Completely Taktless! What Is Pull in the Context of the Process Industries?

Stewart Stevenson and Pauline Found

Abstract The widespread implementation of lean in discrete manufacturing has changed the face of those businesses with mechanisms such as setup reduction, bounded WIP, takt time, level scheduling and other elements of pull production aimed at reducing variation to create flow with minimal inventory, improving lead time, cost and service. While in the process industries, much is written regarding traditional approaches to planning and production control (PPC), the lean paradigm and pull production remain largely unadopted. This paper explores the nature of process industries and inadequacy of existing taxonomies to understand the underlying complexity, which significantly impacts planning and production control. Definitions and principles of pull are considered alongside existing process sector PPC and the fundamentals of demand, capacity and variation, to demonstrate that a contingent approach, which considers the environment is required. A manufacturing case study is used to confirm the underlying complexity and explain how the inherent variation and resulting trade-offs impact the applicability of discrete pull mechanisms with potential process manufacturing pull definition and mechanisms concluded. Furthermore, a pull system implementation in the case company operation is examined and simulated concluding the fundamental importance of sequence to flow and pull in process manufacturing and its impact on capacity, utilisation, waste and service.

Keywords Lean · Pull · Process industries · Production planning

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1 Introduction

There is evidence that the competitive environment of process industries is becoming more challenging as firms in a sector which is already cost focused are forced to control their costs while pursuing new markets, or improve their flexibility and responsiveness to defend existing markets (Yoho and Rappold 2011). The impact of this includes increasing product variety, reduced order size and reduced lead time, leading to increased manufacturing complexity, which when the fixed and inflexible nature of process manufacturing capacity is considered, results in significant challenges in the areas of planning and production control (PPC).

Since the 1980s, discrete manufacturers have benefitted from lean manufacturing techniques and pull production, to better align demand and capacity (Lyons et al. 2013) and create flow, delivering improvements in lead-time and cost. The process industries however have been slow to follow the discrete sector in the use of alternate PPC approaches to improve competitiveness (Dennis and Meredith 2000b). It has been suggested (Abdulmalek et al. 2006; Pool et al. 2011) that this is due to the unsuitability of process industry product/process characteristics, which may hinder the use of such mechanisms.

The authors of this paper would argue that the unsuitability lies with the mechanisms themselves, which are discrete industry founded, and so may not necessarily apply to the process environment, or help process firms compete in the same way they have discrete manufacturers (Crama et al. 2001). Fundamentally, there would appear to be a lack of evidence to support the application of pull in such environments (Belvedere and Grando 2005) and this paper is intended to address that deficiency.

2 Literature Review

2.1 The Process Industries

It is argued that the competitive environment of process manufacturing firms is becoming more difficult (Yoho and Rappold 2011), forcing changes in fulfilment strategy, which brings challenges for PPC and issues of ‘fit’ between fulfilment and manufacturing (Karmarkar and Rajaram 2012, p. 680). Numerous frameworks have been developed (Lyons et al. 2013) that classify products against processes to understand different operations and their manufacturing strategies (Stavrulaki and Davis 2010).

2.1.1 Published Industry Taxonomies

Hayes and Wheelwright (1979) built on the work of Skinner (1969) and Abernathy and Townsend (1975) cited in Lummus et al. (2006) introducing the product-process framework for aligning products and their life cycles with their corresponding production process life cycle. Traditionally the process industries have been clustered in the bottom right hand zone of the matrix. Crama et al. (2001) and McDermott et al. (1997) claim that firms should rarely exist off this diagonal due to the impact on cost/profit.

However, with changing markets, hybrids which compromise traditionally accepted manufacturing strategies are becoming increasingly common (Crama et al. 2001). Safizadeh et al. (1996) observe that most of these off-diagonal companies belong to the process industries where Kemppainen et al. (2008) suggest a "misfit" between capital-intensive equipment and expensive product changes.

Numerous authors have discussed the validity of this product-process approach (Kemppainen et al. 2008; McDermott et al. 1997; Stavrulaki and Davis 2010) proposing additional dimensions including batch consistency, material and product variety. Dennis and Meredith (2000a) argue that as Hayes and Wheelwright's (1979) model was originally developed for the discrete industries, the assumption is that process firms will face the same challenges and can use the same solutions as a discrete firm based on their position on the diagonal. They (ibid) propose that in contrast, manufacturing systems are actually organised by how products are made rather than by the actual end product itself. Abdulmalek et al. (2006) propose the additional dimension of discretisation, which, consistent with the process sector's 'off-diagonal' movement, can facilitate fulfilment flexibility (Pool et al. 2011). Due to fundamental differences (Crama et al. 2001) however process industries may not be comparable with discrete industries.

To distinguish between process and discrete manufacturing (Taylor et al. 1981) as two mutually exclusive strategies is inconsistent with manufacturing reality (Abdulmalek et al. 2006). Most process plants are actually hybrids because their non-discrete products become discrete at some point (Billesbach 1994). Pool et al. (2011) summarise production characteristics on either side of this point, which they claim can support different PPC approaches. Puttman (1991) and Abdulmalek et al. (2006) suggest however that in some systems, characteristics might actually be shared. The literature discusses characteristics typical of the process industries as shown in Table 1.

In more recent years differences within the process industries have received more attention. Fransoo and Rutten (1994) distinguish between process/flow and more flexible batch/mix industries but their model is arguably a constituent of those presented a decade earlier, implying that firms within each group have similar processing patterns (Dennis and Meredith 2000a). While Fransoo and Rutten (1994) lacked an "empirical approach" (Van Donk and Fransoo 2006, p. 211), Dennis and Meredith (2000a) addressed this with their study of the differences within process industry firms proposing that there is considerably more complexity in the process industries than previous research suggests.

In conclusion there remains relatively little research on the nature of the process industries (Crama et al. 2001; Dennis and Meredith 2000a). There has been much analysis and validation of models but the fundamentals of many such models remain founded in discrete manufacture and so there is limited consensus as to their applicability in the process industries. This suggests that due to the diverse nature (Lyons et al. 2013) and increasingly 'off-diagonal' behaviour of process

Table 1 Nature and impact of process industry characteristics

Materials	Variability	Natural sourcing and variability (Rice and Norback 1987)
	Inventory	Due to lead time, shelf life, seasonality and managing supply risk e.g. "months of tobacco" v "days of milk" (Rutten and Bertrand 1998, p. 630; van Dam et al. 1993, p. 581)
	Complexity	Claimed simplicity unfounded (Dennis and Meredith 2000a). Combinations of both low/high volume/variety (Abdulmalek et al. 2006)
	VAT	Typically V-plants (Cox and Spencer 1998; Fransoo and Rutten 1994)
	Push	Due to geographically diverse suppliers so purchases made in MRP 'buckets' (Karkarmar 1991, p. 361)
	Value	Cost represents both a major part of production cost and sales value (Crama et al. 2001)
	Capacity	Varies with material characteristics (Bolander and Taylor 1993; Crama et al. 2001)
BOM	Variability	Varies with material price, availability and quality (Fransoo and Rutten 1994)
	Divergent	Unlike discrete BOMs convergent parent recipe can diverge into differently packaged SKUs bringing decoupling point into play (Crama et al. 2001)
	Complex Products	Chemical BOM processing reactions can result in complex products even from simple BOMs (Crama et al. 2001)
Quality/Yield	Variability	Due to variable materials, BOMs and processing (Abdulmalek et al. 2006; Crama et al. 2001; Fransoo and Rutten 1994)
	Unknown	Often until processing started (Fransoo and Rutten 1994, p. 49)
	Load	Waste of making defective parts (King 2009) Waste can impact load (Bicheno 2011) Similarities with Seddon's (2003) 'failure demand' in service
	Capacity	Must account for scrap rate (King 2009, p. 62)
	Setups	Impact quality/yield due to "warm up"/"time to equilibrium" (King 2009, p. 127; Yoho and Rappold 2011, p. 59) driving tendency towards long runs (Pool et al. 2011)
Processing Equipment	Variability	Large scale, cooking/chemical reaction difficult to control giving rise to complexity and waste (Fransoo and Rutten 1994)
	Capacity	Generally constrained by equipment (Ivanescu et al. 2006) as opposed to discrete industry where capacity is people (Funk 1995)
	Capital Intensive	Capacity expansion can be prohibitively expensive (Abdulmalek et al. 2006)
	Setups	Focus on setup cost and utilisation (Schuster et al. 2000)
	Non Dedication	In contradiction to early literature assumptions (Dennis and Meredith 2000a, p. 1088) bringing sequencing issues (Dennis and Meredith 2000a; Schuster et al. 2000)

firms (Crama et al. 2001) the current literature frameworks are inadequate and may lead to selecting the wrong PPC approach.

2.2 *Planning and Production Control (PPC)*

Taylor and Bolander (1994) state that a firm's planning and scheduling must be tailored to its manufacturing environment and competitive strategy, which in turn has implications for off-diagonal process manufacture. In order to discuss the applicability of production control systems, Kingman's equation is used to explain the impact of variation and the interplay between variation and utilisation. There are three factors within Kingman: arrival variation; process variation and utilisation, all of which influence waiting times or cycle time. Expanding on Kingman we can determine that variation is buffered by Inventory, Capacity or Time (Bicheno 2011) and that the mechanisms available stem from these three fundamentals (Fig. 1).

De Treville and Antonakis (2006) agree, suggesting that the lean paradigm can be defined as a system which maximises capacity utilisation and minimises buffer inventories through minimising variability. In some environments capacity can be increased or utilisation reduced by adding labour whereas in others the only option is capacity in the form of plant/equipment. As this normally comes at significant cost, manufacturers normally focus on reducing variation using the mechanisms discussed above. The use of an appropriate pull system can also serve to reduce variability (Schonberger 1983) and stabilise flow.

