similarly, the proposal from Ashmos et al. (2000) that organisations which adopt complexity absorption (goal, interaction and structural complexity) perform better than those organisations just looking to reduce complexity may also be explored further using this new model. The new CT model also provides a framework to consider findings from Aitken et al. (2016) who investigate the elimination and absorption of complexity according to upstream, internal and downstream position in the SC. For example, the new model proposes that in supplier-customer dyads, external imported complexity can be absorbed, and that internally-generated complexity can also be managed.

In building on previous work, the proposed new CT model (see Figure 1) considers the balance between an organisation’s capacity to manage its own internal complexity and to

manage the external transfer of complexity at its supplier and customer interfaces. Similar to Sivadasan et al. (2004), the new model incorporates both an organisation's ability to absorb and generate internal complexity as well as an organisation's ability to externally import or export complexity at the SC interface.

Internal complexity refers to the fact that all manufacturing organisations are likely to be subject to stochastic perturbations to its production schedule. We propose that an organisation that can manage well the complexity of its own internal operations is an Absorber. It is an organisation that can cope with its own complexity as well as any complexity imported from their SC partner, so it manages to adhere well to its internal schedule, with low levels of complexity. This behaviour may be achieved by having a limited range of products, flexible production capacity and some inventory. This organisation will likely adhere to its promised delivery schedule, with respect to both time and quantity delivered. In contrast, a Generator is an organisation that does not have good control of its internal operations, as will be evident from measurements of its internal complexity, which are likely to be in the upper half of the range, from Medium to Extremely High. This organisation will have poor control of its operations, with internal schedules that are not adhered to, both in terms of timing and quantities of the goods produced. Because of its poor levels of internal complexity management, this will likely be evident to its customers and suppliers, through poor adherence to delivery schedules, and frequent change requests to its suppliers and delayed or incorrect deliveries to its customers.

External complexity refers to how an organisation copes with the demands of its suppliers and customers. By measuring the complexity at the interfaces between an organisation's suppliers and customers, we can determine whether an organisation is an Exporter or Importer of complexity, depending on the balance between the complexity it

generates and accepts across the interface with its SC partners. The new model of CT in supplier-customer systems is presented in Figure 1.

