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Operations Flow Effectiveness: A Systems Approach to Measuring Flow Performance

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Purpose

Effective operations management systems (OMS) measurement remains a critical issue for theorists and practising managers (Neely, 2005, Bititci et al., 2012). Traditional labour efficiency measures sufficed when all that was made could be sold or when mass production systems filled warehouses with stock and the OMS had little relationship with 'the consumer'. Modern manufacturing systems require a different form of flow optimisation (beyond labour efficiency) measurement (Schmenner, 2015). The essential unit of measure for all OMS designs is the optimal use of time for process value-adding and the flow of materials into and from the conversion process. Timely flow, therefore, satisfies the needs of multiple organisational stakeholders including cash flow (accounting), consumer reaction times (marketing) and the general steady state flow of materials (sales and supply chain). This paper presents the results of testing a new performance measure of Operations Flow Effectiveness (OFE) with ten purposively selected cases.

Design/Methodology

The paper is theory building using ten, purposively selected, longitudinal case studies drawn from the UK high-value manufacturing (HVM) sector using a pluralist methodology of interviews, observation and secondary data.

Findings

The Operations Flow Effectiveness (OFE) measure provides a holistic view of material flow through the input-process-output cycles of a firm. The measure highlights OMS design weaknesses and flow inhibitors that reduce cash flow using a time-based approach to measuring OMS performance. The study validates the OFE measure and has identified six key design elements that enable high flow performance.

Originality/Value

The paper tests a new process-focused flow performance measure. The measure supports a holistic approach to the manufacturing enterprise and allows different OMS designs to be evaluated so that organisational learning may be enacted to support performance improvement.

Keywords

Flow, Performance measurement, High-value manufacturing, Case study.

Introduction

Modern operations management discourse, in an era of make-to-order, smaller batch sizes, and a greater emphasis on waste elimination (Womack and Jones, 1996), has returned to the central question of what is flow and how should it be measured. The traditional dominance of mass production measures – myopically focused on labour productivity and maximum utilisation of the production process – has attracted criticism in most volume and repetitive order settings. For the modern business, measuring and managing for pure process efficiency is unlikely to nurture the 'externally supportive' position so cherished by Hayes and Wheelwright (1984) nor does such "traditional efficiency" (essentially labour productivity) align well with a modern concern for 'servitization', personalized production, mass customization, and the new technological advances presented by Industrie 4.0, 3D Printing and new technology-based 'S' curves (Rogers, 2010).

The concept of 'system flow' is poorly defined for these new emergent operations management models. The increasing emphasis on the circular economy and a migration to higher value adding sectors for mature economies, means productivity-based cost efficiency measurement is increasingly a questionable operations management measure (Schulte, 2013, Bonciu, 2014, Lewandowski, 2016). The dysfunctions of applying ineffective or poorly aligned 'flow' measures has been well explored in the literature (Goldratt, 1990, Deming, 2000), however, agreement on effective flow performance measures has yet to be reached for new high-value manufacturing contexts and a new world of ultimate flexibility and personalisation. The latter may provide manufacturers with access to product markets where greater profits exist from personalized production but it does not allow operations managers to ignore the measurement of process 'efficiency' for learning and control (Technology Strategy Board, 2012a, MacBryde et al., 2013). It is not just a 'developed' country challenge to transition to higher value manufacturing. Emerging manufacturing economies have already overtaken France and the United Kingdom in terms of manufacturing Gross Value Added GVA (Mckinsey Global Institute, 2012) so despite the progress made in operations management technology and models, the measurement of flow remains a key challenge. The modern imperative is therefore to measure value added time and understand how high performance is supported by organizational features that optimize people, information, equipment, material flows and improvement based on organizational learning to occur (Größler et al., 2006).

This paper focuses on purposively selected cases drawn from the British High-Value Manufacturing (HVM) sector as a context most likely to reflect the general movement from traditional mass production designs to more experimental OMS models. A cross-comparative case study involving ten manufacturers was selected and the Operations Flow Effectiveness measure was applied to assess the flow performance of each organization as a means of validating the measure. Additional assessments of the 'states' of six key design elements were undertaken to determine how these 'states' support high levels of operations management flow performance.

Operations Management & Measurement

A systematic literature review was undertaken using key word searches and citation databases including EBSCO, Google Scholar, Emerald Insight and Science Direct archives to identify studies of operations management performance measures. The key words used for searches included operations management and measurements, supply chain management and measurements, material flow measurement and other synonyms aligned with the subject of flow measurement. The results showed a lack of systematic studies and conceptual studies and a bias of papers towards lean systems reviews, environmental/green and sustainability performance measures, studies of risk measurement or humanitarian logistics performance measures, modelling of specific cases, sector specific measures and benchmarking studies. These studies were reviewed and, whilst useful, most failed to conceptualize material flow. After systematic reduction, only 33 papers, published since year 2001, were considered of use to this study and deemed to meet the qualities of process measures of flow with properties that support flow measurement of firm-level process performance.

Literature Review

The review of the extant literature commences with the positioning of OM measures for strategic elevation and the relevance of OM to a modern business. It will highlight the importance of 'material flow' and its central relationship with improved cash flow (economic sustainability), and then expose the measurement gap in the modern approach of 'Swift and Even Flow' (SEF).

The modern debate concerning OM measures and objective setting (Neely et al., 2005) can be traced to (Skinner, 1969) and the rejection of the cost efficiency 'trade-off' where a cost focus compromised all other performance objectives. For Skinner, performance was conceptualized as lowest unit cost and set within the dominant model of scientific mass production. A cost focus led to a focus on productivity through utilisation to the point of making products without orders. Later authors, founded their applied models on a 'quality first' approach to flow (Nakane, 1986, Ferdows and De Meyer, 1990) which better aligned with a competitive market environment, differentiation and the corporate sales function. The OMS 'sandcone' model (Ferdows and De Meyer, 1990) exemplified this distinct logic and evolutionary approach to performance objective mastery based on quality and treated cost as the outcome of OM design decisions (technology, layout, etc.). The quality focus generated benefits in terms of time compression, dependability and later flexibility of the production process as the competitive weapon for strategic elevation that Skinner (1969) and Hayes and Wheelwright (1984) so desired.

The 'quality first' agenda of the 1980s and 1990s onwards, supported the Total Quality Management and later the lean approaches to OMS and extended measurements towards a holistic understanding of end-to-end performance measurement. The emphasis on quality improvement and waste reduction supported business viability by linking the OMS with better financial performance, greater cash flow and better cash management to avoid insolvency of fundamentally profitable businesses (Boer et al., 2015).

In the quality and lean era of flow measurement, information and material flow were linked to cash flow and the economic success of the firm through a minimal consumption of cash. Unlike the traditional mass production measures that accelerated the consumption of cash through over-production, additional storage requirements and obsolescence costs (Womack and Jones, 1996). The lean approach exposed the apparent traditional low unit production costs as masking a higher overall total cost of production (Ohno, 1988). The Lean approach based greatly on Deming (2000) supported the hypothesis that sustainable competitive advantage was founded upon high material flow derived from high quality processes (Womack et al. (1990).

However, lean systems and quality systems rely heavily on repetitive flows of standardized products and a movement from large to small batches then one-piece flow (Womack and Jones, 1996). But these methods are employed in relatively closed and oligopolistic industries where demand can be controlled and products can be standardized. Internal measures of lean systems favour a rhythm (Takt time) to replenishment or measures such as the Overall Equipment Effectiveness of a given asset (Nakajima, 1988) and where production was nonetheless controlled. Indeed, during this era of manufacturing (post mass production) the ‘Theory of Swift and Even Flow’ (SEF) by Schmenner and Swink (1998) emerged but stopped well short of offering a set of performance measures that can be used to test the effectiveness and viability of lean manufacturing (Gregory, 2007, Ríos, 2010). The lean approach did however introduce the concept of time compression and just in time management (Monden (2011) as well as a movement from a current designed OM ‘steady state’ to a future state where OM redesign would enhance flow in a closed system – such as the automotive, aerospace, electronics and food production sectors (Rother and Shook, 2003). The application of lean flow systems in more open systems, where control is less easy to apply proved a challenge and resulted in maintaining excessive capacity to absorb less regular demand or a return to greater inventories of standardized products (Klug (2013).

Swift and Even Flow therefore rested heavily on enhanced physical flow through a reduction of ‘noise’ in production subsystems (making), and informational exchanges (that trigger production). Where information could not be controlled and departmental measures of utilization were present, local process optimization inhibited the system level of material flow needed for effective cash flow. System ‘noise’ and variations within a lean steady state arise from erratic demand and are amplified by unreliable equipment, erratic supplier performance, and inaccurate customer forecasts. They inhibit progress towards stockless make to order production and these variations halt the flow of materials for an entire closely coupled production and supply system. Closed lean systems and SEF seek to reduce the noise of system dynamics (Forrester, 1961, Burbidge, 1985, Towill, 1997, Forza and Salvador, 2001, Childerhouse and Towill, 2003, Geary et al., 2006, Durugbo et al., 2014, Huo et al., 2014) to enhance process flow (Schmenner and Swink, 1998, Schmenner, 2001, Schmenner et al., 2009, Schmenner, 2015). The underlying premise of the theory is that *"the more swift and even the flow of materials through a process, the more productive that process is"* (Schmenner and Swink, 2009, p.102), regardless of the capital intensity or products offered by the firm.

Despite the weaknesses of SEF, it explicitly seeks to maximize 'value added' activities whilst minimizing 'non-value added' wasteful ones internally (Ohno, 1988). SEF also supports organisational learning and improvement processes using Six Sigma, etc., to reduce such noisy variation (Schroeder et al., 2008). Schmenner and Swink (1998) argue noise and waste elimination result from management decision-making and operations management working practices and include attempts to dampen it through lean practices (Shingo, 1981), and the poorly researched methodology of Total Productive Maintenance TPM (Nakajima, 1988). SEF also seeks bottleneck optimisation by reducing process variation and reducing the forms of noise and compromised 'laws of variability' identified by Hopp and Spearman (2008) and the earlier works of Goldratt (1990).

At this current juncture in operations management thinking, SEF appears appropriate for the design of technical systems for speed and time compression based on the 'quality first' approach to optimising available productive time (minimizing errors/noise) to achieve greater flow performance. However, SEF has significant weaknesses and poorly accounts for modern approaches to manufacturing, the provision of higher value added products and the personalization of goods needed when dealing with modern customers. In short SEF is effective for relatively closed systems making standardised products. Yet modern conditions call for specialised products made in a much more flexible approach to product delivery, new socio-technical system designs needed to support truly 'on demand' manufacturing, and a fundamental need to review how flow is measured. This new 'post lean' manufacturing domain includes the challenge of Industry 4.0 and cyber-physical systems (Liao et al., 2017). Despite decades of operations management thinking, modern OMS advances have exposed fundamental issues with the conceptualization of and 'supporting states' of organisational features that support high levels of flow for a firm (Boer et al., 2015). The next section will explore the alignment of performance management systems and the exploitation of flow by an OMS.

Performance Management and Measurement Systems

There is no universally agreed constitution of an effective performance management system (Pinheiro de Lima et al., 2013), yet Franco-Santos et al. (2007) found seventeen different definitions for the term. Definitional disagreement has created confusion which limits the generalizability of traditional research (Marr and Schiuma (2003). Neely et al. (2005) usefully argue that a performance measurement system (PMS) is *"the set of metrics used to quantify both the efficiency and effectiveness of actions"* (p.1229), they also argue for a portfolio of measures to be used for modern complex and contextually embedded businesses (Srimai et al., 2011). PMS structure superordinate company goals into measures for control purposes and the measurement of flow. Traditional labour productivity and crude measures of cost efficiency oppose modern priorities for profitable customer satisfaction with minimal delay, maximum personalization at the lowest possible level of waste.

PMS should support and focus operations management (Drucker, 1954, Power, 1997), yet it can also become an inhibitor when mismatches exist between corporate need and OM measurement (Neely et al., 2005). Further aligned goals and flow measurement feedback must also be calibrated to meet the speed of the market environment if feedback is to be used to stimulate adaptation of performance and avoid noise. Too frequent feedback creates distortions and triggers reactions in the form of a "permanent sense of crisis" and time-lagged feedback can inhibit flow, particularly cash flow. As such a robust measure of OM resource flow, aligned within a PMS, can optimize flow and learning (Srimai et al. (2011) to once again achieve a swift if not even flow of materials to customers and the achievement of business strategy (Pinheiro de Lima et al., 2013). In modern times, lean systems may be regarded as achieving quality and delivery of standard products yet the realization of the flexibility stage of the 'sandcone' model of mastery and to survive in the harsh modern competitive and pen market requires a fundamental rethink of a PMS and what it promote (Neely et al., 2005).