2.2.1 Production Control Systems

Pull versus push is the control of WIP versus the control of throughput, typically controlled in relation to capacity which must be estimated and is subject to variation (Hopp and Spearman 2004). Pull systems are more responsive than push systems

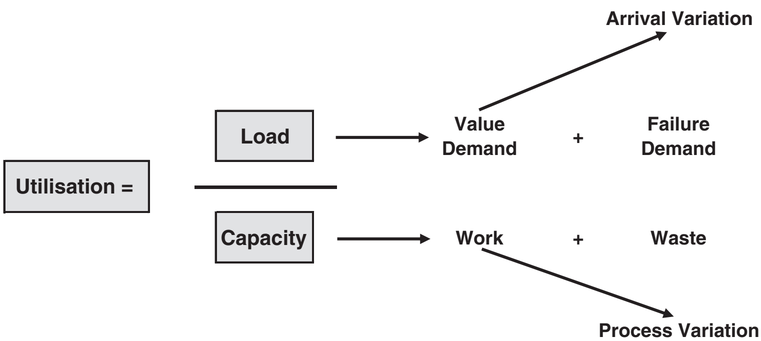

Fig. 1 Expanding on Kingman's equation (Bicheno 2011, reprinted with permission)

(Cheng and Podolsky 1993 cited in Hopp and Spearman 2004). By accounting for system status, pull improves manufacturing cycle times to achieve a lead time shorter than the expected delivery time. Spearman et al. (1990, p. 880) explain however that push and pull are not mutually exclusive concepts and that most systems are hybrids of the two "containing make to order (MTO) and make to stock (MTS) elements".

Whilst kanban was the first production control system to be termed pull (Hopp and Spearman 2004) its limited applicability (Bicheno and Holweg 2009; Hall 1983; Liker 2004) has motivated the generation of alternatives (Gaury et al. 2000) such as CONWIP (Spearman et al. 1990) and DBR (Goldratt and Fox 1986) in addition to various hybrids. However, whilst discrete manufacturers have benefitted from such pull production control systems (Lyons et al. 2013), the literature is "devoid of examples" which address process manufacturing (Yoho and Rappold 2011, p. 61).

Dennis and Meredith (2000a) explain how process industries have had mixed success with ERP systems with Van Donk and Fransoo (2006) suggesting that one of the main issues has been the inadequacy of MRP to plan process industry capacity. MRP logic tends to assume infinite capacity, fixed lead times, (Yoho and Rappold 2011) fixed batch sizes (Darlington and Schmidt 2013) regardless of plant loading and product mix (Karkarmar 1991) and when used for shop-floor scheduling ERP is effectively a push system (Powell and Strandhagen 2011). Schedule feasibility/adherence issues are exacerbated in process industries where materials, BOMs, yield and changeovers are all sources of variation and where there is the need to sequence production based on shared capacity and constraints (Schuster et al. 2000). Consequently other methods to guide and execute the schedule must be found (Schuster et al. 2000).

Based on the practices of process firms, Taylor and Bolander (1994) propose PFS a general approach to scheduling. In contrast to MRP (which uses product structure), PFS uses process structure to find a feasible schedule where capacity, due date, lot sizing and sequence dependency can be accounted for. However infrequent schedule violations are an assumption of PFS (Schragenheim et al. 1994) and as such it may not be suitable in higher product variety, contingent capacity process environments. Hubbard et al. (1992) incorporate the group technology (GT) philosophy into process scheduling. GT improves efficiencies by exploiting similarities and has been successful in cell manufacture where it normally involves equipment dedication (Shahin and Janatyan 2010). However, the philosophy can also be employed in constructing shared capacity schedules (Jamshidi 2009) by grouping products into families (Shahin and Janatyan 2010; Soman et al. 2004).

2.2.2 Planning and Production Control in the Process Industries

Process industries "lag" behind discrete manufacturers in the effective use of PPC (Dennis and Meredith 2000b, p. 68) despite more complex decisions regarding product replenishment (Yoho and Rappold 2011). An increasingly competitive environment for process industries has ushered a shift from MTS to hybrid MTO/MTS, (Crama et al. 2001; Fransoo 1992) bringing with it additional PPC complexity. Combined MTO/MTS is "neglected in the literature" and much of what does exist has limited applicability in process industries assuming for example no setups and batch sizes of one (Soman et al. 2004). The relationships between setups, process yield and differences in run productivity cause issues with estimating process industry capacity and plan feasibility. Bottlenecks can move (King 2009) and schedules initially found to be reasonable can become invalid (Fransoo 1992) because the impact of product mix and sequence are not considered (Dennis and Meredith 2000b), rendering the critical piece of processing equipment a constraint by the number of setups (Schragenheim et al. 1994).

This relationship between demand, capacity and inventory in the process industries creates real cost trade-offs (Fransoo 1993 cited in Crama et al. 2001), which must be managed. Combined MTO/MTS creates issues for shared capacity production control. Stock production is sometimes manufactured in the queue ahead of real demand, creating trade-offs between due-date performance, inventory, flexibility and capacity. The key issue in planning this capacity therefore is to determine what level of inventory is appropriate, how to make that decision and which products to produce at which time, to meet demand in the most cost effective manner (Cooke and Rohleder 2006). This creates further trade-offs between setups which result in waste/lost capacity and larger lot sizes which reduce waste/increase capacity but impact on service (ten Kate 1994). Toelle (1996) cited in Schuster et al. (2000) suggests that the lot sizing trade-off should be viewed as one between set-up costs and capacity constraints. In the context of the process industries waste, contamination and quality costs should be added (Cooke and Rohleder 2006).

In process manufacture, production sequence which is often determined by setups (Van Dam et al. 1993) is of particular importance. In light of the competitive developments in process industry markets, in addition to capacity and waste/cost, trade-offs arguably include service levels all of which can be mitigated by production sequence (Clark et al. 2010; Cooke and Rohleder 2006; Soman et al. 2004) which the authors conclude to be of fundamental importance to PPC in the process industries. This is well supported in the operational literature.

2.3 Flow and Pull

Bonney et al. (1999) suggest that in practice most systems comprise elements of both push and pull. Pull however cannot be viewed in isolation and whilst it is outside the scope of this paper, the authors recognise that pull is effectively a constituent part of "the larger lean construct" (Hopp and Spearman 2004, p. 144).

Lean manufacturing (Krafcik 1988) emerged in post-war Japan (Womack et al. 1990) where observations of the work of Ford creating flow in a mass production environment and learning from other leading intellectuals were assimilated by Japanese industrialists. They combined them with their own ideas to create a hybrid, (Bicheno and Holweg 2009) holistic and sustainable system of management focused on reducing waste (Womack et al. 1990). This system compressed lead time (Schonberger 2015) leading ultimately to the creation of flow in a low volume, high variety environment with pull as a core concept (Liker 2004).

Pull and the achievement of flow are fundamental elements of the five lean principles (Womack and Jones 1996). For Ohno and Toyota the mantra was "flow where you can, pull where you must" (Rother and Shook cited in Liker 2004, p. 108) suggesting that even for Toyota, achieving flow was not straightforward.

There is considerable ambiguity (Bonney et al. 1999) regarding the definition of pull in the literature with JIT, kanban and pull often used interchangeably (Hopp and Spearman 2004). In the mid 1990s the definition of pull became distorted and synonymous with MTO. Hopp and Spearman (ibid) cite Womack and Jones' (1996) introduction to pull as a key catalyst of this distortion:

> Pull in simplest terms means that no one upstream should produce a good or service until the customer downstream asks for it…

Hopp and Spearman (2004) caution against distinguishing pull/push by either MTO or MTS, arguing that both can be either pull or push. King (2009, p. 241) argues that Ohno "didn't explicitly define pull" with Hopp and Spearman (2004) describing Ohno's (1988) picture as a high level, conceptual view of pull as opposed to the means to make it work. They (ibid) distinguish between "strategic" and "tactical" pull, or what Bicheno and Holweg (2009, p. 148) term "principle" and "mechanism" arguing that it is here that the ambiguity has arisen.

Hopp and Spearman (2004) suggest that the literature requires a definition of pull based on what is needed to obtain its benefits rather than on how it is executed, concluding that unlike push, pull explicitly limits system WIP. The over-riding distinction between the two then is that the pull system takes account of system status, preventing both the system from becoming overloaded and the queue from growing exponentially resulting in stable and minimal cycle and lead times.

Hopp and Spearman (2008) suggest that Toyota's success was achieved as a result of a pull based system which improved material flow, lead time, quality, flexibility and hence stability and service. However, their conclusions are discrete industry founded with a lack of evidence regarding the applicability of discrete mechanisms (see Table 2) in process manufacture (Abdulmalek et al. 2006; Yoho and Rappold 2011).

There remain gaps in the literature as the vast majority of research is focused on the implementation of pull in discrete manufacturing environments (Belvedere and Grando 2005; Crama et al. 2001; Yoho and Rappold 2011). Furthermore there is a lack of evidence but the literature suggests that discrete pull mechanisms do not directly transfer to process manufacture (Abdulmalek et al. 2006; Pool et al. 2011). However, with a contingent approach, opportunities to create flow may exist in terms of aligning demand and capacity and minimising interruptions (Lyons et al. 2013).