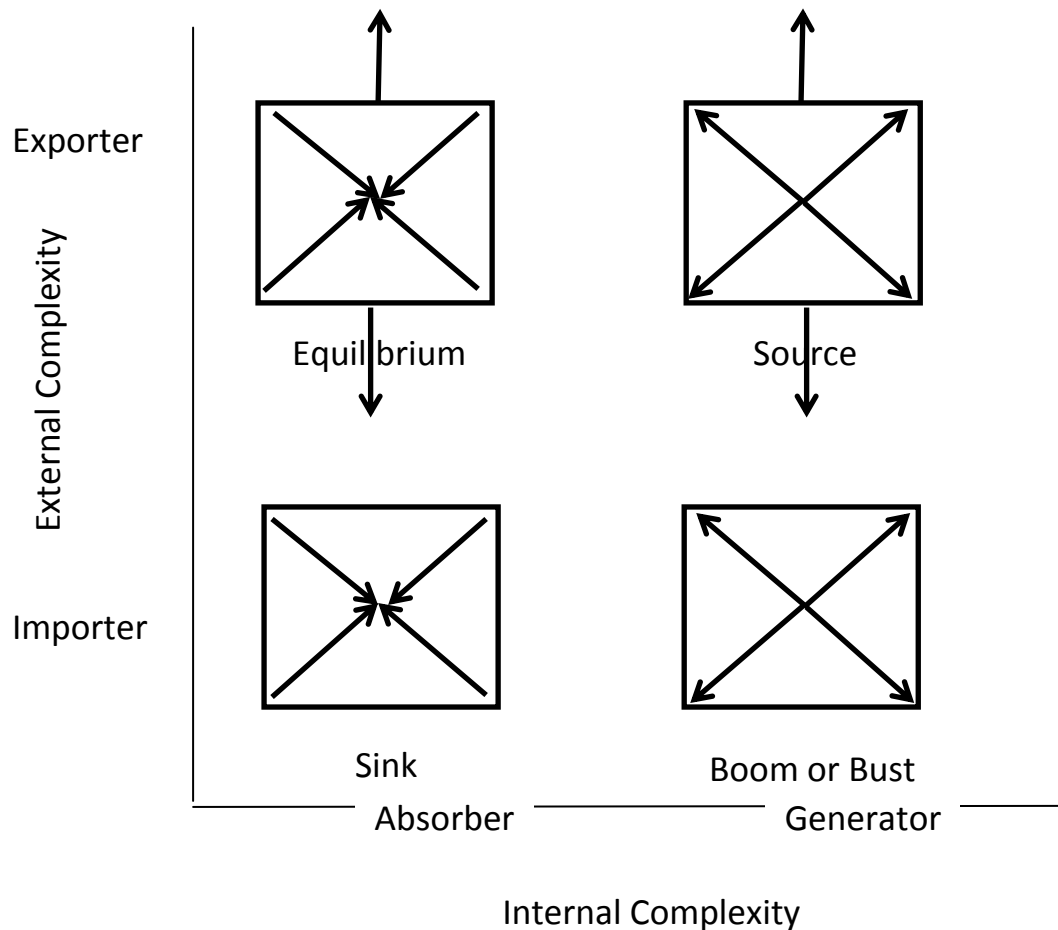


Figure 1: A new model of Complexity Transfer (CT) showing the relationship between internal and external complexity.

In addition to identifying complexity Sinks and Sources (Sivadasan et al., 2004), the new proposed model also extends the CT concept to include ‘equilibrium’ in relation to organisations that both export and absorb similar levels of complexity, and ‘boom or bust’ in relation to organisations that both generate and import complexity.

- Sink (Absorber and Net Importer): Typically, a Sink organisation is effective at handling the complexity being transferred to it by suppliers and customers.

Its suppliers are not reliable, but it counteracts this with inventory and/or excess production capacity. Its customers issue late change requests, which it usually accepts, requiring adjustments and updates to internal plans and schedules, or drawing down from Finished Goods Inventory. Manufacturing organisations, e.g. the supplier organisation in FMCG and Co-located FMCG (Cases A and B) are very good at absorbing, and will accept imported complexity, mainly from their customers (Table 3). In fact, the reliability of their deliveries was a feature of this supplier, which it was able to achieve by holding quantities of stock and, after co-location, a flexible approach to schedule management. In the cases considered, the CT for Sink organisations was mainly from their customers.

- Source (Generator and Net Exporter): A Source organisation generates a high-level of complexity internally, which affects their suppliers and/or customers. Manufacturing organisations, e.g. the customer organisations in all three cases, with the result that their complexity was exported to suppliers, which rebounded on their supplier-customer interfaces, see Table 3.
- Equilibrium (Absorber and Net Exporter): An Equilibrium organisation absorbs some of the complexity it self-generates or that is transferred inwards by its suppliers or customers. Equilibrium organisations are successful in managing CT, balancing the stability of their internal operations with those of their suppliers and customers. In the case of suppliers, they are encouraged to be reliable by developing close relationships, and in the case of customers they are charged extra for any changes to the original plan. This willingly adaptive behaviour may be perceived by their customers as flexibility. This was observed in Aerospace (Case C). The supplier of the Aerospace supplier-

customer system showed complexity rebound to its larger customer, as a result suffered high levels of complexity at its interface, the supplier was able to satisfy the customer by charging a premium to deter some of the complexity imports, see Table 3. Therefore, Equilibrium organisations have complexity-absorbing or complexity-deflecting response mechanisms in place, e.g. premium charges, good inventory management or clear boundaries in terms of exchanging information.

- Boom or Bust (Generator and Net Importer): ‘Boom or Bust’ organisations generate high levels of complexity internally, but they also allow suppliers and customers to add to it by accepting change requests from their customers and unreliable deliveries from their suppliers. These were not observed in any of the case studies carried out by the authors. Two extreme modes can be considered to characterize this ‘Boom or Bust’ behaviour. First, consider the mode where detrimental complexity is being generated and imported. Any organisation operating in this situation would be ‘fire-fighting’ and would likely collapse in the long term due to its inability to manage internal and interface complexity. Next, consider the mode where only beneficial complexity is generated and imported. Organisations operating in this extreme case are likely to be highly nimble ‘entrepreneurial agents’ or ‘creative hot-houses’ maximizing their responsiveness to the uncertainty and variability of customer demands through their internal creativity and spontaneity. Therefore, ‘Boom or Bust’ organisations are difficult to observe or have their complexity measured in practice, since they do not display stationary behaviour.

All organisations which participated in the case studies presented in this paper are classified according to the new CT model. See Figure 2.

External Complexity	Interface Exporter	EQUILIBRIUM <i>Supplier in Aerospace</i>	SOURCE <i>Customer in FMCG</i> <i>Customer in Co-located FMCG</i> <i>Customer in Aerospace</i>
	Interface Importer	SINK <i>Supplier in FMCG</i> <i>Supplier in Co-located FMCG</i>	BOOM or BUST
		Absorber	Generator
		Internal Complexity	

Figure 2: Case study examples and how they fit into the new model of CT

Insights from the new model of CT can have practical implications for SC configuration and SC design. To some extent, as Inman and Blumenfeld (2014) propose, SC design is affected by the complexity of the products being made. On a more general level, as the supply network consists of a series of supplier-customer systems (dyads), the choice of SC partners will also have an effect on the design, configuration and performance of the SC (Chopra and Meindl, 2012; Song et al., 2018). So, if an organisation is an Exporter, partnering with an Absorber organisation is more likely to lead to a complementary SC partnership – and the relationship is more likely to survive than if the Exporter was partnered with a Generator organisation.

