The extension and exploitation of the inventory and order based production control system archetype from 1982-2015.

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Abstract

In 1994, through classic control theory, John, Naim and Towill developed the ‘Automatic Pipeline, Inventory and Order-based Production Control System’ (APIOBPCS), which extended the original IOBPCS archetype (Towill 1982) — a well-recognized as a base framework for a production planning and control system. Due to the prevalence of two original models in the last three decades from academic and industrial communities, this paper aims to systematically review how the IOBPCS archetypes has been adopted, exploited and adapted to study the dynamics of individual production planning and control systems and whole supply chains. Using Scopus, Web of Science, Google Scholar, we found that the IOBPCS archetypes has been studied regarding the a) modification of four inherent policies related to forecasting, inventory, lead-time and pipeline to create a ‘family’ of models, b) adoption of the IOBPCS ‘family’ to reduce supply chain dynamics, and in particular bullwhip, c) extension of the IOBPCS family to represent different supply chain scenarios such as order-book based production control and closed-loop processes. Simulation is the most popular method adopted by researchers and the number of works based on discrete time based methods is greater than those utilizing continuous time approaches. Most studies are conceptual with limited practical applications described. Future research needs to focus on cost, flexibility and sustainability in the context of supply chain dynamics and, although there are a few existing studies, more analytical approaches are required to gain robust insights into the influence of nonlinear elements on supply chain behaviour.

Keywords: IOBPCS, APIOBPCS, Production/Planning control, supply chain, bullwhip effect

1. Introduction

Current production planning systems and supply chains are becoming increasingly dynamic under the volatile conditions of the business environment, triggered by globalisation and optimisation management, e.g., reducing inventory, decreasing the number of suppliers and outsourcing one’s own business. Dynamic characteristics, particularly the bullwhip effect (Lee et al. 1997b), are considered the main sources of disruptions in the business world (Christopher and Peck 2004). The bullwhip effect refers to a phenomenon in which low variations in demand cause significant changes in upstream production for suppliers, with associated costs, such as ramp down and ramp up machines, hiring and firing of staff and excessive inventory (Wang and Disney 2015).

Among various methods and tools developed to reduce such dynamics in the production and control system, Control theory with feedback thinking has been well-recognized for a long history pioneered by Simon (1952). In 1994, through the adoption of a classic control engineering approach, John, Naim and Towill developed the Automatic Pipeline, Inventory and Order-based Production Control System (APIOBPCS) (John et al. 1994), which extended the original IOBPCS archetype (Towill 1982) by incorporating an automatic work-in-progress (WIP) feedback loop. In this paper, APIOBPCS represents both IOBPCS and APIOBPCS, and the IOBPCS family refers to the two original models and all their variants. These two original models and their variants have been recognised as a framework for a production planning and control system, as they are general laws that represent many supply chain contexts including the famous beer game decision-making heuristic (Sterman 1989), the order-up-to (OUT) policy (Zhou et al. 2010), as well as many other industrial practices in the United Kingdom (UK) (Coyle 1977). Therefore, the main purpose of this work is to explore how, after three decades, other authors adopt, exploit and adapt the IOBPCS family to understand supply chain dynamics more completely. By systematically reviewing the work by Towill (1982) and John et al. (1994), we also explore how the IOBPCS family is studied through various methods and present a research agenda regarding the application of the IOBPCS family.

This work synthesises existing studies on the adoption of the IOBPCS family in the context of supply chain dynamics, summarising research conducted over the last 30 years, while also indicating possible directions for future research. There are many excellent reviews on the application of control theory in production/inventory systems; see Axsater (1985), Edghill and Towill (1989), Ortega and Lin (2004) and Sarimveis et al. (2008) for more information. However, the former two works are two decades old, suggesting that an up-to-date review is required. The latter papers are recent, but the reviews cover topics other than the IOBPCS family exclusively. Therefore, this paper will refresh the knowledge of the IOBPCS family to inform researchers and practitioners in this area of study as to the major developments in the field.

The remainder of the paper is organised as follows: section 2 provides an overview of the APIOBPCS ordering model. Section 3 illustrates the method and the process of data collection and analysis. The next two sections summarise and synthesise the collected data. Conclusions, including the future research agenda and contributions/limitations of this study, are outlined in final section.