It is interesting to note discussion regarding the lack of process industry lean/pull literature and case implementation in the 1990s (Billesbach 1994;

Table 2 Literature summary of pull production characteristics

Pull production characteristic	Literature discrete manufacture overview	Literature process manufacture issues
WIP limit	Systematically limits releases to limit the total work in the system (Hopp 2008) ensuring system is not overwhelmed	• WIP is often bounded by equipment so blocking occurs naturally (Hopp and Spearman 2004)
	Targeted at reducing cycle time (Little's Law) and both reducing and stabilising lead time (Hopp 2008) and inventory	• In a process environment finished product inventory can build as a result of poor flow (King 2009, p. 25) and so like discrete WIP it may also be bounded (Liberopoulos and Dallery 2002)
Setup/batch size reduction	A consequence of pull-based production is small lot sizes which results in many setups, in turn disrupting flow (Thun et al. 2010)	• Small batch sizes impact capacity resulting in longer lead times when batch sizes are large, but saturation when batches get so small that setups create a constraint (Kim and Tang 1997; Schragenheim et al. 1994; Hopp and Spearman 2004)
	Changeovers are a source of variation (Bicheno and Holweg 2009) and if the degree of variation is large, scheduling becomes more difficult and both lead time and cycle time less predictable	• Setups disrupt flow (Thun et al. 2010) so facilitating "flow with minimal interruptions, delays and variations" (Lyons et al. 2013, p. 477) is an alternate approach for process industries
Production smoothing/ level loading	Discrete industries have benefitted from level loading or Heijunka (Liker 2004; Yoho and Rappold 2011) which balances work, supporting pull (Hopp and Spearman 2004) and flow (Hüttmeir et al. 2009; Liker 2004)	• Makes discrete industry assumptions that demand can be buffered by capacity in the form of people, changeover time can be eliminated and using time to drive down batch size (Bicheno and Holweg 2009) is optimal
	Liker (2004) and Duggan (2002) advocate a mixed model approach where demand is smoothed through the schedule by volume and product mix	• Mixed model is not suitable for all environments (Bicheno and Holweg 2009). The elimination of setup time (Liker 2004) and other setup waste is a pre-requisite
		• Yoho and Rappold (2011) claim that production smoothing is not yet defined for the process industries proposing predictable production cycles to stabilise manufacturing lead times supported by an inventory policy to absorb random demand (Liker 2004; Yoho and Rappold 2011)
	Level loading delivers responsiveness/flexibility for the customer, improved quality, higher utilsation, balanced use of resources and even demand on upstream processes (Duggan 2002; Hüttmeir et al. 2009; Liker 2004)	• Fixed cyclic schedules reduce manufacturing flexibility (Pool et al. 2011) and total costs increase (Jamshidi 2009) so not suitable for off-diagonal process manufacture

(continued)

Table 2 (continued)

Pull production characteristic	Literature discrete manufacture overview	Literature process manufacture issues
Takt time and pitch	Once demand is established it can be divided across an available time to establish takt, the pace needed to work at to meet that demand (Brown et al. 2006, p. 8)	• Where product/process characteristics are variable or process times are fixed and can't respond to demand fluctuations, takt is not appropriate and a time based view of capacity is required
		• In theory the products being scheduled shouldn't matter but in environments with variable product/process characteristics the products do matter and consequently takt/pitch are less applicable where resources are shared, demand is highly unstable or production cycle times are variable (Bicheno and Holweg 2009; Duggan 2002)
Variation reduction	To combine high capacity utilisation with low inventory (De Treville and Antonakis 2006, p. 102; Suri 2003, cited in Hüttmeir et al. 2009) in discrete industries there is a focus on variation reduction (Hüttmeir et al. 2009)	• In process manufacture variation is unavoidably inherent (e.g. natural materials) and as in service organisations (Frei 2006) variation must be accommodated
	Variation reduction is "critical for the effectiveness of pull systems" (Samaddar and Hill 2007, p. 250)	
Inventory reduction	Lean paradigm often associated with inventory reduction (Hall 1983; Hopp and Spearman 2004)	• Association of lean with inventory reduction "misunderstands lean" (Yoho and Rappold 2011, p. 61)
	Appropriate inventory can support flow (Bicheno 2006, p. 46). While one of the aims of Ohno's supermarket inspired system was inventory reduction, a supermarket always maintains a level of inventory on the shelves (Huang and Kusiak 1996, p. 169)	• Targeting a low inventory policy may be wholly inappropriate for process manufacture. An inventory policy which absorbs demand, maintains service and accounts for equipment limitations is required (Yoho and Rappold 2011)
Process layout	Discrete manufacturers have facilitated flow through process layout (Emiliani and Seymour 2011; Hounshell 1984; Liker 2004)	• Flow must be facilitated in a different way, minimising interruptions, delay (Lyons et al. 2013) and setup waste and maximising asset productivity (King 2009)
	Cell layout in particular is associated with improving capacity, flow and productivity in the discrete industries (where people = capacity) through waste reduction, line balancing, single piece flow, inventory and movement reduction, visibility and labour flexibility/productivity (Bicheno and Holweg 2009; Liker 2004)	• In the process industries much of this doesn't apply as equipment dictates capacity and is often fixed and inflexible (King 2009)

Schragenheim et al. 1994) and the fact that over a decade later the literature is still making the same point (Belvedere and Grando 2005; Pool et al. 2011; Yoho and Rappold 2011).

2.4 Conclusions on the Literature

In conclusion, further examination of flow and pull based PPC models in the process industries would add to the current body of knowledge.

The bulk of the literature is focused on MTS environments and research on MTO is scarce (Germs and Riezebos 2010). The fact that most process businesses are a combination of both carries questions with regard to how pull should be implemented, when capacity is shared and consumed by competing value streams and production for both real orders and stock. This forces the issue of prioritisation (Germs and Riezebos 2010), which in process manufacture brings trade-offs and decisions regarding production sequence where there is a deficiency in the lean literature.

This is particularly striking when the "unparalleled" (Kouvelis et al. 2005, p. 462) extent of the traditional operational literature on scheduling and sequence is considered.

3 Methodology

A single case study of a process industry that supplies commercial fish food has been selected with triangulation achieved through the existing body of knowledge on the process sector, PPC approaches and pull, with case company data comparison and discussion, accompanied by simulation to combine theory and case environment.

The research was conducted at Skretting UK's operation in Longridge, England.

Nutreco is a global animal nutrition company with approximately 10,000 employees in 30 countries of which Skretting is a global subsidiary specialising in the manufacture of high energy pelleted fish feed for commercial fish farms, being part of the aquaculture value chain. Skretting has operations in 14 countries, selling approximately 1.9 million tonnes of feed for over 60 species of farmed fish and shrimp.

Skretting Longridge is the UK's speciality feed plant manufacturing in excess of 200 different products, for 7 species of fish, on a single extrusion line for more than 400 customers UK wide. An increasingly diverse product portfolio accompanied by pressure on customer lead time and shared capacity has led to an increased focus on PPC and flow as a means to improve responsiveness (Schonberger 2015), which provides a suitable environment for the research.

The case company will be compared with the literature characteristics and taxonomies of process industries and the case environment considered in terms of the fundamentals of demand, capacity and variation, the PPC literature and suitability for pull. A sequencing simulation will be carried out to compare typical pull scheduling methodologies with that of the case company's pull system.

4 Case Study Analysis and Discussion

Comparing the case company to the literature on process and discrete industries highlights some differences (see Table 3).

Table 3 Characteristics of Skretting as a process business

Relationship with market	Process industries	Discrete industries	SKRETTING
Product Type	Commodity	Custom	Hybrid
Product assortment	Narrow	Broad	Hybrid
Demand per product	High	Low	Hybrid
Cost per product	Low	High	High
Order winners	Price	Speed of delivery	Price
	Delivery guarantee	Product features	Delivery guarantee and product performance
Transporting costs	High	Low	High
New products	Few	Many	Hybrid
The product process			
Routings	Fixed	Variable	Fixed
Layout	By product	By function	By product
Flexibility	Low	High	Low
Production equipment	Specialised	Universal	Specialised
Labour intensity	Low	High	Low
Capital intensity	High	Low	High
Changeover times	High	Low	Medium
Work in process	Low	High	Low
Volumes	High	Low	Hybrid
Quality			
Environmental demands	High	Low	Medium
Danger	Sometimes	Hardly	Hardly
Quality measurement	Sometimes long	Short	Hybrid
Planning and control			
Production	To stock	To order	Hybrid
Long term planning	Capacity	Product design	Capacity

(continued)

Table 3 (continued)

Relationship with market	Process industries	Discrete industries	SKRETTING
Short term planning	Utilisation capacity	Utilisation personnel	Trade offs—capacity/ service/waste
Starting point planning	Availability capacity	Availability material	Availability capacity
Material Flow	Divergent + convergent	Convergent	Divergent + convergent
Yield variability	Sometimes high	Mostly low	Sometimes high
Explosion' via	Recipes	Bill of materials	Recipes
By and Co products	Sometimes	Not	Always
Lot tracing	Mostly necessary	Mostly not necessary	Necessary
Additional characteristics			
Material variability	Yes	Low	High
Material availability	Variable	Stable	Variable
BOM/recipe	Sometimes variable	Stable	Always variable
Quality variability	Yes	Reasonably stable	Yes
Process variability	Yes	Reasonably stable	Yes
Contingent capacity	Depends on product	No	Yes
Material cost	Low	High	High
Trade-offs	Sometimes	Low	Significant, always
Changeover waste/ contamination	Depends on product	No	Always

Adapted from Abdulmalek et al. (2006), Crama et al. (2001), Fransoo and Rutten (1994), Rice and Norbrack (1987), Soman et al. (2004), Voss (1995)

This analysis confirms both the inadequacy of comparing process and discrete industries and the generalisation that process industries consistently show the same characteristics. Skretting is not an exact fit with either classification and in addition to hybrid and certain unique characteristics, clearly displays aspects of both process and discrete manufacture.

Skretting is typical of the literature which considers that many process industry products become discrete late in the transformation. However, in contrast to Pool et al. (2011) Skretting demonstrates significant complexity and commonality in characteristics on both sides of this point (see Fig. 2) suggesting that the additional complexity of batch/mix process businesses brings elements of both process and discrete manufacture.

Despite fitting the APICS (2013) definition of batch/mix production, when Skretting is considered in the context of Fransoo and Rutten's (1994) model of process industries it is found to be atypical of batch/mix businesses and as such its place within process industry taxonomy remains unclear. This is confirmed using a qualitative view (supported by Lyons et al.'s (2013) descriptions) of Skretting's position on Dennis and Meredith's (2000a) four criteria model where Skretting displays two

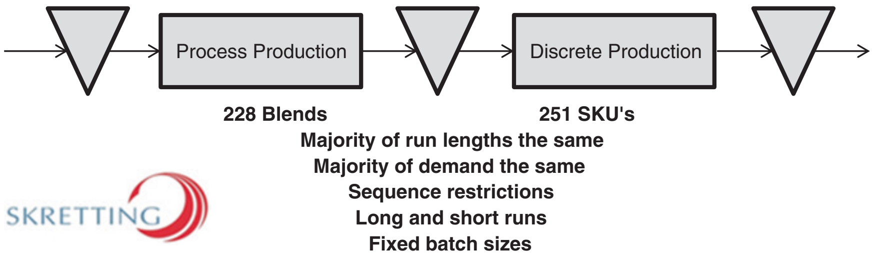

Fig. 2 Skretting process versus discrete manufacture (adapted from Pool et al. 2011)

significant differences which bring trade-offs between equipment flexibility and variety, impacting on PPC:

- **Equipment v Materials Diversity**: Skretting had a significantly higher number (×10–20) of raw materials and finished goods than those businesses which had similar equipment characteristics (and displayed the lowest material diversity). This raises PPC issues in terms of flexibility and responsiveness, cost, fulfilment strategy and service level;
- **Equipment v Run Time**: Average run time at Skretting was 10 times shorter than the lowest run time average and more than 50 times shorter than those plants with similar equipment characteristics. In the context of process manufacture this brings PPC issues in terms of run length, changeover, waste and capacity.