An effective PMS derived measure will also unite and engage internal stakeholders (Melnyk et al., 2004) thereby reducing the dysfunctions of inconsistency and misalignment of measures between managers (Pinheiro de Lima et al., 2013); authors advocate a top-down and process-focused set of measures to achieve world class performance (Akao, 1991, Jonsson and Lesshammar, 1999, Franco-Santos et al., 2007, Hanson et al., 2011). Alignment of process performance measures should exploit organisational dependencies for collaboration to generate and sustain the performance needed to support the organizational needs. Measures that are closest to the input-process-output cycle therefore support process thinking and support an effective PMS (Table 1).

Features of an effective performance measurement system	Author
1. Reflect the overall strategy of the organisation	Drucker (1954), Caplice and Sheffi (1995), Jonsson and Lesshammar (1999), Neely et al. (2005), Tung et al. (2011), Micheli et al. (2017)
2. Provides a grounding for communication between stakeholders	Melnyk et al. (2004), Van Aken et al. (2005), Longo and Mura (2008), Cocca and Alberti (2010), Hanson et al. (2011)
3. Diagnose reasons for the current situation	Johnson and Kaplan (1987), Power (1997), Srimai et al. (2011), Maestrini et al. (2017)
4. Detects abnormality to trigger learning and improvement	Maskell (1991), Bond (1999), Melnyk et al. (2004), Franco-Santos et al. (2007), Gimbert et al. (2010), Franco-Santos et al. (2012)

Table 1: Features of an effective Performance Measurement System
Source: The researchers

A PMS unites an OMS and the measures of flow performance and poorly aligned systems can sub-optimise business performance. Traditionally PMS favoured productivity, profitability, throughput, or quality (Kaynak, 2003, Ahmad and Schroeder, 2003, Koufteros et al., 2005, Merschmann and Thonemann, 2011), and in the main ignored Neely et al.'s (2005) call for pluralism and 'end to end' process approach. Traditional contradictions included achieving optimal labour productivity whilst creating excessive stock, or measures of on time customer service that ignored excessive lead times. Profitability was also a problematic measure that was subject to sales teams (customer price negotiations), and product design process was a measure that could not and typically was not owned by the operations management of a firm. Throughput measurements do support flow, yet are often directed only to system bottlenecks management (Goldratt, 1990). Hence, the correct selection of time-based flow measures to support the corporate PMS goals is vitally important to modern businesses.

In a post-lean world, such measures would tend to favour the management of time and responsiveness to customer order fulfilment. The next section will explore the Overall Equipment Effectiveness (OEE), an associated lean production and world class performance measure (Nakajima, 1988) and how it provides a process focused and time-based measure that can also assess the ability of an operations management design to handle the flexibility to change between products (McKone et al., 1999) needed for modern open markets. Andersson and Bellgran (2015) argue OEE is one of the most commonly cited OM performance measures in lean operations alongside productivity and has long been used to measure maintenance system performance (Nakajima, 1988) and also production lines (Oechsner et al., 2002, Nachiappan and Anantharaman, 2006). Despite its focus on optimal time-usage for value adding (100% OEE), OEE has attracted criticism (Suzuki, 1994, Oechsner et al., 2002, Garza-Reyes et al., 2015). Suzuki (1994) argues operations effectiveness is not purely equipment dependent (materials and labour need to be considered) and Oechsner et al. (2002) propose it should only be applied to individual isolated equipment. Other authors propose inadequacies concerning ‘green factors’, labour variances, and supplier performance (Garza-Reyes et al., 2015). These criticisms are contested by McCarthy and Rich (2015) who claim most criticisms are effectively managed by the measure and its sub-measures see Figure 1. Logistical delays are captured by the asset ‘availability’ and machine speed, availability, process quality, product quality, and supply variances are all captured and can be identified by the original OEE measure of Nakajima (1988).

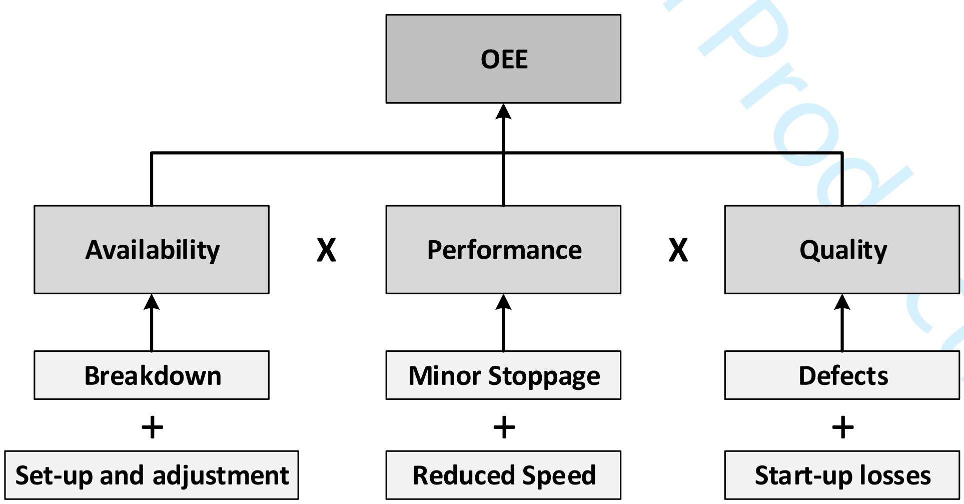

Figure 1: Calculation of Overall Equipment Effectiveness
Source: The researchers, adapted from Nakajima (1988)

Nakajima (1988) OEE measure evaluate progress towards the 'zero loss' and ideal state of Total Productive Maintenance (TPM). This measure is comprised of three components (Jonsson and Lesshammar, 1999) which are the availability (A), performance (P), and quality (P) – each expressed as a percentage – with OEE expressed by multiplying these three factors together. A resulting OEE therefore indicates performance improvement (Bamber et al., 2003) and it is argued to assist double loop employee learning (Garza-Reyes et al., 2015).

However, research concerning OEE usage (Nachiappan and Anantharaman, 2006, Tsarouhas, 2012, Garza-Reyes et al., 2015) have mainly been case studies and lacked generalization (and were discounted from this study). The authors accepted these criticisms as a failure to holistically measure flow beyond a single asset or tightly coupled production line. It was also perceived to miss the timely provision of inputs and outputs. The contemporary operations management requirement is to adopt a 'whole process' view that the traditional OEE 'point measure' could not provide and any measure would need to be capable of usage in different operations management contexts. The OEE measure could be operationalized, with modification, to measure swift and even flow when integrated with input and output quality and delivery performances.

The contemporary context of modern manufacturing is post-lean, it requires rapid and timely order fulfilment of diverse and customized product ranges and takes performance to a higher level of flexibility than previously posited by the 'sandcone' model (Ferdows and DeMeyer, 1990). SEF has been theoretically attributed to high OM performance (Schmenner and Swink, 1998, Seuring, 2009) but it lacks a measure of holistic flow performance. Given the high priority attached to the context of High-Value Manufacturing (HVM) by developed and developing economies, few studies of flow performance exist, hence this gap became the focus of this theory building study. The HVM sector represents a diverse manufacturing sector with significant variability in products and supply chains that are more representative of the different forms of OM process choice.

Research Design

The authors adopt a realist approach in grounding this context-rich study of performance measurement (MacCarthy et al., 2013). The approach allows for theory building and to identify 'outliers' whose OM systems defy the norm (Voss et al., 2002, Sousa and Voss, 2008). The HVM sector is under-researched and the poor definition of the subject and this context made the study inappropriate for a positivistic methodology (Stuart et al., 2002). Flynn et al. (1990), Eisenhardt (1991), and Yin (2013) all support the appropriateness of such a methodology as presented in Figure 2.

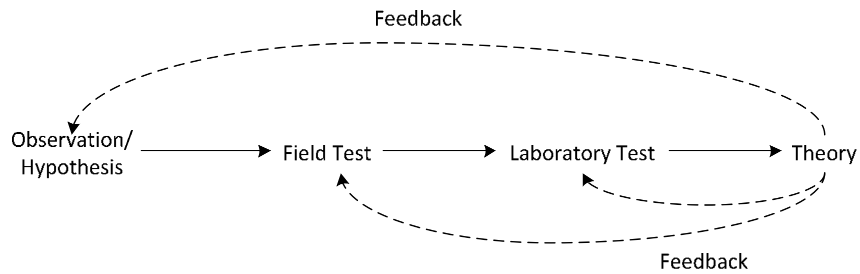

Figure 2: A strategy for combining laboratory tests with field tests in theory development
Source: Swamidass (1991)

Operations management theory has often been derived from actual practice particularly in areas such as quality, process improvement and performance in operations (Safizadeh et al., 1996, Narasimhan and Jayaram, 1998, Gotzamani and Tsiotras, 2001, Radnor and Gosselin, 2005, Größler and Grübner, 2006, Narasimhan et al., 2006, Zotteri and Kalchschmidt, 2007, Bou-Llusar et al., 2009, Khan et al., 2011, Phan et al., 2011, Soni and Kodali, 2012, Jasti and Kodali, 2014). However, much remains to be understood about OM system performance and measures. The case strategy is an accepted approach and a preferred method for complex organisational analysis (Meredith, 1998, Voss et al., 2002, Stuart et al., 2002, Flyvbjerg, 2006, MacCarthy et al., 2013). The case study increases the likelihood of novel theory development (Boer et al., 2015) especially when applied as with a cross-case comparative method (Leonard-Barton, 1990, Voss et al., 2002).

Given the limited number of cases which can usually be studied in a population of HVM businesses, the definition of HVM is drawn from the UK Government's TSB (now called Innovate UK), and 10 purposively selected cases were selected and included a diversity of technologies, products and market sectors as per Flynn et al. (1990) advocate to select cases that appear to violate the proposed theory. The inclusion of cases that disprove theory ironically enriches theory by showing where it is inapplicable (Eisenhardt and Graebner, 2007). Ten cases were selected of which eight were high-value manufacturers and from the two low value manufacturing category See Figure 4. The cases were drawn from pharmaceutical, low volume vehicles, electrical mechanisms, semi-conductor, automotive and industrial products, electrical systems, medical support devices, home furnishings, filtration, and ventilation equipment. The purposive selection criteria and justification draws from the recommendations for generalization from a purposive or theoretical sampling (Silverman, 2013) – see Table 2.

Selection criteria	Main purpose
End-product falls in the TSB criteria of high-value	To test the theory in the context of high-value manufacturing sector
Manufacturing sites located in the UK	To ensure all cases are operated under British business laws
End-product falls in the TSB criteria of low-value	To understand if the theory holds outside the high-value manufacturing sector as well
Management structure of +100 employees	To increase the probability that a formal management structure exists
Mature site (more than 5 years)	To assure that a culture and customary practices exists
No focus on financial performance	To avoid problems concerning the financial performance of the firm

Table 2: Purposive case study selection criteria
Source: The researchers

Qualitative data was strengthened by quantitative data (Eisenhardt and Graebner, 2007) drawn from multiple sources and informants (Jick, 1979) and are shown in Table 3. The choice of management informants was restricted to management grades as they hold responsibility for designing features that enable or inhibit high OM performance (Table 4).