2. An overview of the original APIOBPCS archetype

Towill (1982) developed the IOBPCS framework in a block diagram format to represent a feedback-based production/inventory system, extending the work conducted by Coyle (1977). The model focused on products at an aggregate level. Three system parameters were identified as fundamental for ideal production/inventory control system design: lead time (T_p) for production, a proportional controller (T_i) to adjust inventory discrepancy and demand smoothing level (T_a). John et al. (1994) then incorporated an automated WIP closed loop (T_w) in the IOBPCS framework, which led to the APIOBPCS archetype, as shown in Figure 1 (all nomenclature is outlined in Table 1).

Terms	Meaning
AINV	Actual inventory
AVCON	Average consumption
AWIP	Actual WIP
DWIP	Desired WIP
COMRATE	Completion rate
CONS	Consumption rate
DINV	Desired inventory
ORATE	Order rate placed on pipeline
T_a	Time to average consumption
T_i	Proportional controller for inventory adjustment
T_w	Proportional controller for WIP adjustment
T_p	Actual pipeline lead time
$T_{p'}$	Estimated pipeline lead time
s	Laplace operator

Table 1. Notations used in the APIOBPCS model. Source: The authors.

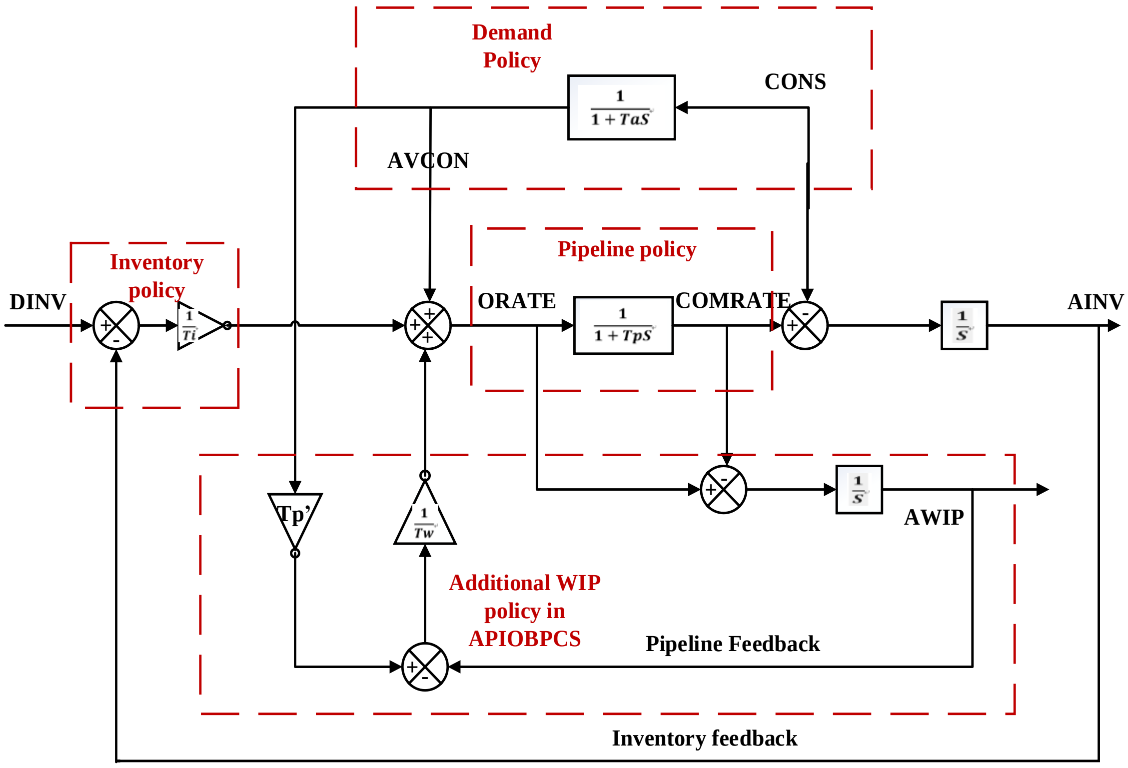


Figure 1. A block diagram representation of APIOBPCS. Source: Originally developed by John et al. (1994) and adapted by Sarimveis et al. (2008)

Thus, the APIOBPCS model can be described as follows: set the order rate as equal to the summation of demand averaged over T_a time units (demand policy), plus the T_i adjustment of inventory discrepancy (inventory policy) and the WIP adjustment of T_w (WIP policy). In addition, lead time must be modelled appropriately (lead time policy) because it is difficult to alter physical lead time. The APIOBPCS model is essentially equal to the IOBPCS model if $T_w = \infty$, i.e., in the case that the WIP products are not included. Therefore, the designer must select the appropriate values of T_a, T_w and T_i to achieve two conflicting objectives: 1) rapid inventory recovery to ensure an adequate level of customer service and 2) attenuation of unknown demand fluctuations to level the production rate. The second objective is also known as reduction of the bullwhip effect (Lee et al. 1997b).