In conclusion, analysis suggests that while clearly a process manufacturer, Skretting arguably displays complexity not described by the literature and exhibits characteristics of process/flow, batch/mix and discrete industries.

4.1 Skretting Manufacturing, PPC and Fulfilment

Typical of the process industries (Crama et al. 2001), the Skretting facility is V plant oriented (Cox and Spencer 1998). Skretting has three points of differentiation which typically provide opportunity to alter fulfilment strategy by relocating the decoupling point (Naylor et al. 1999) but this is practically and economically unviable. This combination of inflexible plant and limited decoupling means that Skretting fulfilment is a combination of MTS decoupled at finished goods inventory and MTO decoupled at raw material inventory.

Skretting's continuous layout means that intermediate process WIP is both constrained and almost non-existent. It could be argued at a mechanistic level that as a result of this natural bounding of WIP, the Skretting system cannot be overloaded and is already pull based. However, demand and capacity can still be misaligned and the wrong product/quantity manufactured, resulting in over-production waste, slow moving inventory and poor flow to the customer despite this apparent bounding of WIP. As such it could be argued that the mechanistic definition of discrete industry pull in terms of bounded WIP does not apply to process manufacture.

Skretting's V plant configuration includes shared capacity common routing which, consistent with the literature, brings trade-offs between cost/waste, capacity and service which render scheduling critical. In V plants, scheduling is typically focused at constraints and points of differentiation where traditionally opportunities for decoupling exist. Due to decoupling limitations, Skretting scheduling focuses on the former, where due to the combination of early product commitment and resulting setups, extrusion is the dominating process constraint. Historically, Skretting scheduling has been MRP push (Hopp and Spearman 2004). This push approach has resulted in misalignment of demand and capacity with off-peak over-production, and a finished goods inventory curve which doesn't reflect seasonality. As a result Skretting has implemented a pull based system which is discussed in Sect. 4.2 below.

Skretting's hybrid MTO/MTS fulfilment is an industrial reality, but is not well described in the literature creating issues for PPC frameworks which regard MTO and MTS as mutually exclusive fulfilment strategies requiring disparate manufacturing characteristics. In the case of Skretting, this is not practically possible and so a solution must be found in terms of PPC, however the literature PPC frameworks do not adequately describe hybrid fulfilment. As such in the context of this paper, it is considered necessary to examine PPC fundamentals to determine opportunities for hybrid fulfilment solutions and the implementation of pull.

Annual demand is seasonal fluctuating significantly with customer growing strategies, harvest plans, water temperatures and oxygen levels. Product demand follows typical Pareto behaviour. Order demand follows a similar pattern with the majority of customer orders smaller than the minimum run length. This 'long tail' (Anderson 2009) provides further PPC challenges where early committed products are manufactured on inflexible process industry equipment. This supports both the need for a MTS/MTO fulfilment strategy with finished goods inventory buffering based on robust demand analysis (King 2009) and the equipment/variety conflict highlighted by the analysis of Skretting using Dennis and Meredith's (2000b) model.

Arrival variation is atypical of the process industry literature and confirms Skretting's off-diagonal position. Several decision points/handovers are present in the Skretting supply chain and manufacturing is decoupled from real demand resulting in amplification (Lee 1997). Numerous countermeasures have been implemented but short term demand is still subject to significant biological and environmental variation. This variation is confirmed using demand class analysis (Boylan et al. 2008; Syntetos et al. 2005) where over 50 % of Skretting SKU's are higher variation 'lumpy' or 'management control' with significant variation within these demand classes. Furthermore, only 3 % of volume has a low coefficient of variation (CV).

Analysis demonstrates that Skretting process variation is consistent with the process industry literature:

- **Material Variation**—processing functionality variation (not explicit until processing has started) due to natural sourcing and seasonal availability;
- **BOM Variation**—variability of material quality, availability and price results in BOM variation which can cause significant change in processing functionality impacting product quality, yield and capacity due to changing proportions of variable materials;
- **Machine Variation**—equipment is large scale, capital intensive and processing is inexact cooking/chemical reaction giving rise to significant process variation of which changeovers are a significant proportion impacting on time, capacity, material waste and quality;
- **Yield/Quality**—The combination of material, BOM and process variation results in variation in both yield and right first time (RFT) quality, impacting flow, system predictability and service levels.

In conclusion the Skretting case demonstrates a significant degree of variation in processing, materials, BOM and yield/quality that is consistent with the process industry literature providing less opportunity for reduction than that within discrete manufacturing and so any buffering strategy should take this into account.

This, coupled with long tail demand, arrival variation and off-diagonal fulfilment not typical of the process industry literature results in a particularly high variation environment for Skretting as a process manufacturer (see Fig. 3).

Skretting setups/changeovers are frequent and constrain capacity (Schragenheim et al. 1994). Changeovers are also sequence dependent (Yoho and Rappold 2011) consuming different amounts of time and so capacity varies with product mix, and the number (lot size) and type of changeovers. In addition to lost capacity, setups/changeovers also incur energy cost and generate material waste.

The significant impact of setups/changeovers are consistent with the literature and indicate that the typical discrete-pull focus on setup/batch size reduction (Thun et al. 2010) is less suitable for the process manufacturing environment at Skretting, due to increased waste and potential capacity constraint (Kim and Tang 1997; Schragenheim et al. 1994).

Consequently, typical discrete industry workload levelling would also be unsuitable in the Skretting process environment (Bicheno and Holweg 2009) due to the increased number of changeovers (Powell et al. 2009).

Analysis shows that Skretting Capacity is contingent on:

- **Product Mix**—due to the processing speeds of different sizes and product types which require varying difficulty of production effort (Seidman and Holloway 2002);
- **Constituent Materials**—due to their processing functionality which can cause the bottleneck to shift;
- **Bill of Materials**—due to changing proportions of variable raw materials;
- **Yield/Quality**—due to large scale, inflexible inexact processing and variable BOMs/Materials.

Figure 4 illustrates the cumulative capacity impact of each variation source contrasted with the capacity contained within MRP.

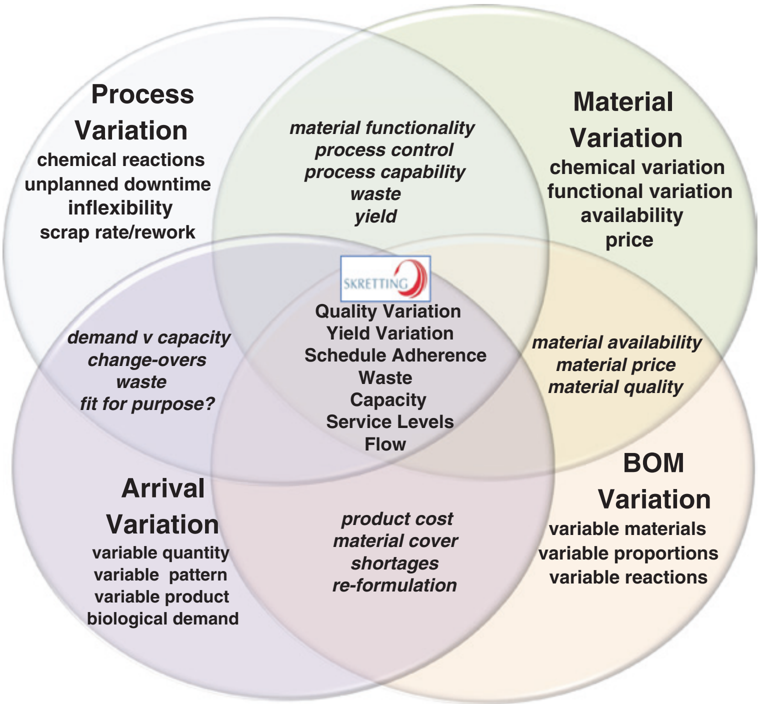

Fig. 3 Euler diagram illustrating Skretting variation complexity

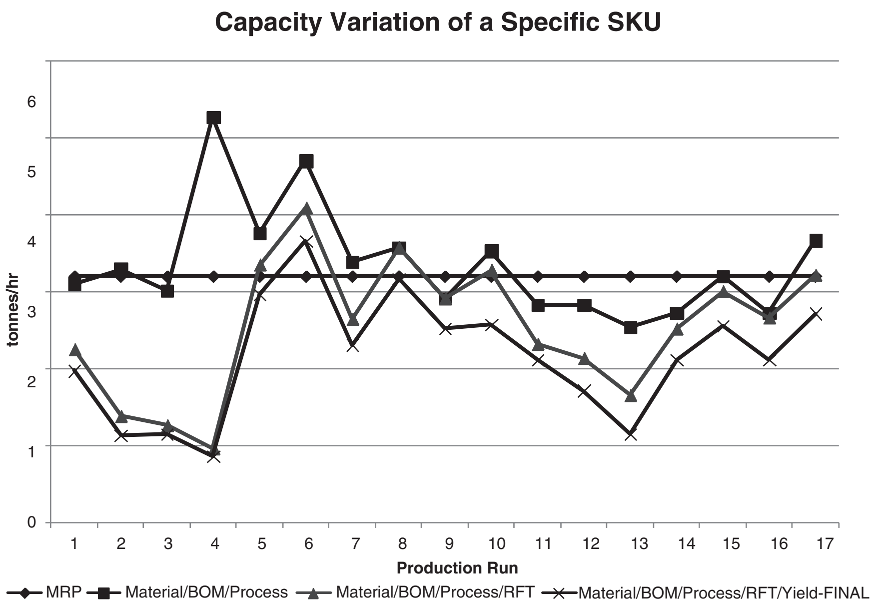

Fig. 4 Cumulative impact of variation on capacity of a specific SKU

This contingent capacity has implications for PPC and establishing flow, while in the context of pull mechanisms, the variable product/process characteristics and cycle times, also confirm the unsuitability of discrete industry takt for the Skretting environment.