Discussion and conclusions

This paper set out to address three research questions.

- What are the response mechanisms of CT in supplier-customer systems?’

There are various mechanisms of CT in supplier-customer systems used by organisations in order to cope with complexity from variations in deliveries from suppliers, variations in production schedules internally and variations in despatches to customers. The case studies have shown the implementation of response mechanisms through which organisations can cope with the demands of the SC partner. Examples of response mechanisms discussed in this paper included: clear boundaries for exchanging information, effective inventory management systems, and premium charges to reflect costs associated with re-scheduling production. This is in line with current literature that provides some guidance on either reducing or absorbing complexity, as response to managing complexity (Aitken et al., 2016).

- What is the impact of CT on the organisations within those supplier-customer systems?

It may be inferred here that Source and Sink organisations would be expected to work well together in a supplier-customer relationship. The Sink manufacturing organisation can absorb / import complexity. However, it is unlikely that a Sink organisation could successfully cope in the long-term with continuously absorbing increased sources of complexity without imposing penalties or contractual changes, as coping with complexity adds costs to an organisation’s operations. Furthermore, although CT has been acknowledged in the literature to occur towards upstream SC partners (from suppliers to customers), findings from this paper suggest that complexity is also transferred towards downstream SC partners (from customers to suppliers).

- How could these organisations respond to manage complexity effectively?

Organisations can look at their current supplier-customer systems and plan to make informed decisions when renewing or entering new partnerships. By knowing their own CT behaviour, they can compare and contrast with the type of CT of potential SC partners that would be most beneficial for them in future. Therefore, this new CT model could help a future SC configuration or SC design decisions. Alternatively, organisations can implement structural or policy changes in order to change their CT behavioural pattern, within a supplier – customer relationship (dyad). This approach is consistent with the context- and interaction-specific view of SC complexity taken by Dittfeld et al. (2018).

The proposed new model of CT is a novel contribution towards wider theoretical developments in SC research. The development of a new model of Complexity Transfer (CT) in this paper, which is currently lacking in the literature, represents a novel contribution towards the push for more theoretical developments in SC research. Among those we have for example, Halldórsson et al. (2015) on SCM theorising from different angles: interdisciplinary, to/from practice, or from practice only, also Carter (2011), Carter et al. (2015) on developing a SC theory, and Mena et al. (2013) on multi-tier SCM theory. In this vein, the proposed new CT model provides the means to monitor and manage the balance between internal and transferred complexity, especially when most of the literature is biased towards supply side amplification, i.e. the bullwhip effect. This paper uses information-theoretic entropy to measure complexity to provide some evidence that CT may also occur towards downstream SC partners.

Some research findings suggest that close supplier integration works well in risky environments (Wiengarten et al., 2016) and that SC information integration is valuable under high product and market complexity (Wong et al., 2015). The findings in this paper present evidence that supplier integration is effective if the SC partners show the right combination of

CT, e.g. Source and Sink. Also, CT could lead to the situation of a Source organisation entering an inadequately supported relationship with another Source, which could lead to both shifting towards 'Boom or Bust'. When an organisation has identified itself as a complexity Source, it will need to put its own house in order or be willing to accept the demands made by Sink or Equilibrium SC partners, which will put in place measures to protect their own stability.

The CT model provides a categorisation of organisations according to their management of internal and complexity transferred to/from their SC partners. By analysing SC partners in terms of their propensity to generate or absorb complexity, we give SC managers and buyers a new tool to identify those organisations that are likely to be able to collaborate well, given their own needs for flexibility. Although organisations have policies and good intentions to adhere to their production schedules, for a variety of reasons they may not be able to achieve and maintain their desired standards. This paper provides SC managers with (i) additional, sound, quantitative evidence and qualitative insights that they need to measure the complexity-managing performance of their SC partners, and of themselves, and (ii) the necessary measurement methods. Organisations are encouraged to use these methods to identify where, i.e. internal or at the supplier-customer interface, and types of strategies needed, in order to suitably manage the levels of CT.

Managers may benefit from using the new CT model to understand the impact of poor complexity management on their own operations, and its impact on their SC partners, whether customers or suppliers. Organisations will be able to understand the need for systemic changes to manage the costs associated with complexity, and to inform long-term strategic decisions to improve the performance and stability of their SC partnerships. Furthermore, the understanding of the model of CT behaviours could be used as a means to guide the distribution of costs and benefits between SC partners. This paper also points out

the specific methods that organisations have used to cope with complexity when they have found themselves in a supplier-customer relationship with an organisation that is a complexity Source, such as holding inventory and spare capacity, or physical re-location, to improve the exchange of goods and information. Our case studies have shown that sustained, evidence-based, systemic changes to an organisation and its SC have led to better managed SC complexity.