Instrument	Form	Theory building	Theory testing
Semi-structured interviews	Multiple interviews with multiple management informants at each case study	Yes	No
Observational methods	Shop-floor tours and observations of production performance and workplace organisation	Yes	No
Archival document tools	Diverse collection of company documents including strategy booklets, performance measurement databases, and internal communications	Yes	No
Researcher daybook	A personal log was kept throughout the research phases used to document reflections and taking notes	Yes	No
Self-completion questionnaire	1-6 Likert scale to investigate strategy, communications, socio-technical system, supply chain relationships, learning and improvement, and performance	No	Yes

Table 3: Data collection instruments and research phases
Source: The researchers

Management informant	Reason for selection
Operations Director/Managing Director	Responsible for overseeing the whole system and for matching the operations resources with the environmental demands
Operations/Manufacturing/Production Manager	Responsible for the conversion process and ensuring that the production resources are utilised efficiently
Quality Manager	Responsible for the quality of the materials and the end-products
Maintenance Manager	Responsible for the reliability and availability of the conversion process
Supply Chain/Procurement/Purchasing Manager	Responsible for ensuring the availability of high quality materials for production on time and in full
Logistics/Customer Service Manager	Responsible for delivering the output on time and in full to the customer
Human Resource Manager	Responsible for the recruitment, training, and development of staff
Product Design and Development/NPI Manager	Responsible for the design and development of new products

Table 4: Reasons for selecting the management informants
Source: The researchers

Research designs and practical considerations create limitations and for this study include the deliberate exclusion of R&D and design functions and the relationship with flow performance. The definition of high-value manufacturing businesses implies a reasonable spend by the organisation on R&D activity (Technology Strategy Board, 2012a), and a theoretical link already exists between high R&D investment and potentially high performance. This link was not tested in this research and nor was the product design and development in general. Moreover, the financial stability of the cases was not undertaken as financing was not seen as a high influence on operational performance (beyond interruptions to material flow, if accounts were unpaid). No such disturbances were found during the research Measures of profitability were not used because some businesses were cost centres, some engaged in transfer pricing for international businesses and the vagaries of profit generation.

This study does not compare direct competitors, instead the flow measure is used to test different OMS contexts. The study of direct competitors within the case studies would have provided an interesting insight as the environment, technology, supplier base, and customers, are the same or similar. Thus, the only differentiation would have been the operations design; such a scenario did not exist in this study.

Another limitation, by design, originates from the UK base for all businesses. As such, there is a single national culture involved with this study and affecting the participating cases. Even though the study focuses on the design of operations, a problem facing all operations managers, national culture will have implications in the treatment and extent to which labour can engage in improvement and how far managers will empower the workforce or organise them into teams.

The UK High-Value Manufacturing Sector

The UK High-Value Manufacturing (HVM) sector is critical to national prosperity. UK economic manufacturing output, as measured by GVA, has endured a steady decline for many decades from more than 30% in the early 1970s to 10% in 2014. Although the relative importance of the sector has reduced it has reached a plateau Figure 3, countries such as Italy, Brazil, South Korea, and France, have surpassed the UK's position despite the UK remaining strong in key industries (including aerospace where it ranks second only to the United States and is the host country to the Head Quarters of two of the top six pharmaceutical companies see (Advanced Institute of Management Research, 2008). It also boasts one of the most productive automotive plants in Europe operated by Nissan in Sunderland. These national assets in sectors including aerospace, automotive, pharmaceuticals, and food were identified by the UK Government's Technology Strategy Board (TSB) – now known as Innovate UK - as critical to the UK's future viability and strategy for 2025 (Technology Strategy Board, 2012b).

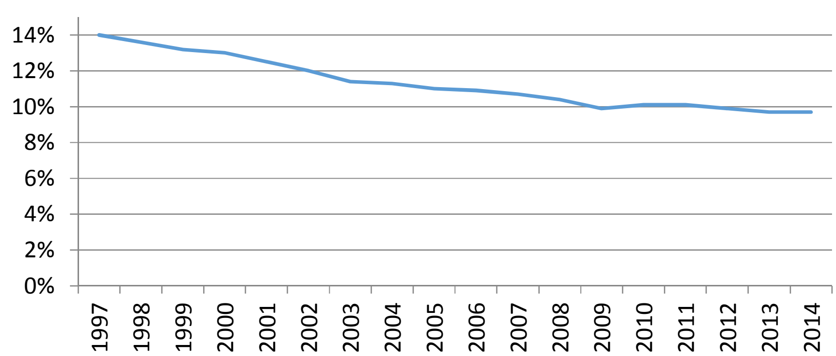

Figure 3: Manufacturing gross value added as percentage of total economy
Source: House of Commons Library (2015)

Defining HVM

The Technology Strategy Board (2012a) defined 'High Value Manufacturing' as *"the application of leading-edge technical knowledge and expertise to the creation of products, production processes, and associated services which have strong potential to bring sustainable growth and high economic value to the UK. Activities by high-value manufacturers may stretch from R&D at one end to recycling at the other"* (p.6). However, according to the Advanced Institute of Management Research (2008) high-value manufacturers are defined as *"…firms that do not compete primarily on cost. Instead they deliver value for one or more of their stakeholder groups by contracting for capability, delivering product/service innovation, establishing process excellence, achieving high brand recognition and/or contributing to a sustainable society"* (p.5). In other words, manufacturing organizations must go beyond the traditional views of production and historic models of high performance to exploit value from modern complicated supply networks (Technology Strategy Board, 2008).

MacBryde et al. (2013) argue that high-value manufacturing is a state that is achieved when firms move away from competing primarily on 'cost' and add value through other means, often by services or high efficiency of production processes making high value goods. As such, *"there is no simple definition of high-value manufacturing"* (Institute for Manufacturing, 2006) albeit the TSB offers a typology of R&D expenditure and potential for economic growth as key dimensions of HVM Figure 4. The sectors include food & drink, marine & other transport, aerospace, automotive, pharmaceuticals, computers, electronics, optical products, chemicals, and electrical equipment and these sectors produce high performance products, have significant investment in high technical R&D, and employ highly skilled staff.

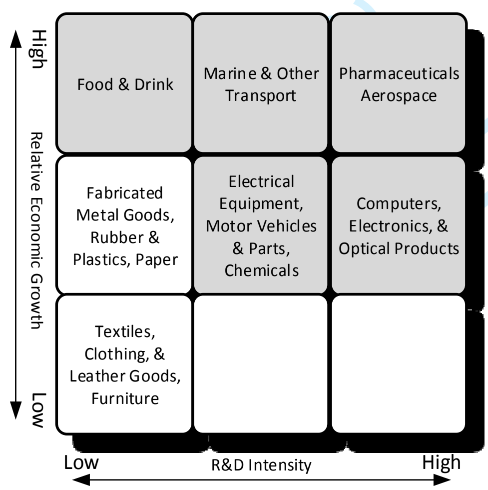

Figure 4: TSB matrix identifying high-value manufacturing sectors
Source: TSB (2012a)

Data Analysis and Findings

To holistically measure materials flow, the OEE measure (collected over a period of 28 weeks) was extended by including the measurement of quality and delivery reliability of system inputs/outputs to enable the measurement of material flow through the whole system Figure 5. The quality and delivery performance of suppliers was based on the average performance of product specific materials for 28 weeks. Customer quality and delivery performance focused on the typical product which utilized the most resources. Quality was measured as a percentage (defects per hundred) and delivery was calibrated to +/- 2 hours of when the product was expected for delivery. The authors considered this measure to be more robust and holistic that those adopted by previous studies.

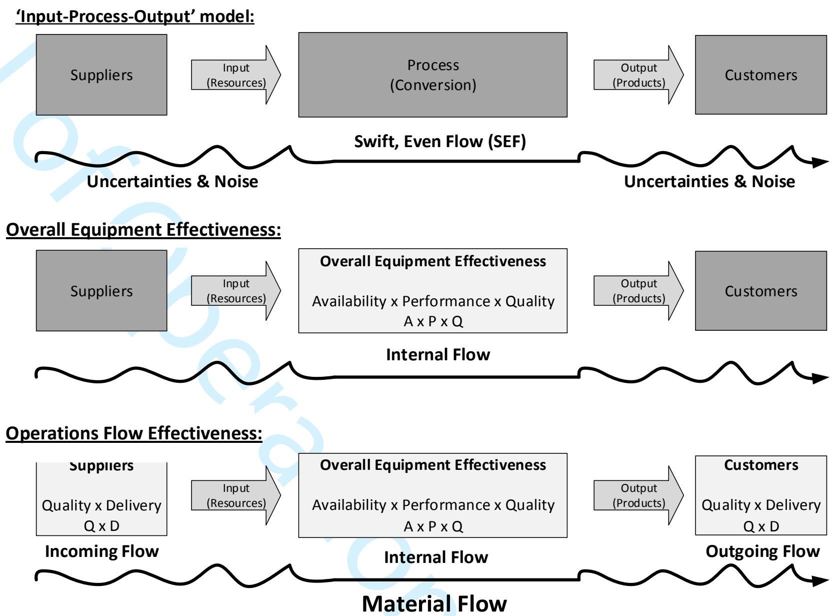

Figure 5: Performance measures used to assess the case studies
Source: The researchers

The results of this case performance analysis allowed the classification of low performer, average performer, or high performer to be allocated to each case (Table 5 and Table 6 show case performance). Figure 6, shows the material flow performance – the incoming flow, the internal flow, and the outgoing flow. The data for the high performers shows that these organizations perform exceptionally well on all the measures, whereas other organizations do not show a consistent level of performance. As such, the performance of a manufacturing organization is therefore not only dependent on its own operations, but also on the performance of other members in the supply chain. Consequently, the competitive position of each case will depend highly on the 'weakest link' in the chain (Seuring, 2009). This suggests that the strategic configuration of the supply chain is a critical task, which comprises supplier selection as well as the distribution among the customers, and the efficient managing of internal operations.

Classification	Low performers	Average performers	High performers
Material flow	Less than 50%	Between 50% and 80%	More than 80%

Table 5: Classification of operations systems based on their Material Flow performance
Source: The researchers

Analysis criteria		1	2	3	4	5	6	7	8	9	10
QD of suppliers	Quality	81%	97%	80%	99%	99%	99%	95%	98%	99%	99%
	Delivery	84%	85%	90%	96%	99%	97%	96%	97%	98%	98%
OEE	Availability	82%	83%	79%	81%	85%	87%	85%	92%	94%	96%

	Performance	**87%**	**84%**	**95%**	**89%**	**88%**	**95%**	**96%**	**88%**	**93%**	**95%**
	Quality	**91%**	**91%**	**97%**	**96%**	**97%**	**99%**	**98%**	**98%**	**99%**	**99%**
QD to customers	**Quality**	**98%**	**99%**	**97%**	**97%**	**99%**	**99%**	**99%**	**99%**	**99%**	**99%**
	Delivery	**82%**	**89%**	**97%**	**98%**	**99%**	**90%**	**99%**	**97%**	**99%**	**99%**
Incoming flow		**68%**	**82%**	**72%**	**95%**	**98%**	**96%**	**91%**	**95%**	**97%**	**97%**
Internal flow		**65%**	**63%**	**73%**	**70%**	**72%**	**82%**	**80%**	**79%**	**85%**	**90%**
Outgoing flow		**80%**	**88%**	**94%**	**95%**	**98%**	**89%**	**98%**	**96%**	**98%**	**98%**
Material flow		**36%**	**46%**	**49%**	**63%**	**69%**	**70%**	**72%**	**72%**	**81%**	**86%**

Table 6: Performance of the cases for various analysis criteria, ranked by Material Flow
Source: The researchers

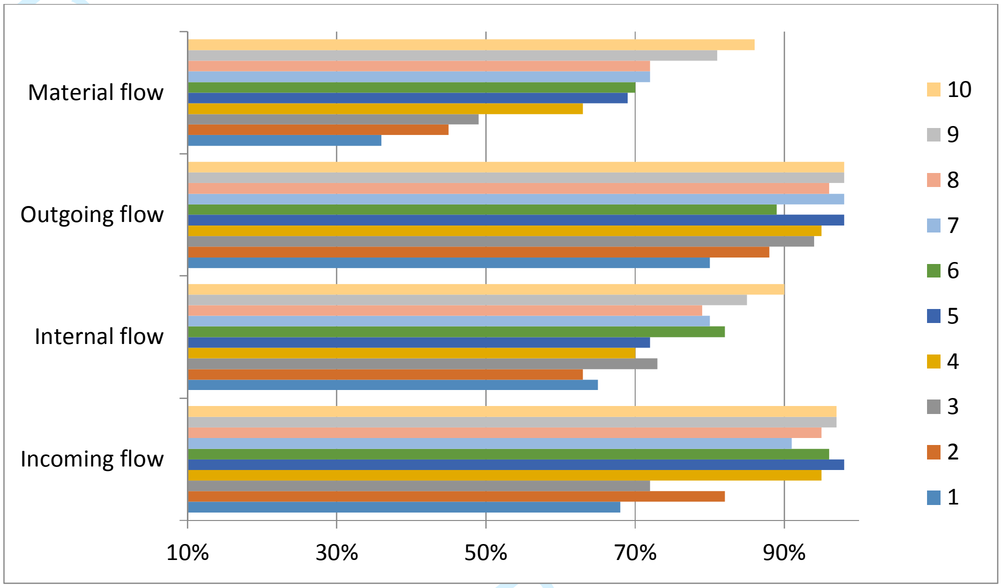

Figure 6: Different flow performances of each case study
Source: The researchers

To enable cross-case comparison, data collected was populated into data tables (Miles et al., 2014) to permit a robust cross-case comparison. Axial coding was chosen to reduce the data set and better manage the comparisons to more effectively identify patterns of design features that promoted high as well as 'swift and even flow' of material. Using significant wall space to present the cross-case comparison tables it was possible to see 'the big picture' and from which, and over 8 rounds of data reduction and pattern identification, Figure 7 was generated to show the significant features that support flow.