4.2 Pull in the Skretting Process Environment

Analysis of the Skretting production environment suggests that many of the traditional mechanisms of discrete pull may not be applicable to process manufacturing at Skretting (see Table 4).

However, a pull system has been introduced at Skretting, which is consistent with the principles of flow and pull and the fundamentals of demand, capacity and variation (see Table 5).

In summary, Skretting now employ hybrid MTO and demand based pull replenishment MTS using a combination of time and inventory buffers and Advanced

Table 4 Summary of implications of Skretting manufacturing environment for pull

Skretting environment factor	Implications for pull
Differentiation/ decoupling	• No opportunities for intermediate decoupling due to equipment restrictions. Only able to pull from decoupled Raw Material (MTO) or Finished Goods (MTS)
WIP	• WIP is already bounded due to equipment restrictions so Skretting pull cannot and should not be defined by limited WIP. However demand and capacity can still be misaligned resulting in poor flow so pull should be defined in another way
Demand	• Long tail, variable nature of Skretting demand conflicts with fixed, inflexible process industry equipment (confirmed by Dennis and Meredith 2000b analysis). Results in lack of ability to MTO all products due to resulting setup constraint so can't pull from raw material. WIP restrictions mean Skretting can't pull from intermediate buffers so confirms need to pull from MTS FG buffer. Demand is not actual consumption so subject to amplification—demand analysis to support the MTO/MTS decision
Capacity	• Capacity is shared, highly contingent, subject to significant variation and impacted by setup and sequence. Product/process characteristics and highly variable cycle times confirm an environment not suitable for using takt. Time based view of capacity is required
Setups	• Setups are sequence dependent and have a significant impact on capacity, waste and flow. Confirms that traditional discrete industry MMS level scheduling and batch size reduction are likely to be unsuitable. Time buffer will enable smoothing of the schedule to reduce setup interruption and waste
Variation	• High level of inherent variation results in unpredictable output further advocating MTS FG buffering to achieve stable flow to the customer. Downtime and setup process variation to be focused on to maximise equipment uptime. Operator competence extremely important to manage/accommodate variation

(continued)

Table 4 (continued)

Skretting environment factor	Implications for pull
Waste	• Setups generate time, material and energy waste and interrupt flow. Despite bounded WIP, poor alignment of demand and capacity can result in overproduction and inventory waste
Inventory	• High variation and requirement for high service level mean that inventory is a justifiable option. Raw Material inventory required due to nature of sourcing, FG buffers required due to unpredictable processing and combination of long tail variety and lack of equipment flexibility
MRP/ERP	• Use of fixed lead time, average throughput and setup result in issues of schedule adherence and frequent re-running of the schedule. Inability to account for sequence dependency leads to suboptimal sequencing resulting in longer manufacturing lead times and increased material waste. Supports use of pull to execute the schedule but system must account for sequence

Table 5 Elements of Skretting pull system and their consistency with the literature

Pull system

Element	Description
On time in full (OTIF) measure	• to monitor flow performance to the customer (Womack and Jones 1996) and service levels pre and post pull system introduction
Demand analysis	• to understand the nature of demand and its variability and support MTS/MTO decisions (King 2009)
MTO/MTS Policy	• (by product) based on demand analysis
Periodically reviewed demand based pull inventory replenishment	• for MTS products (using historical demand and statistical algorithms to set stock levels) to align demand and capacity and stabilise production cycles (Fernandes and Filho 2011; Huang and Kusiak 1996; Yoho and Rappold 2011)
Finished goods stock 'bounding'	• (as opposed to discrete-pull WIP) (King 2009) by actual warehouse space
Use of advanced demand information (ADI) in combination with pull	• to further optimise production run lengths, inventory levels and manage finish goods inventory limitations (Claudio and Krishnamurthy 2009)
Time (customer lead time) and Inventory (finished goods MTS) variation buffers	• (Bicheno 2011; Hopp and Spearman 2004) which allow smoothing of the schedule and responsive service to the customer
Sequencing by product size and family	• (Shahin and Janatyan 2010) to improve flow by minimising changeover interruptions, delays and variation (Lyons et al. 2013) and reduce material, energy and capacity waste
Time based capacity planner	• to better understand capacity, bottlenecks, sequence and product mix impact and the ability to provide promise dates to the customer. While the production line itself is 'naturally bounded' (Yoho and Rappold 2011), in combination with the lead time buffer this avoids overloading the system

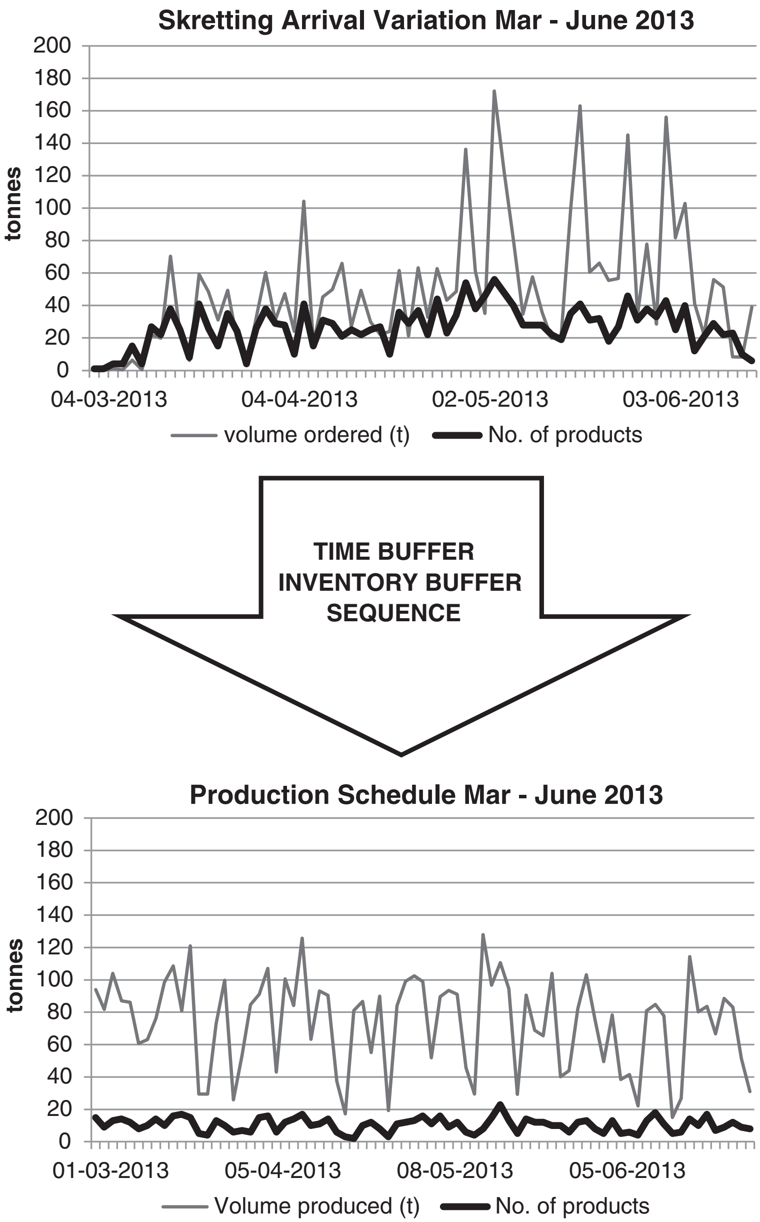

Fig. 5 Buffering of arrival variation to smooth the schedule at Skretting

Demand Information (ADI) (Claudio and Krishnamurthy 2009) to reduce changeovers and enable schedule smoothing (see Fig. 5) on a product group basis to deliver high service levels while mitigating the trade-off impact of changeovers to reduce waste and improve flow.

As a result of this demand based pull, run lengths and inventory levels for higher demand, more stable products have been extended reducing material waste and shortened for lower demand, more variable products improving obsolescence. The periodic review system has also stabilised manufacturing cycles (Yoho and Rappold 2011) reducing the standard deviation of time between cycles. However, Skretting did not experience an improvement in quality/yield (ibid) as a result of more stable production cycles. As a result of this improved alignment of demand and capacity, system flow is improved resulting in a more stable inventory profile and an upward trend in OTIF.

Since the original research, analysis by a third party working capital consultancy one year after the pull system was implemented has confirmed the reduction of weighted average maximum and minimum system lead time by over 50 %.

4.2.1 Conclusion on Pull in the Skretting Process Environment

From the analysis above, the authors conclude the potential for and benefits of pull production control in a process environment as demonstrated by the Skretting pull system case, further proposing that sequence is an important element of the Skretting pull system and a critical element of achieving flow and pull in a process environment which will be examined next.

4.2.2 Importance of Sequencing in the Skretting Pull System

In this section simulation will be used to evaluate the importance of sequence as a constituent element of pull in the Skretting case.

To simulate sequencing the production demands generated by the Skretting pull system for 15 separate weeks in 2013 were re-sequenced using the following scheduling methodologies associated with lean/pull production (Bicheno and Holweg 2009; Hopp and Spearman 2008):

1. Shortest Processing Time (SPT)
2. Earliest Due Date (EDD)
3. Level Scheduling/Mixed Model (Level)

The results of the three lean scheduling methodologies are compared, (Table 6) with that of the actual Skretting sequence (Skr Seq).

The SPT sequence gave the worst performance and in contrast to the literature (Hopp and Spearman 2008) did not decrease average manufacturing times. Rather than consolidating short runs (GT) to reduce setups and waste, SPT separates them to complete them first, exacerbating the number and severity of changeovers.

The impact of EDD and Level Loading are similar, increasing changeovers to either prioritise due dates (EDD) or spread workload (Level Loading). In contrast to the literature, level loading did not deliver higher utilisation, or when feasibility was accounted for, responsiveness for the customer (Hüttmeir et al. 2009).