Standard control engineering approaches are used to quantify the performance of four policies that adhere to two objectives under linear, continuous, infinite system capacity assumptions in APIOBPCS. In terms of objective one, inventory response is evaluated by introducing a step input demand with respect to performance metrics, such as rise time, setting time and maximum overshoot. The initial and final value theorems, as well as Laplace inverse transform, are also applied to provide a mathematical crosscheck. Regarding objective two, noise bandwidth (W_N) measures the ability of the system decision parameters (T_i , T_a and T_w) to remove unwanted high-demand frequency. Using these measurement methods, John et al. (1994) developed a system that ensured a high level of customer service, while levelling the production rate by selecting $T_w = 2T_p$, $T_a = 2T_p$ and $T_i = T_p$. The authors also concluded that incorporating an automatic WIP controller damps the oscillations of COMRATE and reduced maximum overshoot, while eliminating the inventory drift by assuming that $T_p = T_{p'}$. These outcomes allowed for a high-quality control system, though a slight increase in setting time was identified.

3. Method

Figure 2 outlines the data collection process. To search for papers that cited Towill (1982) and John et al. (1994), three electronic databases in the fields of business/management were selected: Scopus, Web of Science and Science Direct. Google Scholar was used to cross check citations. We only selected peer-reviewed academic journals in English to guarantee that quality citations were selected. In total, 216 papers were identified, including 153 papers citing Towill (1982) and 122 papers citing John et al. (1994). There were 59 overlapping citations. Towill (1982) was cited more frequently than John et al. (1994) (153 versus 122). In addition, the total number of independent citations was nearly twice that of the dependent citations (142 versus 74), suggesting that the IOBPCS archetype was recognised in research communities on a global scale.