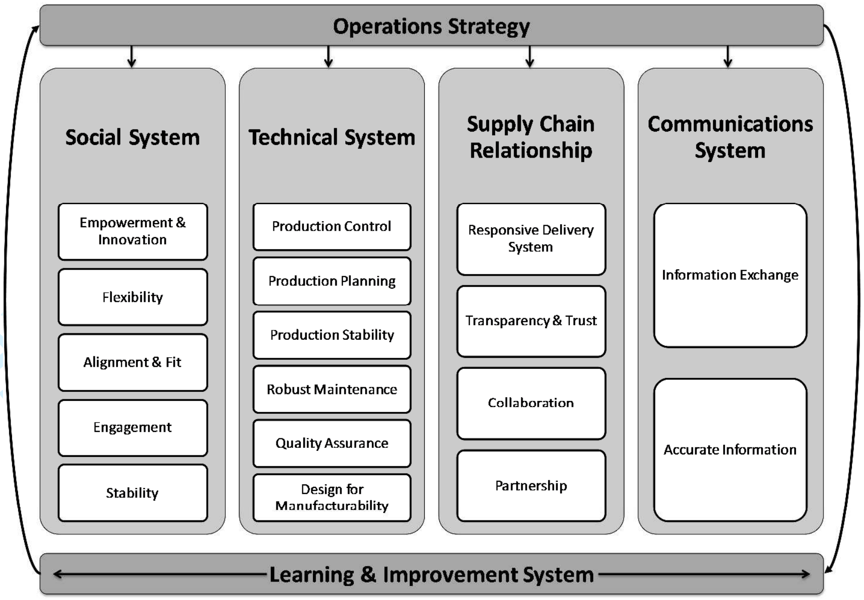

Figure 7: Design elements and features of high performance operations
Source: The researchers

Operations Strategy

The importance of a guiding operations strategy, its development, and its purpose in relation to the different case studies (shown in Table 7) highlights the significant differences between high and low performing manufacturing organizations. A fundamental finding shows swift and even flow is enabled by adaptiveness and multi-layered feed-forward planning design element, combined with an open systems approach to strategy and with more frequent updates (to cope with and adapt to the competitive and dynamic environment). It also shows the strong involvement and alignment of staff. The uniting bond of the system is a 'quality first' approach adopted by the organization towards customers, suppliers and staff and additional competitive priorities such as speed, dependability, and flexibility so that the business can deliver on its promises and generate higher flow performance.

Performance of organization	Formal strategy	Environment	Rigidity of strategy	Focus	Involvement across layers and function	Commitment to Quality	Competitive priorities
High	Present	Competitive and dynamic	Adaptive	Future and externally	Deep and broad	Yes	QSDFC
Low	Present	Competitive and dynamic	Planned	Present and internally	Limited to elite	Yes	QC

Table 7: Main findings between high and low performance in the operations strategy
Source: The researchers

Communications System

Table 8 shows significant differences between the case studies with regards to their communication system and information sharing (internally and with supply chain partners). Fundamentally, the long-term plans (accompanied by short cycles of control feedback) provide organizations with clearer predictions of the future changes and enables them to quickly detect changes/react to maintain SEF the swift and even flow of materials. Sharing of information by using a variety of methods for different purposes engages everyone in the organization, and it gives the lowest hierarchical levels a 'voice' as well as the opportunity to innovate and contribute to the overall improvement of the organization. In this manner, information exchange and clarity are used to prevent excessive stocks and chaotic production (information has replaced physically stocked products) and it can be argued that that long feed-forward plans, accompanied by short and frequent feedback cycles result in enhanced performance and enables swift and even flow of materials.

Performance of organization	Feed-forward planning	Feedback control cycles	Information feedback mechanisms	Information sharing mechanisms
High	Long	Short	Present	Rich
Low	Short	Long	Rare	Poor

Table 8: Main findings between high and low performance in the communications system
Source: The researchers

Supply Chain Relationships

The performance of supply chain flow is critical to operational performance of quality material flow. Table 9 shows partnering with other supply chain members and the sharing of useful information promotes and enhances material flow. Collaborative working improves flow by sharing the benefits of these improvements of improvements and across the whole chain. Selecting the suppliers and customers with the right capabilities is clearly shown as vital to partnership and uninterrupted material flow. Finally, the maintenance of an alternative and capable supply base ensures risks are reduced and flow can be maintained in the event of a catastrophe at a main supplier.

Performance of organization	Process improvements	Benefits and blame	Sharing of information	Relationship duration	Relationship strength	Selection of supply chain members	Alternative supplier base	Deliveries	Customer service
High	Present	Shared	High	Long	Partners	Present	Present	Frequent	Protected

Low	Limited	Private	Low	Long	Close	Limited	Absent	Infrequent	Loose

Table 9: Main findings between high and low performance in the supply chain relationships
Source: The researchers

Technical System

The best technical system will never be optimized without robust controls to ensure line availability and quality of the machine, process and material flow. Table 10 shows a series of control mechanisms including staff engagement and double loop learning are employed at and beyond the focal case organization. These simple devices and artefacts allow operators to escalate concerns and prompt greater responsiveness to restore flow production (they heighten the situational awareness of all staff to flow underperformance and abnormal variance) and thereby prevent waste and interruption. Proactive asset maintenance guarantees availability and production speeds which ensures production plans can be achieved and reduces management noise and re-planning. An effective technical system design is therefore found to be critical to swift and even material flow.

Performance of organization	Production mode	Maintenance units	Systematic breakdown management	Workplace organization	Process standardization	Quality assurance	Design of Equipment	Concurrent Engineering	Design for manufacturability
High	Pull	Proactive	Present	High	All	Total	Present	Present	Present
Low	Push	Reactive	Absent	Basic	Most	Limited	Absent	Limited	Limited

Table 10: Main findings between high and low performance in the technical system
Source: The researchers

Social System

A culture of teamwork and heightened interpersonal dependency is a foundation for modern dominant OM models - but there are significant variances in the range and focus of the skill-sets between workers in organizations of different performance classifications. The high performing organizations rely on staff trained in determining variation in delivery and speed as well as quality variation detection (this allows better use of management as noise is reduced). The low performers use only quality variation detection methods and are unaware of asset underperformance from (operating at lower speeds). The finding shows the critical role that workers have on controlling the environment, the machinery, and the quality and a pivotal aspect of swift and even flow of materials. Investments and improving the social system is a major investment by high flow performers acting as learning organizations (Table 11).

Performance of organization	Teamwork	Skills set	Product quality skills	Diagnostic skills	Ownership of production process	Machinery skills	Environmental skills	Innovation	Learning capabilities
High	Present	Multiple	Same	High	High	High	High	Enabled	Improved
Low	Present	Limited	Same	Low	Low	Low	Low	Restrained	Basic

Table 11: Main findings between high and low performance in the social system
Source: The researchers

Learning & Improvement System

Staff Knowledge of the technical system promotes learning and improvement of efficiency and effectiveness of OM and Table 12 shows the relationship between learning and flow improvement. High performing organizations reveal high organizational learning capabilities reflecting that adaptation is a desired outcome of learning especially in ever changing fiercely competitive markets. Being 'fittest' not only involves continuous improvement but a greater integration of worker and machine to achieve greater levels of technical competence and mastery – which again heightens situational awareness of staff to abnormal processing conditions and so to prompt a quicker countermeasure to maintain SEF.

Performance of organization	Improvement culture	Problem solving and learning	Improvement across the supply chain
High	Strong	Continuous	High
Low	Weak	Irregular	Low

Table 12: Main findings between high and low performance in the learning and improvement system
Source: The researchers

The key to OM system viability and cash flow management, the primary reason for the Just In Time system (renamed 'lean' by Womack et al. (1990) and an underpinning feature of agile systems, is swift and even flow of materials to customers and a creation of a dependent system whereby flows are uninterrupted and aligned. As production batches head towards personalised production in search of higher value adding then it is important to conceptualise flow in a means that reinforces a process view of the firm. The findings show an interesting insight into the design of high and low flow performance businesses operating in modern dynamic conditions.

Discussion

The concept of Swift and even material flow is intriguing but lacks a measure of flow performance that is holistic and can be used to learn which aspects of operations management design and support structures improve the value adding of production time, and more importantly, flow between the organisation and customers/suppliers. Most organisations have ignored Neely's (2005) call for pluralist measures and legacy measures from the mass production era (cost not value focused) remain to generate dysfunctional behaviour and stresses. The Operations Flow Effectiveness measure was found to provide meaningful measurement of supplier performance (on time and in quality) with internal flows through processing lines and the onward quality and delivery performance to customers – a process that mimics cash flow and viability of the OMS. Stocks within and between organizations exist to balance flow or compensate for variations in forecasts, etc. (reflecting a risk appetite for a business). The new flow measure, based on measuring at a higher level ('Flexibility level') of the 'sandcone' model (Ferdows and De Meyer, 1990) is uncompromising as the perfect 100% score is truly optimal for a business and its existing social and technical features. The measure also identifies the weakest design elements (supply, processing or distribution) and features that need to be improved to move closer to optimal levels of flow (greater availability, cycle time speeds, process quality, etc.) so that learning, mastery, and commercial gain results. Moreover, the OFE measures the typical disturbance effects commonly found in manufacturing organizations and combats the weaknesses of the SEF approach (Table 13).

Typical disturbances effects	Examples	Performance measure	Performance objectives
Material Shortages	- Delays in deliveries - Incorrect materials or components	Delivery Dependability	Dependability
Breakdowns	- Unplanned maintenance - Employee absenteeism - Information system	Availability	Flexibility
Reworks	- Poor product quality	Quality	Quality
Non-standard production	- Variability in manufacturing lead time - Variability in delivery times	Speed	Speed

Table 13: Typical disturbances in production systems, their performance measure, and performance objectives
Source: The researchers

The lowest performing flow cases reveal a poor cohesion between operations strategy and the effectiveness of other OM features (social, technical and supply chain relationships) and reinforces the need to design rather than emulate. Poor integration, PMS alignment and poor learning result in poor cash flow management (the modal reason for exhausting cash flow and business viability) resulting in a competitive disadvantage. The study finds no individual design element could be identified out as the main contributor and sole responsibility for the overall flow ranking performance and this again reflects the need for a holistic and contingent OM design for flow. High performance businesses operate high flow and highly integrated systems where dependency is high between all direct and indirect functions. The latter "supportive" internal and external environment of customer/supplier relations supports Hayes and Wheelwright's (1984) proposition that OMS is as competitive weapon even when tightly coupled.

Disturbances to the production system, to the input and/or output linkages, come in the form of machine breakdowns, tool wear, absent workers, poor information systems and such like. Such inconcistencies and variation in speeds and delivery schedules affects the of utilisation of machines or availability of materials. In general production system disturbances to and from the case study are due to delays or incorrect orders and deliveries which confirms the views of (Golinska et al., 2011). Within a case, poor quality is the main cause of disturbance to material flow and such forms of 'operational noise' all reduce the physical and information triggered material flow. Such 'operational noise' can therefore be defined as *"any event, process, or activity that creates excess errors, delays, and/or rework as a result of uncertainties caused by poor information exchange or physical processing"*. Operational noise is a main cause for poor SEF and poor material flow which is amplified by:

- Ineffective design/redesign decisions that do not support the business in achieving its goals,
- Problems and loss of productive capacity,
- Problems associated with inbound supply,
- Lack of or inconsistencies in quality and quantity of information exchange.