The main limitation of case-based research is its limited ability to generalise results. This has been mitigated in this paper by using a multi-case methodology and applying the same complexity measurement to diverse case-studies, with large number of data points for each case. Nevertheless, in terms of generalisation it has been shown that a complexity index cross-case analysis can be carried out, by using the standardised instrument described earlier for assessing complexity levels associated with late or early deliveries.

In practice, SCs and supply networks are not simple linear dyadic partnerships and often organisations will partner with multiple suppliers and customers and thus simultaneously operate in several SCs and networks. This may mean that, for any isolated supplier-customer dyadic relationship analysed, the same organisations may find that it is operating in different quadrants of the CT model. The findings from each supplier-customer analysis would still be valid, but any strategies that are implemented need to take into account any impact on other dyadic partnerships. Interdependencies between different suppliers' deliveries and despatches to different customers may necessitate a different approach to complexity measurement and transfer. Though this is a limitation, the benefit of the dyadic unit of analysis is that any SC or supply network configuration can be modelled using the basic building block of customer-supplier system.

Another limitation of this research is that, the authors have not yet studied organisations that would fall into the 'Boom or Bust' quadrant. Targeted cases would be

needed in order to determine whether or not this quadrant is likely to occur in practice. A ‘Boom or Bust’ organisation would both generate complexity internally, and import complexity from its SC partners. Organisations that would operate in such an unpredictable environment would either ‘fold’ or prosper depending on whether they are ‘fire-fighting’ or leveraging the uncertainty as entrepreneurial agents. However, it could be argued that although companies in trouble and nimble entrepreneurs are fairly common, they were not studied in any of our case studies. One explanation may be that the nature of their business (entrepreneurs) or situation (companies in trouble) means that they are not in a position to take part in or seek out research studies.

A further research avenue would be to explore the impact of CT in SC practices on long-term risk, resilience and sustainability in SCs. So, future studies could focus on complexity transfer (CT) in relation to failures, disruptions or risk propagation, linking to the work by Craighead et al. (2007) and Ledwoch et al. (2018), and to the complexity in sustainable SCs work of Bai and Sarkis (2018). In those papers, the notion of node criticality and topology comes into play, as any disruptions affecting that key supplier (node) will have major consequences for the SC network as a whole. Furthermore, sustainable supply chain complexity involves additional requirements, sustainable practices and performance objectives.

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Appendix A: List of interviewees per case

Supplier-customer case study	Job titles	Key material and information flows monitored
A: Fast Moving Consumer Goods (FMCG)	Supplier: <ul style="list-style-type: none"> Bottles Planner Production Manager Warehouse Manager Managing Director Labels Planner Customer: <ul style="list-style-type: none"> Factory Scheduler Materials Planner Supply Chain Co-ordinator Despatch Planner Warehouse Leader 	Supplier: <ul style="list-style-type: none"> Customer Demand Information (CDI) Forecast, CDI 1 week, Material Requirements Expected and Actual Despatch Scheduled Production, and Actual Production Customer: <ul style="list-style-type: none"> Marketing and Sales Organisation (MSO) Requests, Customer's Revised Plan, White Plan, Blue Plan Actual Production, Actual Deliveries CDI Forecast, CDI 1 week, Material Requirements, Expected Deliveries Expected and Actual Despatch
B: Co-located FMCG	Supplier: <ul style="list-style-type: none"> Factory Planner Production Manager Operations Manager Shift Supervisor Customer: Same as in case A's customer.	Same as case A, without the CDI forecasts and other information flows related to remote deliveries.
C. Aerospace	Supplier: <ul style="list-style-type: none"> Sales Manager Sales officer Engineering Manager Production Manager Accountant Despatch Manager Customer: <ul style="list-style-type: none"> Purchasing Manager Engineering Manager Production Manager 	Supplier: <ul style="list-style-type: none"> Sales: Expected and Actual quantities and dates from Request for quotations, Quotations, Purchase Orders, Progress Report Engineering: Expected and Actual completion date Production: Scheduled and Actual Production, Expected and Actual Despatch Accounts: Expected and Actual Payment Customer: <ul style="list-style-type: none"> Supplier's Acknowledgements - Purchase Orders Supplier's Progress Reports - Purchase Orders Supplier's Deliveries - Purchase Orders

	<ul style="list-style-type: none"> • Quality Manager • Accountant 	<ul style="list-style-type: none"> • Progress Reports – Supplier’s Deliveries • Supplier’s Delivery Dates - Issue Dates • Purchase Orders Due Dates - Issue Dates
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