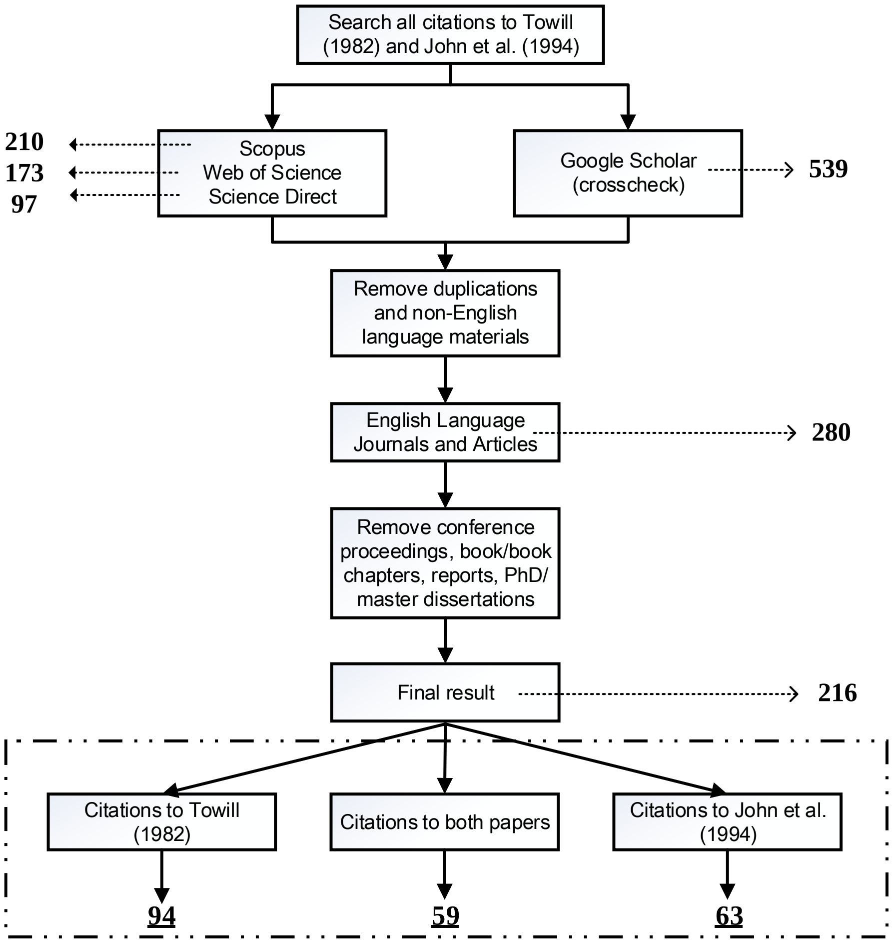


Figure 2. The process and result of data collection. Source: the authors.

To complete the data analysis process, the journal articles were divided into three groups: papers that cited both Towill (1982) and John et al. (1994) were grouped, and separate citations were identified that cited only one of the two papers (two separate categories in which either the APIOBPCS and IOBPCS model was discussed). In each group, two categories were further specified: independent and dependent citations. Independent citations were those in which at least one author was a colleague of Towill, John or Naim, a PhD student or a member of a research team, while independent citations were written by individuals who were academically independent of the three original authors.

The reviewed papers was categorised as one of three types: α, β or γ (Naim and Gosling 2011). α type referred to citations that simply used two papers to increase the quality of the paper's main argument. In the β type category, papers that explored the APIOBPCS archetype based on its inherent four policies were included. Finally, the γ type category included studies that used the complete APIOBPCS model to offer insight into dynamic behaviour or to represent specific supply chain scenarios (extension of the APIOBPCS model). Furthermore, the research methods of all the papers evaluated in this study were counted and categorised, though some authors applied multiple research methods. Content analysis was used to clarify the main findings that the papers developed based on the IOBPCS family.

4. Synthesis of the main findings

4.1 Discussion

Figure 3 provides the results of content categorisation according to the pre-defined α, β and γ citation types. Approximately 110 works were identified as α type. As noted, the authors of papers of this type simply cite the two original papers to strengthen their arguments and historical reviews. For brevity, citations of this type will not be reviewed in detail in this work. Next, 106 citations, including 22 β and 84 γ citations, evaluated the IOBPCS family to study supply chain dynamics. The passing citations (71) were found in the group of papers citing Towill (1982). This acknowledges the contribution of the original IOBPCS, which links the established system of best practices to the model and transfers the optimised design to the production planning and control system.