A variety of strategies were used to manage the dysfunctional impacts of operational noise including dampening techniques such as system buffering (investments in stock to ensure flow but at a cost). Buffering techniques represent a resource-based approach as they require excess materials, machinery, or labour capacity and dampening techniques include information-based approaches based on planning methodologies such as smoothing or physical buffering (Golinska et al., 2011). The study finds an absorptive capacity was created to cope with noise at the high performing cases and a design that, with heightened dependencies between businesses and within the production process improves resilience (Simangunsong et al., 2012). The high performing cases maintained an absorptive capacity rather than attempting 'agile' operating model and had proactively managed risks to flow (Scott, 2003). The flow measure was sensitive enough to detect issues with tightly coupled businesses and the need for stock to maintain resilience.

The study finds the most correlated features to high performance (and swift even flow of materials) are a holistic and adaptive multi-layered feed-forward planning system. The study finds higher performers had a more robust, frequent and sophisticated number and portfolio of future planning activities which were managed to ensure the alignment of all the other systems/organizations for flow. Each of the highest performing cases was synchronized through rich and effective communications in short cycles of control feedback accompanied by long feed-forward plans (allowing process managers and trading partners to look forward whilst controlling short run process variations). The attention to communication system design for the right information at the right time (vertically in both directions and horizontally across the supply chain) is a major distinguishing feature of a higher performing case and interestingly (even allowing for credit terms) for cash flow. It is surmised that higher performing cases are less threatened by bankruptcy due to poor cash flow. Partner relationship management and longevity of trading relationship were equally found at high performing cases which suggests a 'fit' between companies and the use of collaboration to remove power struggles and commercial gaming. It is the role of the technical system to physically 'convert' the materials that arrive from the supplier into products for the customer. The technical system is designed to have processes that can ensure a swift and even flow of materials. As such, it requires a long-term plan and strict control mechanisms to ensure that the materials do not vary in quality, and that the machines are maintained to a good condition and available when needed. The control of the technical system is the responsibility of the workforce in the social system. Therefore, the workforce is empowered and trained to detect any variation in quality, speed, and availability that will affect the flow of materials, and to take appropriate action to rectify the problem. The social system is people-focussed and is multi-skilled to perform various tasks (and absorb product variety to support SEF and avoid the rigidities of staff with limited flexibility and poor learning/adaptation skills). Investment in the human resources of a business in this manner also increases the ability of staff to detect abnormal variation and respond more quickly to such variation to restore flow. Based on the case findings, Figure 8 is presented to show the holistic properties of a higher performing business and how there is integration of six major design elements that are needed for high performance operations and swift and even material flow.

The authors consider the new flow measure a significant and valuable addition to understanding swift and even flow – including the understanding of swift flow in dynamic and uneven market environments. The ability to establish a 100% optimal score for flow (given investments in stock) allows the higher level of the 'sandcone' model to be assessed and enacted. The research also identifies the six major operations management design elements that enable better flow and support higher levels of operations mastery. The measure therefore offers significant insight into the states and features of operations management design that allow such mastery to be effectively exploited in more turbulent product markets as high value manufacturers take the next steps to change technology, increase product variety and reduce product lives to a single bespoke piece. The new flow measure therefore has utility for most manufacturers and a potential new insight into the OM designs that support Industrie 4.0.

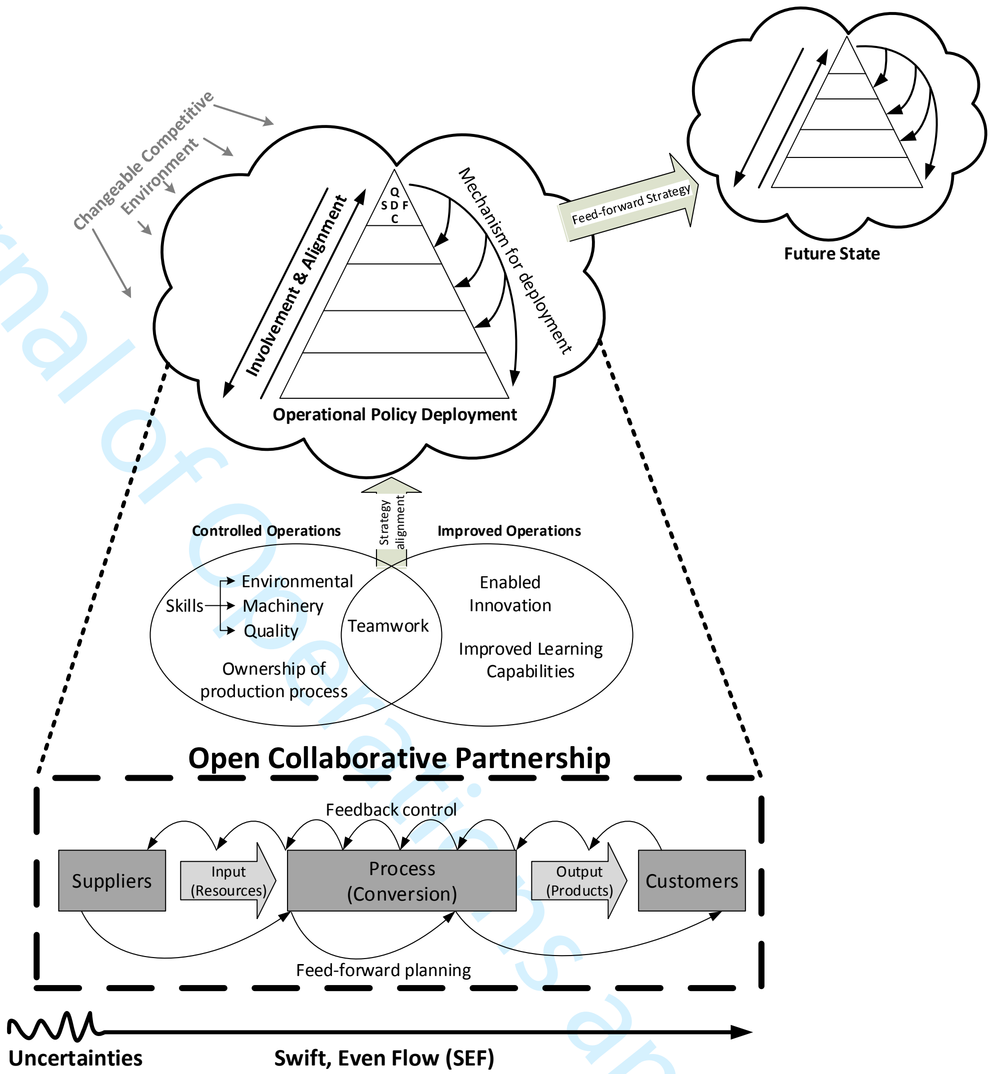

Figure 8: Design elements of high performance OMS for swift and even flow
Source: The researchers

Conclusions

The purpose of this research paper was to develop and test a flow performance measurement and to extend the concept of "swift and even flow", under current dynamic conditions, using the UK High-Value Manufacturing sector to theory build from 10 longitudinal case studies. The research validates the measurement approach and identifies six design elements that are necessary for the achievement of high performance. The new manufacturing era demands greater flexibility of non-standardised products and has evolved from the standardized and limited product ranges associated with more traditional lean systems. The HVM sector was found to operate at high levels of flow using the new measure and that this form of time management could be applied to all cases. The new era of manufacturing places greater emphasis on the management of time as a proxy measure for cash flow. Traditional measures will come under greater criticism as new models, such as Industrie 4.0, place greater stresses on manufacturers for a quality and tailored product fulfilment process. There remain many issues to overcome with modern manufacturing models including skills needed, ability of the supply chain to support personalised production and the redistribution of the manufacturing facility itself. The poor state of current knowledge concerning the measurement of flow for 'cutting edge' business models of 'make on demand' or 'make to order' operations requires a new measure of flow to align operations with the business PMS. A reversion to old and "tried and tested" measures, such a labour productivity, will prove both frustrating and will create dysfunctional behaviours. Under new operations models, labour is likely to have comparatively higher technical skills and the OMS will reflect capacity and time utilization when it is needed.

The ten case study manufacturers, ranging in flow performance, were investigated to reveal the OMS design features that supported or inhibited high material flow. The flow measure was developed by the researchers to close a gap in the literature where, despite the acknowledged importance of effective and aligned performance measures (Neely et al., 2005), no real holistic measures exist to support the modern operating models and OMS. This study reveals six design elements that are necessary to achieve high performance including a holistically aligned operations strategy, a synchronising communications system, a partner-like supply chain relationship, a controlled technical system, an empowered social system, and an adaptive and evolving learning and improvement system. These 'states' support effective flow management.

The findings emphasise a contingent design of operations management features, as no individual design element was identified as the source of higher performance. The study reveals new research gaps in terms of which contingent features (and their sequence of implementation) support new models of operations management. The modern manufacturing era will place greater emphasis on learning and the adaptation of socio-technical operations management features to enhance flow reliability and responsiveness. A holistic approach to OMS design is required if the enablers of swift flow are to be exploited. Emulation of high performance OMS designs, which has long dominated most lean approaches to manufacturing is no longer a viable option. Such contingent OMS designs are important in dynamic markets where customer satisfaction relies upon flow systems that are supported by a strategic focus of resources, IT enabled decision making and a learning capability to ensure a broad range of personalised products are delivered to customers. Modern organisations must operate multi-layered levels of control at the worker, at the process, and at the supply chain to detect abnormalities quicker and react to control flow. The new measurement of flow, investigated by this study, strengthens the role of Operations Management (OM) in designing, implementing, and supporting high performance operations as a contemporary 'competitive weapon'.

The most important activity for operations managers is to maintain the viability of a business and to manage required production time for value added and revenue earning purposes. Figure 8 is a representation of the essential design elements that need to be configured in order to exploit the capabilities of a OMS design for high flow performance. In the absence of 'role models' played by such companies as Toyota in the lean era, operations managers must align working practices with the highest levels of flow and do this as a true 'end to end' measure. The testing of the Operations Flow Effectiveness (OFE) measure was conducted with high value manufacturers that are under pressure to customise and minimise batch sizes, and to improve the generalizability of the measure and approach, other manufacturing contexts will be targeted where product variety is even greater and product life may be as limited as a single piece. Industrie 4.0 (Internet of Things, 3D Printing, Augmented Reality, etc.) provides an ideal opportunity to test the flow measure for swift and uneven flow. It is hoped that this paper will stimulate debate as the cases of this research are continued to form longitudinal studies of change and ideally joined by international partners to test cultural influences on OMS designs and flow performance.

References

Advanced Institute of Management Research (2008) High Value Manufacturing: Delivering on the Promise.

Ahmad, S. & Schroeder, R.G. (2003) The impact of human resource management practices on operational performance: recognizing country and industry differences. *Journal of operations Management,* 21**,** 19-43.

Akao, Y. (1991) *Hoshin Kanri: Policy Development for successful TQM*, Productivity Press. Cambridge, MA.

Andersson, C. & Bellgran, M. (2015) On the complexity of using performance measures: Enhancing sustained production improvement capability by combining OEE and productivity. *Journal of Manufacturing Systems,* 35**,** 144-154.

Bamber, C.J., Castka, P., Sharp, J.M. & Motara, Y. (2003) Cross-functional team working for overall equipment effectiveness (OEE). *Journal of Quality in Maintenance Engineering,* 9**,** 223-238.

Bititci, U., Garengo, P., Dörfler, V. & Nudurupati, S. (2012) Performance measurement: challenges for tomorrow. *International Journal of Management Reviews,* 14**,** 305-327.

Boer, H., Holweg, M., Kilduff, M., Pagell, M., Schmenner, R. & Voss, C. (2015) Making a Meaningful Contribution to Theory. *International Journal of Operations & Production Management,* 35**,** 1231 - 1252.

Bonciu, F. (2014) The European Economy: From a Linear to a Circular Economy. *Romanian Journal of European Affairs,* 14**,** 78-91.

Bond, T.C. (1999) The role of performance measurement in continuous improvement. *International Journal of Operations & Production Management,* 19**,** 1318-1334.