Table 6 Summary of sequencing simulation results

Summary Impact of Sequence				
Measure	Sequencing Method			
	SKR Seq	SPT	EDD	Level
Total Setup Time (hrs)	236	448	397	411
Total Time (hrs)	1,277	1,489	1,438	1,452
Ave. Manuf. Lead Time (hrs)	2.30	2.68	2.59	2.60
Ave. Capacity (t/hr)	4.42	3.79	3.92	3.88
Total Material Waste (£)	£ 18,081	£ 27,960	£ 25,747	£ 26,183
Total Energy Waste (£)	£ 5,449	£ 10,293	£ 9,100	£ 9,336
Initial OTIF % (factory floor)	*98.7%*	*89.0%*	*99.6%*	*99.6%*
FEASIBLE OTIF % (factory floor)	98.4%	87.4%	96.4%	96.2%
Ave. Utilisation	79.3%	92.5%	89.3%	90.2%
CV of Capacity	0.32	0.36	0.38	0.36
CV of Setup Variance	1.10	0.63	0.74	0.70

KEY
best performance
worst performance

As would be expected, Skretting setup variation was highest due to the combination of small changeovers where feasible, accompanied by large setups where unavoidable.

However, significantly and somewhat unexpectedly, the Skretting sequence delivered the lowest capacity CV. Although this result could be a function of the higher SKR sequence capacity, this suggests a degree of what in this environment could be considered level loading achieved by the Skretting methodology, the performance of which compares favourably with the discrete founded level loading sequence.

The importance of sequence was particularly apparent at higher levels of utilisation, which sequence impacted further, where schedule feasibility was a greater issue for the lean scheduling methodologies (see Fig. 6).

In high utilisation weeks, the superiority of the SKR sequence in terms of both material, energy and time waste was most pronounced. When schedule feasibility was taken into account, at high utilisation the SKR sequence also delivered better OTIF. Unsurprisingly, sequence was of lesser importance when product mix complexity was low where the SKR sequence did not deliver significant advantages in either manufacturing lead time or capacity.

The sequence simulation also serves to confirm the contingent nature of Skretting capacity. When the run by run capacity of the (least variable) SKR sequence is plotted against the average capacity (Hopp 2008), the variable and contingent nature becomes evident (see Fig. 7) bringing into question the suitability of this discrete founded capacity definition for building and executing the schedule in process manufacture.

4.2.3 Conclusion on Sequence

In conclusion, the process industry trade-offs identified in the literature are present within Skretting. Consistent with the literature, these trade-offs can be mitigated by a production sequence appropriate for the environment.

	Utilisation % (5 day week)			
	SKR Seq	SPT	EDD	Level
Wk 14	72%	79%	76%	82%
Wk 15	67%	83%	81%	85%
Wk 16	62%	76%	74%	73%
Wk 17	69%	72%	74%	69%
Wk 18	82%	102%	93%	99%
Wk 19	86%	96%	90%	94%
Wk 20	103%	125%	124%	120%
Wk 21	75%	88%	83%	81%
Wk 22	61%	73%	69%	71%
Wk 23	74%	87%	84%	86%
Wk 24	57%	66%	66%	64%
Wk 25	70%	83%	79%	81%
Wk 26	66%	77%	74%	74%
Wk 27	89%	110%	101%	100%
Wk 28	78%	83%	84%	81%

< 80%
< 90%
< 95%
> 95%

	Utilisation % (Overtime)			
	SKR Seq	SPT	EDD	Level
Wk 14	66%	72%	69%	75%
Wk 15	61%	75%	73%	77%
Wk 16	56%	69%	67%	66%
Wk 17	62%	66%	67%	63%
Wk 18	75%	92%	84%	89%
Wk 19	78%	86%	82%	85%
Wk 20	93%	113%	113%	109%
Wk 21	68%	80%	76%	73%
Wk 22	56%	66%	63%	65%
Wk 23	67%	78%	76%	78%
Wk 24	52%	60%	60%	58%
Wk 25	64%	75%	71%	73%
Wk 26	60%	70%	67%	67%
Wk 27	80%	99%	92%	91%
Wk 28	71%	75%	76%	74%

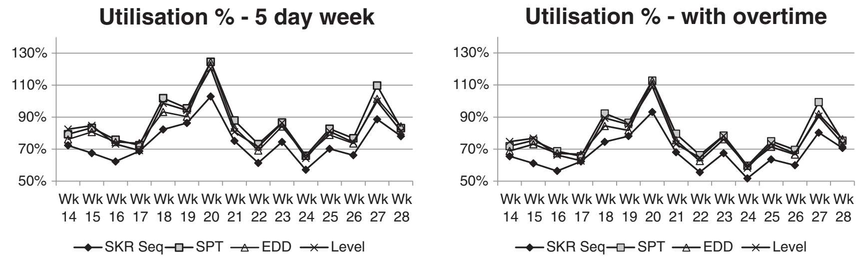

Fig. 6 Impact of sequence on utilisation

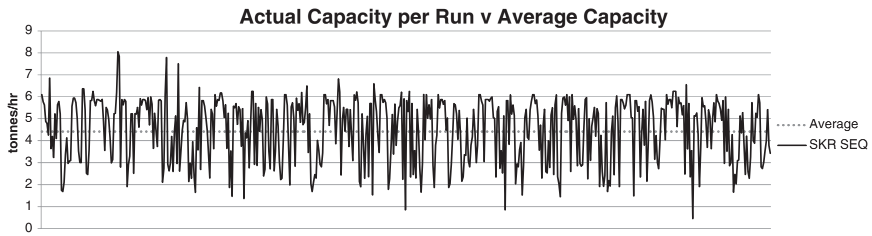

Fig. 7 Actual Skretting sequence capacity against Hopp's (2008) average capacity

In contrast to the sequencing methodologies founded in discrete industry pull, the Skretting sequence provided highest performance in mitigating the trade-offs of capacity (throughput, lead time and variation), waste (material and energy) AND service (OTIF) identified in the literature (see Fig. 8).

In terms of the principles of flow and pull, the Skretting sequence better aligns capacity and demand, minimises waste and optimises flow to the customer and as such in the Skretting case is an essential element of pull in process manufacture.

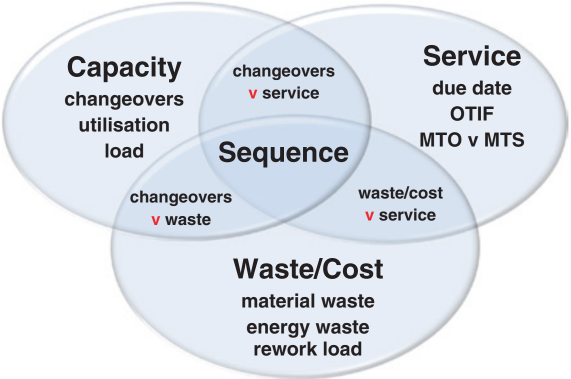

Fig. 8 Literature derived model illustrating analysed Skretting process industry trade-offs and the importance of sequence

5 Discussion

5.1 Pull in the Process Industries

The literature view of pull is both ambiguous and strongly founded in discrete manufacture, focusing on the mechanisms of pull as opposed to the general principles that inspired Ohno. This is particularly evident, for example in Hopp and Spearman (2004), where make to forecast is regarded as pull if it is executed using kanban and takt. Forecast-based overproduction using kanban and takt is nevertheless overproduction and here Hopp and Spearman (2004) are arguably losing sight of the fundamental principles of demand-based flow to the customer in favour of the manufacturing mechanisms of executing pull.

The literature suggests that the process industries have been slow to adopt pull production and this paper concludes that the limitations of discrete based mechanisms contribute significantly to this (Table 7).

The authors agree with the literature distinction between principle and mechanism and conclude that as a result, the principles of pull can be executed in different ways.

The alignment of demand and capacity is at the heart of lean thinking (Lyons et al. 2013) and as such by focusing on the principles of flow and reduction of waste and addressing the PPC fundamentals of demand, capacity and variation rather than prescriptively applying discrete founded mechanisms, pull can be achieved in a process environment.

If we try to define process industry pull purely in terms of mechanisms which constrain inventory, then without the capacity flexibility of discrete firms, the process industries will have issues managing both demand and inherent variation.

This unavoidable process industry variation results in a significantly more hostile environment requiring alternate buffering and a variation accommodation strategy (Frei 2006), as opposed to the variation reduction typically found in discrete manufacturing.

Table 7 Conclusion on discrete lean imperatives and limitations (adapted from Yoho and Rappold 2011)

Lean imperative	Process industry—research conclusions
Smooth or "level-load" production (heijunka)—establish production plans that are smooth with respect to volume and product mix	Discrete type EPE/heijunka increases setups/changeovers to the point where schedules become infeasible and waste generation is high
Establish capacity buffers—scheduling the factory less than 24 h per day	Capacity constrained by equipment which is generally highly utilised. Additional capacity buffers expensive
Reduce setups on equipment—reduce setups, institute single-minute exchange of dies (SMED), convert internal setups to external setups, abolish setups	Batch size and setup not separable, and in contrast to discrete industries setups disturb flow, generate waste (material, time, energy) and impact capacity and utilisation (additional process industry impact on Kingman) ultimately affecting flow of value to the customer (reduced OTIF)
Single piece flow	Impossible/impractical in non-discrete capital intensive process environment
Cross-train workers—because labour is a critical capacity input it is desirable to cultivate a multi-skilled workforce	Labour not a critical capacity input but worker competence critical to 'accommodate' inherent variation so focus on workforce competence as opposed to flexibility
Improve plant layout—adjust plant layout to accommodate less movement of material and employees	Plant is fixed and continuous and as such inherently inflexible
Reduce work in progress	Work in progress often negligible/not visible or non-existent giving no **intermediate** opportunity to decouple at, or pull from WIP buffers. Similar to WIP in a discrete environment Finished Goods can build as a result of poor flow (King 2009) and therefore require more focus and provide an opportunity to pull
Takt—the pace that a facility needs to work at to meet demand	Takt an unsuitable tool due to unstable demand, contingent nature of capacity, shared resources, product/process characteristics and in some cases fixed processing times

Table 8 concludes potential process industry pull mechanisms based on literature principles and the Skretting case environment where continuous and inflexible equipment forces a different solution to discrete industry flexible capacity buffered, intermediate WIP bounded, single piece flow.

The Skretting case approach to pull provides the same benefits of throughput (increased capacity), inventory (reducing age profiles), rework (reduced waste) and customer service (high OTIF) championed by Hopp and Spearman (2008) on behalf of WIP bounded discrete industry pull. In Goldratt and Fox's (1986) terms, inventory is improved, operational expenditure (in the form of material, obsolescence and energy waste) is reduced and service is improved for existing throughput whilst increased capacity is provided for additional throughput.