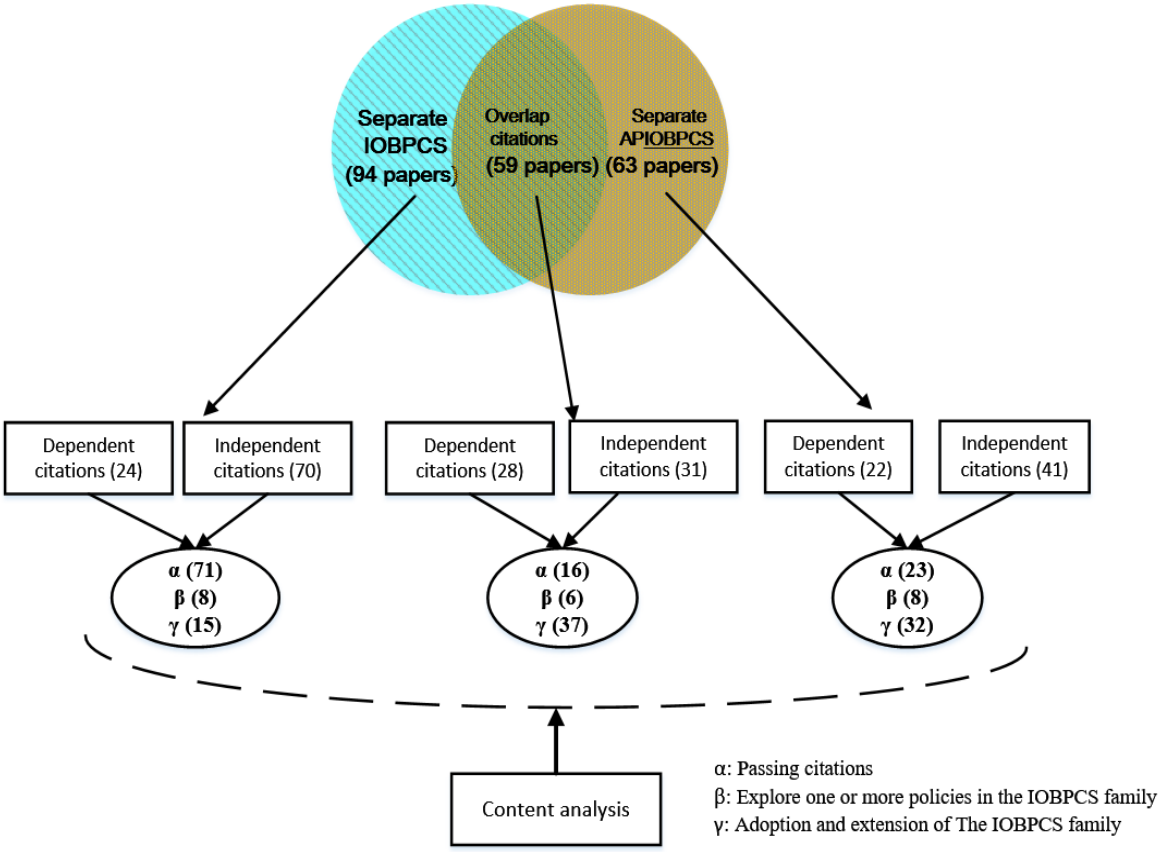


Figure 3. The result of content categorisation. Source: the authors.

Figure 4 highlights the synthesis of the research findings. Regarding category β, we found that