Bou-Llusar, J.C., Escrig-Tena, A.B., Roca-Puig, V. & Beltrán-Martín, I. (2009) An empirical assessment of the EFQM Excellence Model: Evaluation as a TQM framework relative to the MBNQA Model. *Journal of Operations Management,* 27**,** 1-22.

Burbidge, J.L. (1985) Production planning and control: A personal philosophy. *Computers in Industry,* 6**,** 477-487.

Caplice, C. & Sheffi, Y. (1995) A Review and Evaluation of Logistics Performance Measurement Systems. *The International Journal of Logistics Management,* 6**,** 61-74.

Childerhouse, P. & Towill, D.R. (2003) Simplified material flow holds the key to supply chain integration. *Omega,* 31**,** 17-27.

Cocca, P. & Alberti, M. (2010) A framework to assess performance measurement systems in SMEs. *International Journal of Productivity and Performance Management,* 59**,** 186-200.

Deming, W.E. (2000) *Out of the crisis,* Cambridge, Mass., Cambridge, Mass. : MIT Press.

Drucker, P. (1954) *The Practice of Management,* New York, NY, Harper.

Durugbo, C., Tiwari, A. & Alcock, J.R. (2014) Managing integrated information flow for delivery reliability. *Industrial Management & Data Systems,* 114**,** 628-651.

Eisenhardt, K.M. (1991) Better stories and better constructs: The case for rigor and comparative logic. *Academy of Management review,* 16**,** 620-627.

Eisenhardt, K.M. & Graebner, M.E. (2007) Theory building from cases: opportunities and challenges. *Academy of management journal,* 50**,** 25-32.

Ferdows, K. & De Meyer, A. (1990) Lasting improvements in manufacturing performance: In search of a new theory. *Journal of Operations Management,* 9**,** 168-184.

Flynn, B.B., Sakakibara, S., Schroeder, R.G., Bates, K.A. & Flynn, E.J. (1990) Empirical research methods in operations management. *Journal of Operations Management,* 9**,** 250-284.

Flyvbjerg, B. (2006) Five Misunderstandings About Case-Study Research. *Qualitative Inquiry,* 12**,** 219-245.

Forrester, J.W. (1961) *Industrial Dynamics,* Cambridge, MA, MIT Press.

Forza, C. & Salvador, F. (2001) Information flows for high-performance manufacturing. *International Journal of Production Economics,* 70**,** 21-36.

Franco-Santos, M., Lucianetti, L. & Bourne, M. (2012) Contemporary performance measurement systems: A review of their consequences and a framework for research. *Management accounting research,* 23**,** 79-119.

Franco-Santos, M., Kennerley, M., Micheli, P., Martinez, V., Mason, S., Marr, B., Gray, D. & Neely, A. (2007) Towards a definition of a business performance measurement system. *International Journal of Operations & Production Management,* 27**,** 784-801.

Garza-Reyes, J.A., Duffuaa, S. & Duffuaa, S. (2015) From measuring overall equipment effectiveness (OEE) to overall resource effectiveness (ORE). *Journal of Quality in Maintenance Engineering,* 21.

Geary, S., Disney, S.M. & Towill, D.R. (2006) On bullwhip in supply chains—historical review, present practice and expected future impact. *International Journal of Production Economics,* 101**,** 2-18.

Gimbert, X., Bisbe, J. & Mendoza, X. (2010) The role of performance measurement systems in strategy formulation processes. *Long Range Planning,* 43**,** 477-497.

Goldratt, E. (1990) *Theory of Constraints,* Great Barrington, MA, North River Press.

Golinska, P., Fertsch, M. & Pawlewski, P. (2011) Production flow control in the automotive industry – quick scan approach. *International Journal of Production Research,* 49**,** 4335-4351.

Gotzamani, K.D. & Tsiotras, G.D. (2001) An empirical study of the ISO 9000 standards' contribution towards total quality management. *International Journal of Operations & Production Management,* 21**,** 1326-1342.

Gregory, A.J. (2007) Target Setting, Lean Systems and Viable Systems: A Systems Perspective on Control and Performance Measurement. *The Journal of the Operational Research Society,* 58**,** 1503-1517.

Größler, A. & Grübner, A. (2006) An empirical model of the relationships between manufacturing capabilities. *International Journal of Operations & Production Management,* 26**,** 458-485.

Größler, A., Grübner, A. & Milling, P.M. (2006) Organisational adaptation processes to external complexity. *International Journal of Operations & Production Management,* 26**,** 254-281.

Hanson, J.D., Melnyk, S.A. & Calantone, R.A. (2011) Defining and measuring alignment in performance management. *International Journal of Operations & Production Management,* 31**,** 1089-1114.

Hayes, R.H. & Wheelwright, S.C. (1984) *Restoring Our Competitive Edge: Competing Through Manufacturing*.

Hopp, W. & Spearman, M. (2008) *Factory Physics,* Long Grove, IL, Waveland Press.

House of Commons Library (2015) Manufacturing: Statistics and Policy.

Huo, B., Han, Z. & Prajogo, D. (2014) The effect of ISO 9000 implementation on flow management. *International Journal of Production Research,* 52**,** 6467-6481.

Institute for Manufacturing (2006) High Value Manufacturing.

Jasti, N.V.K. & Kodali, R. (2014) A literature review of empirical research methodology in lean manufacturing. *International Journal of Operations & Production Management,* 34**,** 1080-1122.

Jick, T.D. (1979) Mixing qualitative and quantitative methods: Triangulation in action. *Administrative science quarterly***,** 602-611.

Johnson, H.T. & Kaplan, D.P. (1987) *Relevance Lost: The Rise and Fall of Management Accounting,* Boston, MA, Harvard Business School Press.

Jonsson, P. & Lesshammar, M. (1999) Evaluation and improvement of manufacturing performance measurement systems - the role of OEE. *International Journal of Operations & Production Management,* 19**,** 55-78.

Kaynak, H. (2003) The relationship between total quality management practices and their effects on firm performance. *Journal of Operations Management,* 21**,** 405-435.

Khan, M.N.A.A., Baharun, R., Rahim, K.A. & Zakuan, N. (2011) An Empirical Evidence of Performance Measurement of Audit Firms in Malaysia. *International Business Research,* 4.

Klug, F. (2013) The internal bullwhip effect in car manufacturing. *International Journal of Production Research,* 51**,** 303-322.

Koufteros, X., Vonderembse, M. & Jayaram, J. (2005) Internal and External Integration for Product Development: The Contingency Effects of Uncertainty, Equivocality, and Platform Strategy. *Decision Sciences,* 36**,** 97-133.

Leonard-Barton, D. (1990) A dual methodology for case studies: Synergistic use of a longitudinal single site with replicated multiple sites. *Organization science,* 1**,** 248-266.

Lewandowski, M. (2016) Designing the Business Models for Circular Economy—Towards the Conceptual Framework. *Sustainability,* 8**,** 43.

Liao, Y., Deschamps, F., Loures, E.d.F.R. & Ramos, L.F.P. (2017) Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal. *International Journal of Production Research,* 55**,** 3609-3629.

Longo, M. & Mura, M. (2008) Stakeholder management and human resources: development and implementation of a performance measurement system. *Corporate Governance: The international journal of business in society,* 8**,** 191-213.

MacBryde, J., Paton, S. & Clegg, B. (2013) Understanding high-value manufacturing in Scottish SMEs. *International Journal of Operations & Production Management,* 33**,** 1579-1598.

MacCarthy, B.L., Lewis, M., Voss, C. & Narasimhan, R. (2013) The same old methodologies? Perspectives on OM research in the post-lean age. *International Journal of Operations & Production Management,* 33**,** 934-956.

Maestrini, V., Luzzini, D., Maccarrone, P. & Caniato, F. (2017) Supply chain performance measurement systems: A systematic review and research agenda. *International Journal of Production Economics,* 183**,** 299-315.

Marr, B. & Schiuma, G. (2003) Business performance measurement – past, present and future. *Management Decision,* 41**,** 680-687.

Maskell, B.H. (1991) *Performance Measurement for World Class Manufacturing,* Cambridge, MA, Productivity Press.

McCarthy, D. & Rich, N. (2015) *Lean TPM: a blueprint for change*, Butterworth-Heinemann.

Mckinsey Global Institute (2012) Manufacturing the Future: The Next Era of Global Growth and Innovation. McKinsey & Company.

McKone, K.E., Schroeder, R.G. & Cua, K.O. (1999) Total productive maintenance: a contextual view. *Journal of Operations Management,* 17**,** 123-144.

Melnyk, S.A., Stewart, D.M. & Swink, M. (2004) Metrics and performance measurement in operations management: dealing with the metrics maze. *Journal of Operations Management,* 22**,** 209-218.

Meredith, J. (1998) Building operations management theory through case and field research. *Journal of operations management,* 16**,** 441-454.

Merschmann, U. & Thonemann, U.W. (2011) Supply chain flexibility, uncertainty and firm performance: An empirical analysis of German manufacturing firms. *International Journal of Production Economics,* 130**,** 43-53.

Micheli, P., Micheli, P., Mura, M. & Mura, M. (2017) Executing strategy through comprehensive performance measurement systems. *International Journal of Operations & Production Management,* 37**,** 423-443.

Miles, M.B., Huberman, A.M. & Saldana, J. (2014) *Qualitative Data Analysis,* London, Sage.

Monden, Y. (2011) *Toyota production system: an integrated approach to just-in-time*, CRC Press.

Nachiappan, R.M. & Anantharaman, N. (2006) Evaluation of overall line effectiveness (OLE) in a continuous product line manufacturing system. *Journal of Manufacturing Technology Management,* 17**,** 987-1008.

Nakajima, S. (1988) *Introduction to TPM: Total Productive Maintence*, Productivity Press, Inc.

Nakane, J. (1986) Manufacturing futures survey in Japan: A comparative survey 1983-1986. *System Science Institute, Waseda University, Tokyo*.

Narasimhan, R. & Jayaram, J. (1998) An empirical investigation of the antecedents and consequences of manufacturing goal achievement in North American, European and Pan Pacific firms. *Journal of Operations Management,* 16**,** 159-176.

Narasimhan, R., Swink, M. & Kim, S.W. (2006) Disentangling leanness and agility: An empirical investigation. *Journal of Operations Management,* 24**,** 440-457.

Neely, A. (2005) The evolution of performance measurement research: Developments in the last decade and a research agenda for the next. *International Journal of Operations & Production Management,* 25**,** 1264-1277.

Neely, A., Gregory, M. & Platts, K. (2005) Performance measurement system design: A literature review and research agenda. *International Journal of Operations & Production Management,* 25**,** 1228-1263.

Oechsner, R., Pfeffer, M., Pfitzner, L., Binder, H., Müller, E. & Vonderstrass, T. (2002) From overall equipment efficiency (OEE) to overall Fab effectiveness (OFE). *Materials Science in Semiconductor Processing,* 5**,** 333-339.

Ohno, T. (1988) Toyota production system: beyond large scale production. *Productivity Pres, Cambridge, MA*.

Phan, A.C., Abdallah, A.B. & Matsui, Y. (2011) Quality management practices and competitive performance: Empirical evidence from Japanese manufacturing companies. *International Journal of Production Economics,* 133**,** 518-529.

Pinheiro de Lima, E., Gouvea da Costa, S.E., Angelis, J.J. & Munik, J. (2013) Performance measurement systems: A consensual analysis of their roles. *International Journal of Production Economics,* 146**,** 524-542.

Power, M. (1997) *The Audit Society: Rituals of Verification,* Oxford, Oxford University Press.

Radnor, Z. & Gosselin, M. (2005) An empirical study of performance measurement in manufacturing firms. *International Journal of Productivity and Performance Management,* 54**,** 419-437.

Ríos, J.P. (2010) Models of organizational cybernetics for diagnosis and design. *Kybernetes,* 39**,** 1529-1550.

Rogers, E.M. (2010) *Diffusion of innovations*, Simon and Schuster.

Rother, M. & Shook, J. (2003) *Learning to see: value stream mapping to add value and eliminate muda*, Lean Enterprise Institute.

Safizadeh, M.H., Ritzman, L.P., Sharma, D. & Wood, C. (1996) An Empirical Analysis of the Product-Process Matrix. *Management Science,* 42**,** 1576-1591.

Schmenner, R.W. (2001) Looking Ahead By Looking Back: Swift, Even Flow in the History of Manufacturing. *Production and Operations Management,* 10**,** 87-96.