Table 8 Pull in the process industries: potential process industry approaches based on principles of flowal process industry approaches based on principles of flow and pull (adapted from Yoho and Rappold 2011)

Lean imperative	Principle	Process industry—research solutions
Smooth or "level-load" production (heijunka)—establish production plans that are smooth with respect to volume and product mix	Level loading/ align demand and capacity	• **Stable (but not fixed) periodic production cycles** which align demand and capacity but mitigate changeovers (King 2009; Pool et al. 2011; Seidman and Holloway 2002; Yoho and Rappold 2011) • **Sequencing** which minimises capacity variation
Establish capacity buffers—scheduling the factory less than 24 h per day	Buffering/align demand and capacity	• **Combination of time/inventory buffers** which is most appropriate to the environment and supports the alignment of demand and capacity (De Treville and Antonakis 2006; Lyons et al. 2013) - Promise to 85 %, schedule to 100 % - **sequencing** to mitigate impact on both capacity and Kingman fundamentals
Reduce setups on equipment—reduce setups, institute single-minute exchange of dies (SMED), convert internal setups to external setups, abolish setups	Flow/waste	• Reduce impact of changeovers—**sequencing**. Use of Time/Inventory buffers to allow smoothing of the schedule using **sequence** to reduce changeovers, improve flow and minimise waste. (Bicheno and Holweg 2009; Thun et al. 2010)
Single piece flow	Flow	• Single family flow—use of group technology and **sequencing** to schedule like products together to reduce interruption/ waste and improve flow (Hubbard et al. 1992 cited in Shahin and Janatyan 2010; Soman et al. 2004)
Cross-train workers—because labour is a critical capacity input it is desirable to cultivate a multi skilled workforce	Profound knowledge /variation accommodation	• Competence train workers to enhance process knowledge/understanding and enable accommodation of variation to minimise waste
Improve plant layout—adjust plant layout to accommodate less movement of material and employees	Flow/waste	• Maximising uptime of highly utilised plant is crucial therefore <u>maintaining</u> flow (TPM for example) may be higher priority than creating flow. Higher focus on impact of plant inflexibility on **movement, management and waste of material**
Reduce work in progress	System status/ flow/waste (overproduction)	• Buffer with, pull from and BOUND Finished Goods to improve response time (Hopp and Spearman 2008) support **sequencing** and improve flow at the critical constraint. *Toyota—flow where you can and pull where you can't* (Rother and Shook cited in Liker 2004, p. 108)
Takt—the pace that a facility needs to work at to meet demand	Flow	• **Time based view of capacity** which accounts for process/product characteristics and shared/contingent capacity

In conclusion, the Skretting case provides a process industry pull solution that is supported by the literature, the specific mechanisms of which will not necessarily apply to every process business but the principles arguably will. The majority of the literature's attempts to define discrete pull do so referring to the mechanisms rather than the concepts and principles of flow, in response to which the authors propose the following principle based definition of pull in the process industries:

"The alignment of demand and capacity to provide the optimal trade-off between capacity, waste and service that delivers stable and predictable flow of that demand to the customer".

5.2 *The Importance of Sequence*

Expanding on Kingman and the opportunities it presents within PPC, the traditional operational literature suggests that there is an additional element at play within process manufacture—that of sequence which can help mitigate trade-offs. This was supported by the Skretting case analysis where the Skretting sequence not only improved capacity and waste, but less expectedly improved service and unexpectedly reduced capacity variation.

However, the influence of sequence on PPC and the fundamentals of Kingman in the process industries whilst also unexpected, is further concluded here.

Lead-time in a queue is a product of time, utilisation and variation all of which are impacted by sequence in a process industry environment as shown in Fig. 9. In the Skretting case analysis a difference of between 10 and 20 % was seen in total process time, utilisation and capacity variation depending on the sequence used.

Expanding on Kingman, the Skretting case analysis demonstrated that during weeks where utilisation was highest, sequence was extremely important and actually determined schedule feasibility. Changeovers are a source of variation and accordingly in the process industries, sequence impacts capacity in terms of the

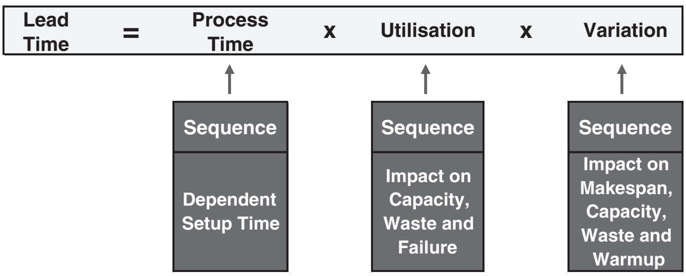

Fig. 9 Model showing proposed process industry impact of sequence on Kingman (adapted from Bicheno 2011)

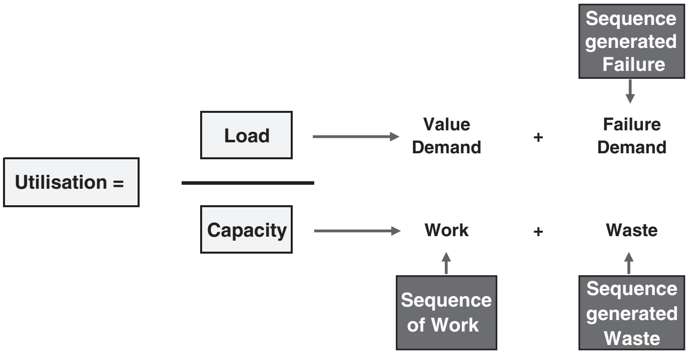

Fig. 10 Model showing proposed process industry impact of sequence on utilisation (adapted from Bicheno 2011)

sequence of work and the generation of waste and load through waste generated failure demand (Seddon 2003) (see Fig. 10).

6 Conclusion

The increasingly competitive environment and resultant 'off diagonal' activity within process manufacture causes issues for traditional literature models founded on the linear product/process approach. Existing literature frameworks are both discrete founded and taxonomy focused, inadequately describing underlying process industry complexity which is both inherent (e.g. complex BOMs, material variation and inexact processing) and relative to the environment (e.g. inflexible capacity combined with significant variability in demand and fulfilment). This complexity brings practical challenges for PPC where literature models do not satisfactorily describe the realities of hybrid MTS/MTO fulfilment and so a contingent approach based on PPC fundamentals and the trade-offs that can be influenced is required.

Discrete manufacturers have benefitted from pull production control resulting in improvements in lead time, cost, inventory and service but the process industries have been slow to follow this approach typically advocated for more stable, predictable production environments. The literature definitions of pull are ambiguous and research is focused on discrete industry implementations and the mechanisms as opposed to the principles of pull and flow. Commonly accepted discrete industry pull mechanisms lack applicability in process manufacturing but the principles of pull and the fundamental alignment of demand and capacity can be used to derive environment appropriate mechanisms which accommodate variation and support flow.

Such mechanisms must consider the process manufacturing trade-offs between capacity, waste and service which can be mitigated by sequence, the significance of which is not explicit in the lean literature. Here it should be noted that the case company sequence outperformed traditional lean scheduling approaches, generating outcomes contrary to the literature.

In process manufacture Yoho and Rappold (2011, p. 60) propose the use of a "complementary inventory policy" with "finished goods inventories *in the right product at the right time*…" (ibid, p. 67) asking "in what quantities and in which specific products should inventory be carried?" (ibid, p 59). In implementing demand based pull in a process environment we should add: "…*and in what order should they be manufactured*?"

Merging the significant operational literature on scheduling with the principles of flow/pull and the Skretting case analysis demonstrating both the influence of sequence on the fundamentals of Kingman and the impact of sequence on flow and waste, the authors conclude that the critical element of pull in the process industries is that of sequence.

7 Limitations and Future Research

Whilst the research accessed a longitudinal study of flow within the case operation, the data collection period, being less than one year does not represent the full extent of case company seasonality. The majority of this data is secondary data, not collected for the purposes of the research and therefore subject to bias and the context in, or purpose for which it was collected.

The conclusion whilst founded in the literature is triangulated using a single case study and, as such, it is not possible to generalise. The process industries encompass a wide variety of manufacturing with differing points of product commitment, differentiation and decoupling (between push and pull) ranging for example from petrochemicals where the vast majority is process based, to food and other FMCG where batch processes exist and products becomes discrete at some point. As a result, further research is recommended to determine if the research conclusions and the criticality of sequence apply to the implementation of pull in other process industry environments.

Additional research including multi-variant analysis is recommended to understand the degree to which each variable impacts flow. This may (dependent on the dominant variable) enable some reduction of influence and consequent reduction of buffers.