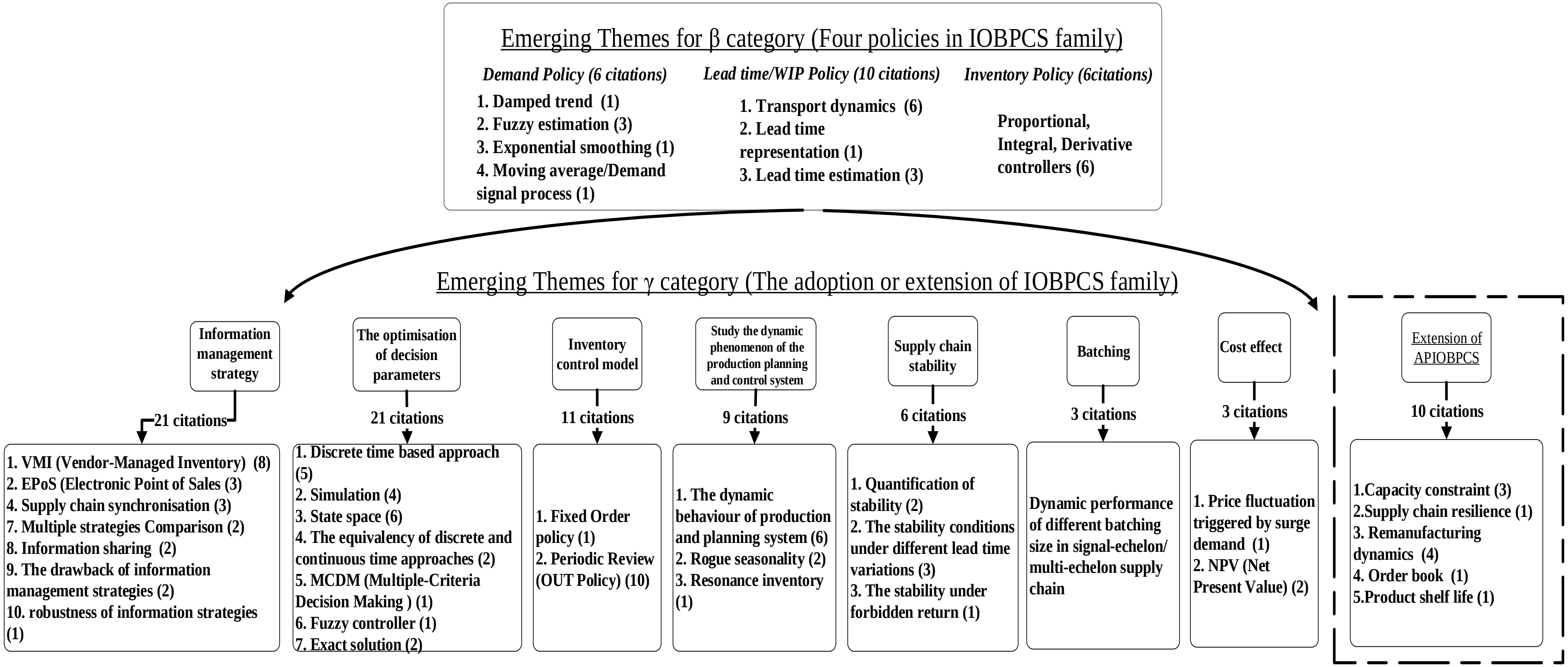


Figure 4. The synthesis of the findings. Source: The authors.

the original APIOBPCS model is explored in terms of its four control policies, including demand, lead time, WIPs and inventory policies, all of which create a family of models. Various forecasting mechanisms on supply chain dynamics are tested, such as exponential smoothing (Dejonckheere et al. 2002) and damped trend forecasting (Li et al. 2014). Forecasting mechanisms have a direct impact on bullwhip generation, in which order variability is amplified downstream to upstream due to errors in forecasting.

Monitoring and modelling of lead time (which are crucial for system design, as it is difficult to alter physical lead time) are also investigated (e.g. Towill et al. 1997). In addition, lead time policies are studied in the context of logistics (e.g. Potter and Lalwani 2008) to clarify how supply chain dynamics influence transport performance. The inventory control policy, which consists of proportional (P), integral (I) and derivative (D) elements, is investigated in the context of various supply chains. For example, Souriranhan et al. (2008) examine the impact of P, PI and PD on the bullwhip effect under different forecasting conditions. Sophisticated proportional-integral-derivative (PID) controllers (e.g. White 1999) have been criticised for the significant effort that tuning requires and for their overlapping role in demand policies. Alternatively, PI controllers are slow in terms of inventory error recovery in short lifecycle products.

Many studies adopt or extend the IOBPCS model and its variants to study supply chain dynamics (γ category). Various emerging themes have been developed that categorise the findings. Firstly, several works focus on a dynamic production and planning system, including order and inventory amplification (e.g. Edghill et al. 1988), rogue seasonality (e.g. Shukla et al. 2012) and resonance inventory (Hodgson and Warburton 2009).

The optimisation of decision parameters (T_i, T_w and T_a) in the IOBPCS family is another emerging topic. This topic can be categorised as a linear- or nonlinear-based approach. In terms of a linear approach, discrete time-based methods, such as z-transform and difference equations, are favoured by researchers (e.g. Disney and Towill 2003c) to represent a real replenishment system. The $T_i = T_w$ proposed by Deziel and Eilon (1967) is effective for bullwhip reduction. Regarding nonlinear mechanisms, simulation is the primary choice to accommodate a real system with a complex structure and nonlinearity. However, few studies consider other approaches, such as exact solutions to understand the relationship between system parameters.

A number of authors (e.g. Mason-Jones and Towill 1997; Disney and Towill 2003a) test the influence of information sharing and supply chain collaboration strategies in mitigating supply chain dynamics based on the IOBPCS family. These authors agree that such strategies, along with smoothing ordering, reduce supply chain dynamics, while maintaining satisfactory customer service levels. However, many studies focus on simple linked supply chains without considering complex structures (divergent supply chains) and nonlinearity (capacity constraints), and few studies consider the negative impact of information management enabled by Information and Communication Technology (ICT). Another current direction in research is the investigation of supply chain stability via the IOBPCS family. From the perspective of control engineering, Riddalls and Bennett (2002) firstly quantify supply chain stability and relevant correction is proposed by Warburton et al. (2004). Supply chain stability is also investigated under different lead time assumptions (Sipahi and Delice 2010).

Inventory control models, particularly the Order-Up-To (OUT) control policy, have been studied extensively. The APIOBPCS archetype is essentially the OUT policy when the set inventory controller and the WIP controller are equal to one, which suggests that the discrepancy is fully corrected in each period of replenishment. Researchers explore the dynamic behaviour of the OUT policy based on various trends in customer demand (Disney et al. 2006a). Incorporating a proportional controller in the OUT policy may significantly reduce dynamic behaviour.