Schmenner, R.W. (2015) The Pursuit of Productivity. *Production and Operations Management,* 24**,** 341-350.

Schmenner, R.W. & Swink, M.L. (1998) On theory in operations management. *Journal of Operations Management,* 17**,** 97-113.

Schmenner, R.W., Wassenhove, L.V., Ketokivi, M., Heyl, J. & Lusch, R.F. (2009) Too much theory, not enough understanding. *Journal of Operations Management,* 27**,** 339-343.

Schroeder, R.G., Linderman, K., Liedtke, C. & Choo, A.S. (2008) Six Sigma: Definition and underlying theory. *Journal of Operations Management,* 26**,** 536-554.

Schulte, U.G. (2013) New business models for a radical change in resource efficiency. *Environmental Innovation and Societal Transitions,* 9**,** 43-47.

Scott, W.R. (2003) *Organizations: Rational, Natural, and Open,* New Jersey, Prentice Hall.

Seuring, S. (2009) The product-relationship-matrix as framework for strategic supply chain design based on operations theory. *International Journal of Production Economics,* 120**,** 221-232.

Shingo, S. (1981) *A study of the Toyota production system: From an Industrial Engineering Viewpoint*, Productivity Press.

Silverman, D. (2013) *Doing qualitative research: A practical handbook*, SAGE Publications Limited.

Simangunsong, E., Hendry, L.C. & Stevenson, M. (2012) Supply-chain uncertainty: a review and theoretical foundation for future research. *International Journal of Production Research,* 50**,** 4493-4523.

Skinner, W. (1969) Manufacturing: The Missing Link in Corporate Strategy. *Harvard Business Review,* May-June**,** 136-145.

Soni, G. & Kodali, R. (2012) A critical review of empirical research methodology in supply chain management. *Journal of Manufacturing Technology Management,* 23**,** 753-779.

Sousa, R. & Voss, C. (2008) Contingency research in operations management practices. *Journal of Operations Management,* 26**,** 697-713.

Srimai, S., Radford, J. & Wright, C. (2011) Evolutionary paths of performance measurement: An overview of its recent development. *International Journal of Productivity and Performance Management,* 60**,** 662-687.

Stuart, I., McCutcheon, D., Handfield, R., McLachlin, R. & Samson, D. (2002) Effective case research in operations management: a process perspective. *Journal of Operations Management,* 20**,** 419-433.

Suzuki, T. (1994) *TPM in process industries*, Productivity Press.

Swamidass, P.M. (1991) Empirical Science: New Frontier in Operations Management Research. *The Academy of Management Review,* 16**,** 793-814.

Technology Strategy Board (2008) High Value Manufacturing: Key Technology Area 2008-2011.

Technology Strategy Board (2012a) High Value Manufacturing: Strategy.

Technology Strategy Board (2012b) A Landscape for the Future of High Value Manufacturing in the UK.

Towill, D.R. (1997) FORRIDGE - Principles of good practice in material flow. *Production Planning & Control,* 8**,** 622-632.

Tsarouhas, P.H. (2012) Evaluation of overall equipment effectiveness in the beverage industry: a case study. *International Journal of Production Research,* 51**,** 515-523.

Tung, A., Baird, K. & Schoch, H.P. (2011) Factors influencing the effectiveness of performance measurement systems. *International Journal of Operations & Production Management,* 31**,** 1287-1310.

Van Aken, E.M., Letens, G., Coleman, G.D., Farris, J. & Van Goubergen, D. (2005) Assessing maturity and effectiveness of enterprise performance measurement systems. *International Journal of Productivity and Performance Management,* 54**,** 400-418.

Voss, C., Tsikriktsis, N. & Frohlich, M. (2002) Case research in operations management. *International Journal of Operations & Production Management,* 22**,** 195-219.

Womack, J.P. & Jones, D.T. (1996) *Lean Thinking*, Simon and Schuster.

Womack, J.P., Jones, D.T. & Roos, D. (1990) *Machine that changed the world*, Simon and Schuster.

Yin, R.K. (2013) *Case study research: Design and methods*, Sage publications.

Zotteri, G. & Kalchschmidt, M. (2007) Forecasting practices: Empirical evidence and a framework for research. *International Journal of Production Economics,* 108**,** 84-99.

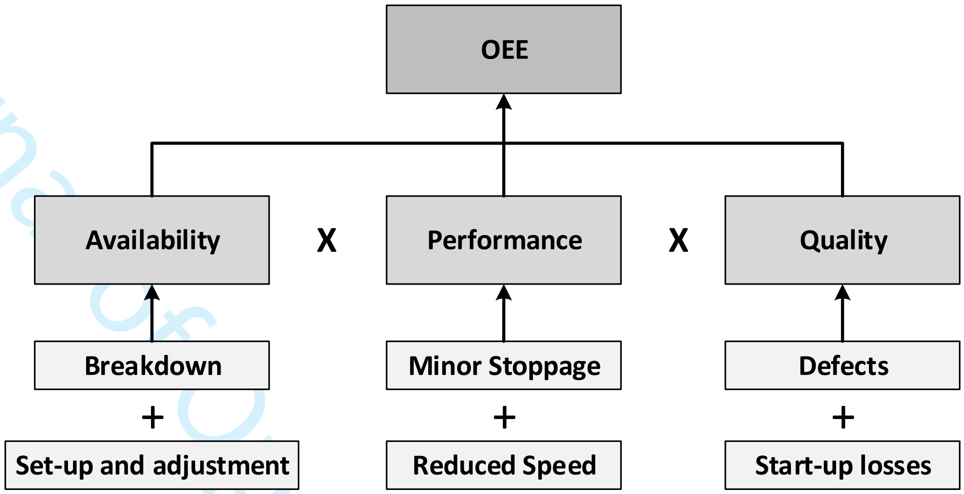

Figure 1: Calculation of Overall Equipment Effectiveness
Source: The researchers, adapted from Nakajima (1988)

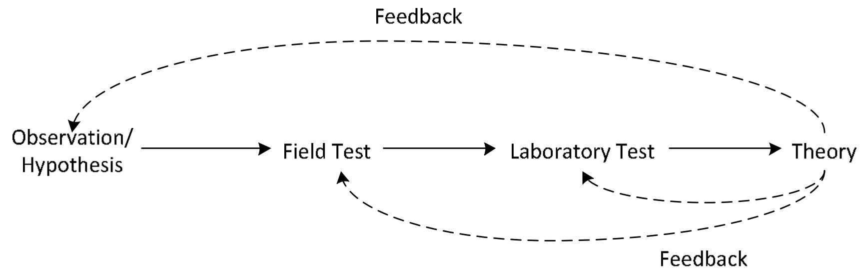

Figure 2: A strategy for combining laboratory tests with field tests in theory development
Source: Swamidass (1991)

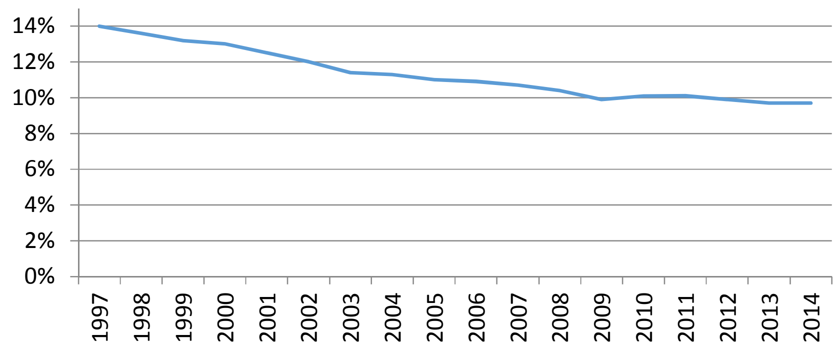

Figure 3: Manufacturing gross value added as percentage of total economy
Source: House of Commons Library (2015)

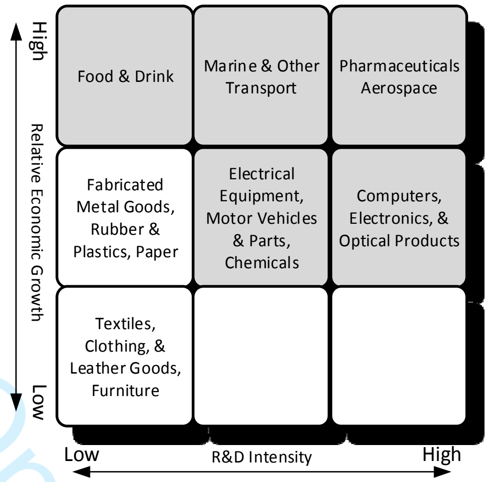

Figure 4: TSB matrix identifying high-value manufacturing sectors
Source: TSB (2012a)

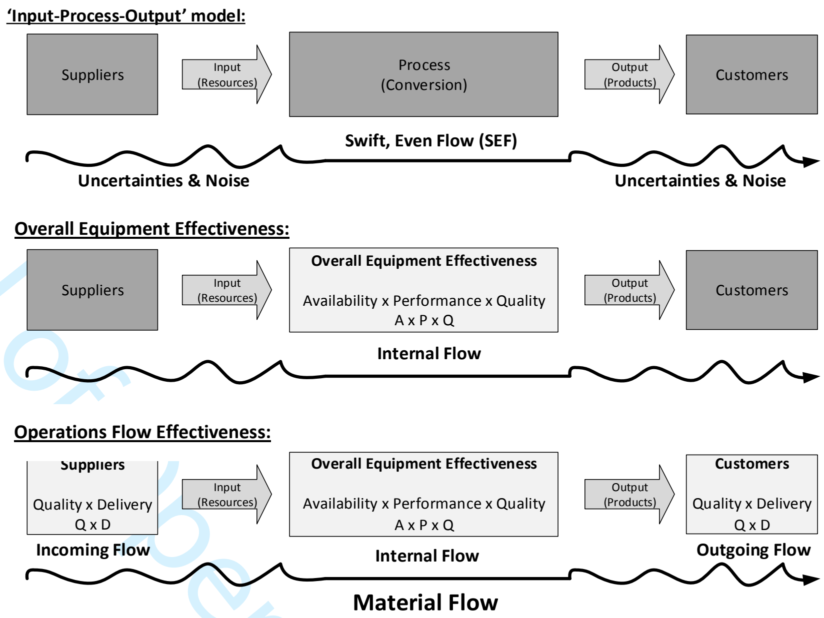

Figure 5: Performance measures used to assess the case studies
Source: The researchers