References

Abdulmalek FA, Rajgopal J, Needy KL (2006) A Classification scheme for the process industry to guide the implementation of lean. Eng Manage J 18(2):15–25

Anderson C (2009) The longer long tail. Random House, London

APICS (2013) APICS dictionary. Available via: http://www.apics.org/dictionary/dictionary-information?ID=3062. Accessed 14 May 2013

Belvedere V, Grando A (2005) Implementing a pull system in batch/mix process industry through theory of constraints: a case-study. Hum Syst Manage 24(1):3–12
Bicheno J (2006) Fishbone flow. Picsie Books, Buckingham
Bicheno J (2011) The king of equations. Lean Manage J 10:16–21
Bicheno J, Holweg M (2009) The lean toolbox, 4th edn. Picsie Books, Buckingham
Billesbach TJ (1994) Applying lean production principles to a process facility. Prod Inventory Manage J 35(3):40–44
Bolander SF, Taylor SG (1993) System framework for process flow industries. Prod and Inventory Manage J 34(4):12–17
Bonney MC, Zhang Z, Head MA, Tien CC, Barson RJ (1999) Are push and pull systems really so different? Int J Prod Econ 59(1–3):53–64
Boylan JE, Syntetos AA, Karakostas GC (2008) Classification for forecasting and stock control: a case study. J Oper Res Soc 59(4):473–481
Brown CB, Collins TR, McCombs EL (2006) Transformation from batch to lean manufacturing: the performance issues. Eng Manage J 18(2):3–13
Clark AR, Morabito R, Toso EAV (2010) Production setup-sequencing and lot-sizing at an animal nutrition plant through ATSP sub-tour elimination and patching. J Sched 13(2):111–121
Claudio D, Krishnamurthy A (2009) Kanban-based pull systems with advance demand information. Int J Prod Res 47(12):3139–3160
Cooke DL, Rohleder TR (2006) Inventory evaluation and product slate management in large-scale continuous process industries. J Oper Manage 24(3):235–249
Cox JF, Spencer M (1998) The constraints management handbook. St Lucie Press, Boca Raton
Crama Y, Pochet Y, Wera Y (2001) A discussion of production planning approaches in the process industry. Working paper GEMME 0102, University of Liege
Darlington J, Schmidt J (2013) Time and money, you get what you design. In: SAPICS 35th annual conference and exhibition, Sun City, South Africa
De Treville S, Antonakis J (2006) Could lean production job design be intrinsically motivating? Contextual, configurational, and levels-of-analysis issues. J Oper Manage 24(2):99–123
Dennis DR, Meredith JR (2000a) An empirical analysis of process industry transformation systems. Manage Sci 46(8):1085–1099
Dennis DR, Meredith JR (2000b) An analysis of process industry production and inventory management systems. J Oper Manage 18(6):683–699
Duggan KJ (2002) Creating mixed model value streams. McGraw-Hill, New York
Emiliani ML, Seymour PJ (2011) Frank George Woollard: forgotten pioneer of flow production. J Manage Hist 17(1):66–87
Fernandes FCF, Filho MG (2011) Production control systems: literature review, classification, and insights regarding practical application. Afr J Bus Manage 5(14):5573–5582
Fransoo JC (1992) Demand management and production control in process industries. Int J Oper Prod Manage 12(7, 8):187–196
Fransoo JC, Rutten WGMM (1994) A typology of production control situations in process industries. Int J Oper Prod Manage 14(12):47–57
Frei FX (2006) Breaking the trade-off between efficiency and service. Harvard Bus Rev 84(11):92–101
Funk JL (1995) Just-in-time manufacturing and logistical complexity: A contingency model. Int J Oper Prod Man 15(5):60–71
Gaury EGA, Pierreval H, Kleijnen JPC (2000) An evolutionary approach to select a pull system among Kanban, Conwip and Hybrid. J Intell Manuf 11:157–167
Germs R, Riezebos J (2010) Workload balancing capability of pull systems in MTO production. Int J Prod Res 48(8):2345–2360
Goldratt EM, Fox RE (1986) The Race. North River, New York
Hall RW (1983) Zero Inventorie*s*. Dow Jones-Irwin, Homewood
Hayes RH, SC Wheelwright (1979) Link manufacturing process and product life cycles. Harvard Bus Rev 133–140
Hopp WJ (2008) Supply chain science. Waveland Press, Illinois

Hopp WJ, Spearman ML (2004) To pull or not to pull: what is the question? Manuf Serv Oper Manage 6(2):133–148
Hopp WJ, Spearman ML (2008) Factory physics, 3rd edn. McGraw-Hill, New York
Hounshell DA (1984) From the American system to mass production 1800–1932: the development of manufacturing technology in the United States. Johns Hopkins University Press, Baltimore
Huang C, Kusiak A (1996) Overview of Kanban systems. Int J Comput Integr Manuf 9(3):169–189
Hubbard DT, Taylor SG, Bolander SF (1992) Process flow scheduling in a high-volume repetitive manufacturing environment. Prod Inventory Manage J 33(4):21–26
Hüttmeir A, de Treville S, van Ackere A, Monnier L, Prenninger J (2009) Trading off between heijunka and just-in-sequence. Int J Prod Econ 118(2):501–507
Ivanescu CV, Fransoo JC, Bertrand JWM (2006) A hybrid policy for order acceptance in batch process industries. OR Spectrum 28(2):199–222
Jamshidi H (2009) Lean manufacturing and formation of production cycles with the Wagner-Whitin algorithm. Journal of Global Business Issues 3(1):67–76
Karkarmar US (1991) Push, pull and hybrid control schemes. Tijdschrift voor Economie en Management 36:345–363
Karmarkar US, Rajaram K (2012) Aggregate production planning for process industries under oligopolistic competition. Eur J Oper Res 223(3):680–689
Kemppainen K, Vepsalainen APJ, Tinnila M (2008) Mapping the structural properties of production process and product mix. Int J Prod Econ 111:713–728
Kim I, Tang CS (1997) Lead time and response time in a pull production control system. Eur J Oper Res 101(3):474–485
King PL (2009) Lean for the process industries, dealing with complexity. Productivity Press, New York
Kouvelis P, Chambers C, Yu DZ (2005) Manufacturing operations manuscripts published in the first 52 issues of POM: review, trends, and opportunities. Prod Oper Manage 14(4):450–467
Krafcik JF (1988) Triumph of the lean production system. MIT Sloan Manage Rev 30(1):41–52
Lee HL (1997) The bullwhip effect in supply chains. Sloan Manage Rev Spring 1997:93–102
Liberopoulos G, Dallery Y (2002) Base stock versus WIP cap in single-stage make-to-stock production inventory systems. IIE Trans 34:627–636
Liker JK (2004) The Toyota way. McGraw-Hill, New York
Lummus RR, Vokurka RJ, Duclos LK (2006) The product-process matrix revisited: Integrating supply chain trade-offs. SAM Adv Manag J 71(2):4–10
Lyons AC, Vidamour K, Jain R, Sutherland M (2013) Developing an understanding of lean thinking in process industries. Prod Plann Control 24(6):475–494
McDermott CM, Greis NP, Fischer WA (1997) The diminishing utility of the product/process matrix: a study of the US power tool industry. Int J Oper Prod Manage 17(1):65–84
Naylor JB, Naim MM, Berry D (1999) Leagility: integrating the lean and agile manufacturing paradigms in the total supply chain. Int J Prod Econ 62:107–118
Ohno T (1988) Toyota production system: beyond large-scale production. Productivity Press, Cambridge
Pool A, Wijngaard J, van der Zee DJ (2011) Lean planning in the semi-process industry, a case study. Int J Prod Econ 131(1):194–203
Powell D, Strandhagen JO (2011) Lean production vs ERP systems: an ICT paradox? Oper Manage 3:31–36
Powell P, Alfnes E, Semini M (2009) The application of lean production control methods within a process-type Industry: the case of hydro automotive structures. Norwegian University of Science and Technology. In: APMS 2009: international conference on advances in production management systems. Springer, University of Bordeaux, Bordeaux, France
Puttman T, Strandhagen JO (1991) Logistics in process industries: is it a specific problem? Prod Inventory Manage J 32(3):61–66
Rice JW, Norback JP (1987) Process industries production planning using matrix data structures. Prod Inventory Manage 28(2):15–23

Rutten WGMM, Bertrand JWM (1998) Balancing stocks, flexible recipe costs and high service level requirements in a batch process industry: a study of a small scale model. Eur J Oper Res 110(3):626–642

Safizadeh MH, Ritzman LP, Sharma D, Wood C (1996) An empirical analysis of the product-process matrix. Manage Sci 42(11):1576–1591

Samaddar S, Hill CA (2007) Controlling adverse effect on work in process inventory while reducing machine setup time. Eur J Oper Res 180:249–261

Schonberger RJ (1983) Applications of single-card and dual-card Kanban. Inst Manage Sci Interface 13(4):56–67

Schonberger RH (2015) Lean is time-based competition. It's that simple and that profound. APICS Magazine, Jan/Feb

Schragenheim E, Cox J, Ronen B (1994) Process flow industry—scheduling and control using theory of constraints. Int J Prod Res 32(8):1867–1877

Schuster EW, Allen SJ, D'Itri MP (2000) Capacitated materials requirements planning and its application in the process industries. J Bus Logistics 21(1):169–189

Seddon J (2003) Freedom from command and control: a better way to make the work work. Vanguard Education Ltd, Buckingham

Seidman TI, Holloway LE (2002) Stability of pull production control methods for systems with significant setups. IEEE Trans Autom Control 47(10):1637–1647

Shahin A, Janatyan N (2010) Group technology (GT) and lean production: a conceptual model for enhancing productivity. Int Bus Res 3(4):105–118

Skinner CW (1969) Manufacturing—missing link in corporate strategy. Harvard Bus Rev 136–145

Soman AC, van Donk DP, Gaalman G (2004) Combined make-to-order and make-to-stock in a food production system. Int J Prod Econ 90(2):223–235

Spearman ML, Woodruff DL, Hopp WJ (1990) CONWIP: a pull alternative to Kanban. Int J Prod Res 28(5):879–894

Stavrulaki E, Davis M (2010) Aligning products with supply chain processes and strategy. Int J Logistics Manage 21(1):127–151

Syntetos AA, Boylan JE, Croston JD (2005) On the categorization of demand patterns. J Oper Res Soc 56(5):495–503

Taylor SG, Bolander SF (1994) Process flow scheduling: a scheduling framework for flow manufacturing. APICS, Falls Church

Taylor SG, Seward SM, Bolander SF (1981) Why the process industries are different. Prod Inventory Manage 22(4):9–24

Ten Kate HA (1994) Towards a better understanding of order acceptance. Int J Prod Econ 37(1):139–152

Thun J-H, Druke M, Grubner A (2010) Empowering Kanban through TPS-principles—an empirical analysis of the Toyota production system. Int J Prod Res 48(23):7089–7106

Van Dam P, Gaalman G, Sierksma G (1993) Scheduling of packaging lines in the process industry: an empirical investigation. Int J Prod Econ 30(31):579–589

Van Donk DP, Fransoo JC (2006) Operations management research in process industries. J Oper Manage 24:211–214

Voss CA (1995) Operations management—from Taylor to Toyota—and beyond? Br J Manag 6(6):17–29

Womack JP, Jones DT (1996) Lean thinking—banish waste and create wealth in your corporation. Simon and Schuster, London

Womack JP, Jones DT, Roos D (1990) The machine that changed the world. Rawson Associates, New York

Yoho KD, Rappold JA (2011) Beyond lean: production and inventory policy for the old economy. Prod Inventory Manage J 47(2):56–68