The IOBPCS family has also been extended to represent many specific supply chain situations, such as closed loop remanufacturing supply chains (Tang and Naim 2004), make-to-order contexts (Wikner et al. 2007) and others. This wide applicability indicates that the IOBPCS family has the capacity to represent many real supply chain systems by analysing their dynamic behaviour. Furthermore, although price fluctuations are essential to bullwhip induction and are understood from other perspectives, e.g. game theory (Özelkan and Çakanyildirim 2009) and operations direction without considering economic consequences (Zhang and Burke 2011), few studies focus on the impact of dynamic pricing on supply chain dynamics based on the IOBPCS family. Similarly, the batching effect (Potter and Disney 2006), a well-understood source of bullwhip generation, has received little attention from the perspective of control engineering.

4.2 Comparison of three citation groups

Table 2 shows that there are more citations to Towill (1982) compared to the other citation groups. More studies incorporate the automatic WIP feedback group with the IOBPCS archetype (essentially the APIOBPCS or its variants) to understand supply chain dynamics. As stated in the original APIOBPCS paper (John et al. 1994), the inclusion of WIP damps the oscillations of COMRATE and reduces maximum overshoot, while eliminating the visibility of inventory drift full lead time. Both are essential for a high-quality control system, though a slight increase in setting time is sometimes identified. Our review also is consistent with Zhou et al. (2010), who argue that the APIOBPCS archetype is a general law representing many supply chain contexts.

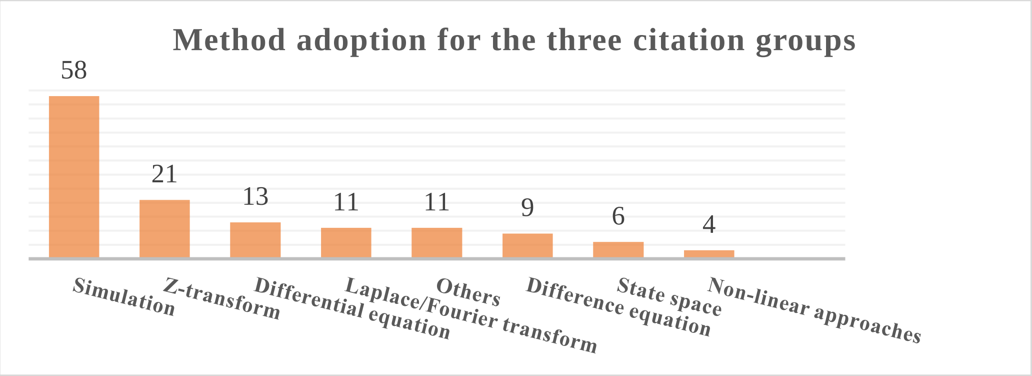
Type	Emerging themes	Towill (1982)	John et al. (1994)	Overlap citations	Total
β	Demand policy	1	3	2	6
	Lead time/pipeline policy	2	4	4	10
	Inventory policy	5	1	0	6
γ	Study the dynamic behaviour of the Production/Planning and control system	4	3	2	9
	The optimisation of decision parameters	5	6	10	21
	Information management and supply chain collaboration	1	12	8	21
	Inventory control models	5	4	2	11
	Supply chain stability	0	2	4	6
	The effect of cost on supply chain dynamics	0	1	2	3
	Extension of IOBPCS	0	5	6	10
	Batching effect	0	0	3	3
	Total	23	40	43	106

Table 2. The comparison of three citation groups based on emerging themes. Source: the authors.

However, the original IOBPCS archetype still offers valuable insight into specific supply chain contexts without the use of WIP products, such as the make-to-order/pull system, the comparison of IOBPCS and VIOBPCS (V refers to various target inventory) for improving customer service and testing continuous or discrete time-based approaches. Future studies must combine traditional push/Make-to-Stock systems and customer-oriented pull/Make-to-Order systems based on IOBPCS and its variants.

5. Research methods for β and γ citations

Figure 5 presents the distribution of methods for β and γ categories of citations. Simulation is the most popular method due to its ability to capture complex dynamic behaviour by recovering a wide range of nonlinear phenomena. Second, discrete time domain approaches (30, including z-transform and difference equations) are given greater consideration compared to continuous time domain approaches (24, including Laplace transform and differential equations), though continuous time-based approaches are adopted in the development of original APIOBPCS. These results are not surprising because the real replenishment rule is dominated by a discrete time ordering policy. However, as indicated by Disney et al. (2006), neither of them is superior in terms of their usefulness for different purposes and their applicability to different scenarios. Few studies consider State Space approaches based on the IOBPCS family, even though it has the ability to be simplified, controlled and observed.