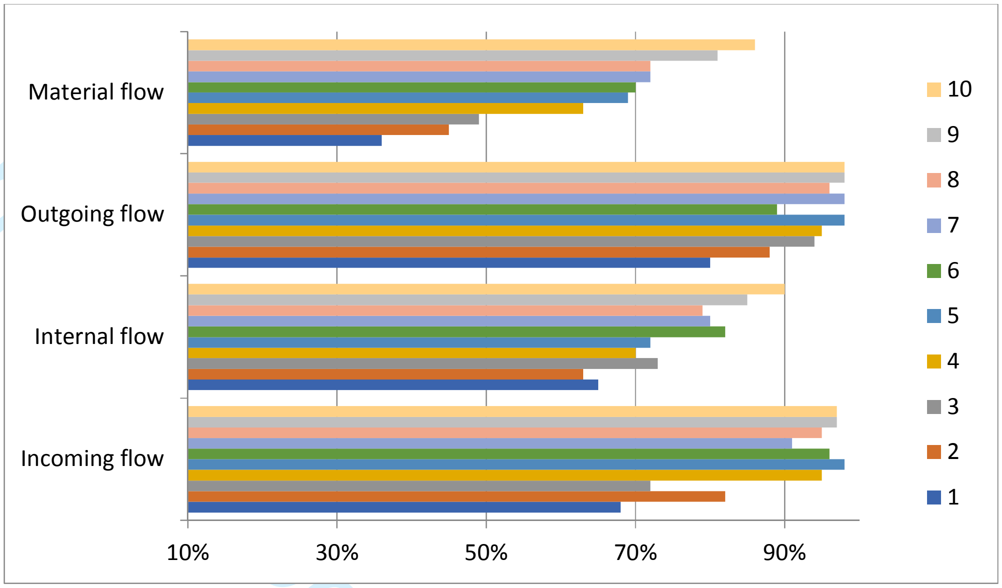

Figure 6: Different flow performances of each case study
Source: The researchers

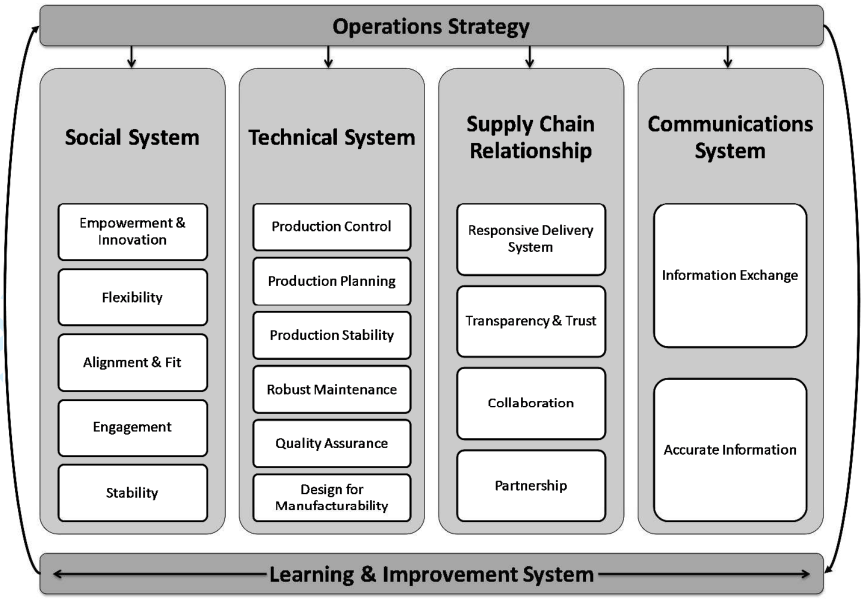

Figure 7: Design elements and features of high performance operations
Source: The researchers

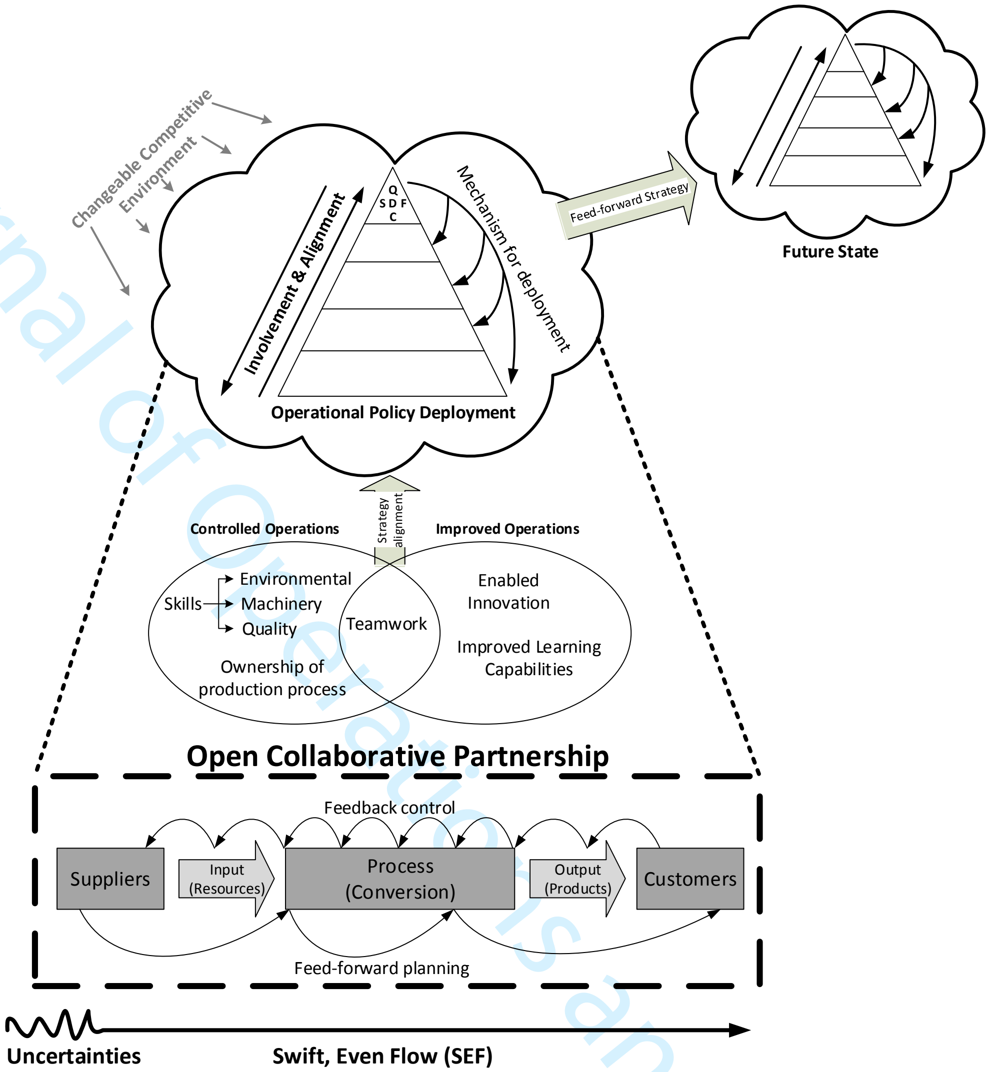

Figure 8: Design elements of high performance OMS for swift and even flow
Source: The researchers

Features of an effective performance measurement system	Author
1. Reflect the overall strategy of the organisation	Drucker (1954), Caplice and Sheffi (1995), Jonsson and Lesshammar (1999), Neely et al. (2005), Tung et al. (2011), Micheli et al. (2017)
2. Provides a grounding for communication between stakeholders	Melnyk et al. (2004), Van Aken et al. (2005), Longo and Mura (2008), Cocca and Alberti (2010), Hanson et al. (2011)
3. Diagnose reasons for the current situation	Johnson and Kaplan (1987), Power (1997), Srimai et al. (2011), Maestrini et al. (2017)
4. Detects abnormality to trigger learning and improvement	Maskell (1991), Bond (1999), Melnyk et al. (2004), Franco-Santos et al. (2007), Gimbert et al. (2010), Franco-Santos et al. (2012)

Table 1: Features of an effective Performance Measurement System
Source: The researchers

Selection criteria	Main purpose
End-product falls in the TSB criteria of high-value	To test the theory in the context of high-value manufacturing sector
Manufacturing sites located in the UK	To ensure all cases are operated under British business laws
End-product falls in the TSB criteria of low-value	To understand if the theory holds outside the high-value manufacturing sector as well
Management structure of +100 employees	To increase the probability that a formal management structure exists
Mature site (more than 5 years)	To assure that a culture and customary practices exists
No focus on financial performance	To avoid problems concerning the financial performance of the firm

Table 2: Purposive case study selection criteria
Source: The researchers

Instrument	Form	Theory building	Theory testing
Semi-structured interviews	Multiple interviews with multiple management informants at each case study	Yes	No
Observational methods	Shop-floor tours and observations of production performance and workplace organisation	Yes	No
Archival document tools	Diverse collection of company documents including strategy booklets, performance measurement databases, and internal communications	Yes	No
Researcher daybook	A personal log was kept throughout the research phases used to document reflections and taking notes	Yes	No
Self-completion questionnaire	1-6 Likert scale to investigate strategy, communications, socio-technical system, supply chain relationships, learning and improvement, and performance	No	Yes

Table 3: Data collection instruments and research phases
Source: The researchers

Management informant	Reason for selection
Operations Director/Managing Director	Responsible for overseeing the whole system and for matching the operations resources with the environmental demands
Operations/Manufacturing/Production Manager	Responsible for the conversion process and ensuring that the production resources are utilised efficiently
Quality Manager	Responsible for the quality of the materials and the end-products
Maintenance Manager	Responsible for the reliability and availability of the conversion process
Supply Chain/Procurement/Purchasing Manager	Responsible for ensuring the availability of high quality materials for production on time and in full
Logistics/Customer Service Manager	Responsible for delivering the output on time and in full to the customer
Human Resource Manager	Responsible for the recruitment, training, and development of staff
Product Design and Development/NPI Manager	Responsible for the design and development of new products

Table 4: Reasons for selecting the management informants
Source: The researchers

Classification	Low performers	Average performers	High performers
Material flow	Less than 50%	Between 50% and 80%	More than 80%

Table 5: Classification of operations systems based on their Material Flow performance
Source: The researchers

Analysis criteria		1	2	3	4	5	6	7	8	9	10
QD of suppliers	Quality	81%	97%	80%	99%	99%	99%	95%	98%	99%	99%
	Delivery	84%	85%	90%	96%	99%	97%	96%	97%	98%	98%
OEE	Availability	82%	83%	79%	81%	85%	87%	85%	92%	94%	96%
	Performance	87%	84%	95%	89%	88%	95%	96%	88%	93%	95%
	Quality	91%	91%	97%	96%	97%	99%	98%	98%	99%	99%
QD to customers	Quality	98%	99%	97%	97%	99%	99%	99%	99%	99%	99%
	Delivery	82%	89%	97%	98%	99%	90%	99%	97%	99%	99%
Incoming flow		68%	82%	72%	95%	98%	96%	91%	95%	97%	97%
Internal flow		65%	63%	73%	70%	72%	82%	80%	79%	85%	90%
Outgoing flow		80%	88%	94%	95%	98%	89%	98%	96%	98%	98%
Material flow		36%	46%	49%	63%	69%	70%	72%	72%	81%	86%

Table 6: Performance of the cases for various analysis criteria, ranked by Material Flow
Source: The researchers

Performance of organization	Formal strategy	Environment	Rigidity of strategy	Focus	Involvement across layers and function	Commitment to Quality	Competitive priorities
High	Present	Competitive and dynamic	Adaptive	Future and externally	Deep and broad	Yes	QSDFC
Low	Present	Competitive and dynamic	Planned	Present and internally	Limited to elite	Yes	QC

Table 7: Main findings between high and low performance in the operations strategy
Source: The researchers

Performance of organization	Feed-forward planning	Feedback control cycles	Information feedback mechanisms	Information sharing mechanisms
High	Long	Short	Present	Rich
Low	Short	Long	Rare	Poor

Table 8: Main findings between high and low performance in the communications system
Source: The researchers

Performance of organization	Process improvements	Benefits and blame	Sharing of information	Relationship duration	Relationship strength	Selection of supply chain members	Alternative supplier base	Deliveries	Customer service
High	Present	Shared	High	Long	Partners	Present	Present	Frequent	Protected
Low	Limited	Private	Low	Long	Close	Limited	Absent	Infrequent	Loose

Table 9: Main findings between high and low performance in the supply chain relationships
Source: The researchers

Performance of organization	Production mode	Maintenance units	Systematic breakdown management	Workplace organization	Process standardization	Quality assurance	Design of Equipment	Concurrent Engineering	Design for manufacturability
High	Pull	Proactive	Present	High	All	Total	Present	Present	Present
Low	Push	Reactive	Absent	Basic	Most	Limited	Absent	Limited	Limited

Table 10: Main findings between high and low performance in the technical system
Source: The researchers

Performance of organization	Teamwork	Skills set	Product quality skills	Diagnostic skills	Ownership of production process	Machinery skills	Environmental skills	Innovation	Learning capabilities
High	Present	Multiple	Same	High	High	High	High	Enabled	Improved
Low	Present	Limited	Same	Low	Low	Low	Low	Restrained	Basic

Table 11: Main findings between high and low performance in the social system
Source: The researchers

Performance of organization	Improvement culture	Problem solving and learning	Improvement across the supply chain
High	Strong	Continuous	High
Low	Weak	Irregular	Low

Table 12: Main findings between high and low performance in the learning and improvement system
Source: The researchers

Typical disturbances effects	Examples	Performance measure	Performance objectives
Material Shortages	- Delays in deliveries - Incorrect materials or components	Delivery Dependability	Dependability
Breakdowns	- Unplanned maintenance - Employee absenteeism - Information system	Availability	Flexibility
Reworks	- Poor product quality	Quality	Quality
Non-standard production	- Variability in manufacturing lead time - Variability in delivery times	Speed	Speed

Table 13: Typical disturbances in production systems, their performance measure, and performance objectives
Source: The researchers