Others: Fuzzy approach, MCDM, Taguchi's design, genetic algorithm, Åström's method, response surface and Jury's inner approach.
Nonlinear approaches: Exact solution, Eigenvalue analysis
Figure 5. Research methods for β and γ citations. Source: The authors.

Control engineering theory guides practitioners in system design and improvement. Classic control theory, along with sufficient mathematical tools, is able to accommodate the bullwhip effect (Sarimveis et al. 2008). On the other hand, simulation contributes to the representation of a real system, incorporating nonlinear components and complex structures, as well as verifying linear control approaches. However, simulation is a process of trial and error and cannot offer rich guidance for system improvement. Other approaches, such as linearization methods and exact solutions, may overcome such limitations. Surprisingly, only four papers consider such methods based on the IOBPCS family.

6. Conclusion and future research agenda

The IOBPCS family has been extensively studied over last three decades as a base framework for a production and planning control system and the aim of this study is to explore its major developments. Using a systematic review, we found that the original IOBPCS archetypes was modified based on its inherent four policies (demand, lead time, WIP and inventory policies).

There is an agreement that forecasting has a direct impact on bullwhip generation, and lead-time visibility is essential to designing a high-quality production/distribution control system. The P controller reduces bullwhip, while PI and PID controllers are not well recognised in the literature.

Also, a great deal of work focuses on adopting the IOBPCS family as a whole system or extends it to study supply chain dynamics. Dynamic behaviour (e.g. bullwhip) is evaluated based on the IOBPCS family. Several approaches have been used to optimise decision parameters. A great deal of research focuses on assessing the OUT policy under different demand patterns due to the popularity of this policy in the industry. Researchers agree that information sharing and supply chain collaboration are effective for bullwhip mitigation, though many studies provide limited insight on the linear assumption for the representation of a real system. Furthermore, few works address the effect of batching size and price fluctuations on supply chain dynamics based on the IOBPCS family, although they are documented as main sources of bullwhip generation.

In terms of methods utilised, simulation remains the ideal choice to assist researchers in understanding the complex, dynamic nature of production and planning systems. However, simulation lacks analytical insight. Many authors prefer linear-based control engineering approaches for system analysis, even though such methods cannot capture realistic supply chain systems in terms of the complex structure and nonlinearity of these systems. Based on the findings, we present the following agenda for future research:

1. *Cost and supply chain dynamics*: Many existing studies view cost as a performance metric to evaluate the dynamic behaviour of systems. More effort should be made to examine the impact of price fluctuations on supply chain dynamics based on the IOBPCS family.
2. *Sustainability dynamics*: Few studies consider the effect of supply chain dynamics on close loop remanufacturing systems. Future research should focus on complex supply chain structures with realistic assumptions (multilevel, divergent networks and nonlinearity) and should focus on other dimensions related to sustainability (e.g. environmental cost including pollutions and carbon emissions).
3. *Flexibility/resilience dimensions for supply chain dynamics*: Supply chain systems must be flexible and resilient in order to cope with various risks or disruptions. These systems should also allow for customisation. However, there is a trade-off between flexibility/resilience and system on-cost triggered by the dynamics response. Future research should explore the applicability of the IOBPCS family in understanding the dynamic nature of supply chain models, such as Make-to-Order, Make-to-Stock or Assembly-to-Order supply chains.
4. *The development of nonlinear methods:* Due to the limited analytical insight of simulation, nonlinear methods should be developed, such as linearization methods, exact solutions and graphical and stability approaches to guide system improvement with realistic representations.

This work gives two contributions to the body of research in this area. First, the adoption, exploitation and adaptation of the original APIOBPCS method are provided, and the methods are categorised. Second, the synthesis of findings and an agenda for future research improve the development of the IOBPCS family, providing the main directions for researchers in this area of study. Though this study offers academic researchers rich insight into development of the APIOBPCS archetype, the findings may be less pertinent to practitioners, as many studies (including the present study) are conceptual, with limited practical applicability. Future research should validate these conceptual works and introduce various methodologies to the industry to gain insight that is more robust.

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