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Full Length Research Paper

Production control systems: Literature review, classification, and insights regarding practical application

Flavio Cesar Faria Fernandes and Moacir Godinho Filho*

Departament of Industrial Engineering, Federal University of São Carlos, via Washington Luiz, Brazil.

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This paper was a review of the literature regarding production control systems (PCS). A classification method based on four categories (order-controlled, stock level-controlled (SLC), flow-scheduled (FS), and hybrid systems) was proposed and used to classify the twenty different systems found in the review. A brief summary of each system was presented, showing the functioning logic and insights with regard to the practical application of each. Some insights arise from this study: (i) the majority of the PCS reviewed are designed for a repetitive, flow shop environment; (ii) the main field of application of all SLC systems is the flow shop, repetitive environment; (iii) in general, the FS systems are more adequate to a non-repetitive environment than are the SLC systems; (iv) hybrid systems constitute a promising field of research regarding the practical application of SCO in job shops and non-repetitive environments.

Key words: Production control systems, production planning and control, literature review, classification, practical application.

INTRODUCTION

According to Burbidge (1990), production control (PC)…. is the function of management which plans, directs and controls the material supply and processing activities in an enterprise'. The problem with regard to PC is to determine when and how much to produce in a given manufacturing system in order to satisfy a set of objectives (Liberopoulos and Dallery, 2000). One of the most important activities of PC is what Burbidge (1990) calls ordering. Burbidge defines ordering as the second level of scheduling in production control, which is concerned with regulating the supply of both manufactured parts and bought items, in order to meet the production programme. This activity is performed by production control systems (PCS), which González and Framinam (2009) define as being a set of rules defining order release and material flow control in a manufacturing system. This paper discusses these systems.

PCS are also known as ordering systems (Burbidge, 1990), production control policies (Sharma and Aggrawal, 2009), material planning methods (Jonsson and Mattsson, 2002), production and material flow control mechanism (Fernandes and Carmo-Silva, 2006), logistics control systems (Ghamari, 2009), material flow control mechanism (Graves et al., 1995), production inventory control policy (Gerathy and Heavey, 2004), and production planning and control systems (MacCarthy and Fernandes, 2000). In this paper, it was called systems for coordination of orders (SCO), once it was we taken into account that the main contribution of such systems is to coordinate the materials and information flow onto the shop floor. SCO schedule or organise material requirements, and/or control the production and purchasing orders release, and/or schedule jobs on machines. From this point, we refer to such systems as SCO.

The study also highlights certain insights regarding practical applications of SCO. Comparisons and selection between different SCO have been (MacCarthy and Fernandes, 2000) and continue to be (Sharma and Agrawal, 2009; Khojasteh-Ghamari, 2009) an important subject with respect to PPC research. This literature is

*Corresponding author. E-mail: moacir@dep.ufscar.br

based mainly on analytical (simulation, Markov chain) or conceptual methodology. Despite the existence of considerable research, the problem as to what is the best choice has not yet been solved. According to Gupta and Snyder (2009), the net results of such research are still inconclusive. The goal of this paper is not to provide such an answer but to contribute in this direction, providing insights regarding SCO application, and relating these insights to characteristics of such systems given by the classification proposed.

PROPOSAL OF CLASSIFICATION METHOD FOR THE SCO

The study was conducted on the basis of databases in which twenty SCO were identified. To accomplish the aims of this study, the research is based on the examination of various journals, all of which are related to supply chain management and production planning and control areas. We use journals because we also believe these are the resources most commonly used to acquire information and report new findings (Ngai et al., 2008). Papers were examined across a range of journals using the following electronic databases: (i) Science Direct; (ii) Compendex; and (iii) ABI/ INFORM.

The main goal of the literature review undertaken in this study was to integrate and summarize the state-of-the art regarding SCO. Therefore, this review is characterized as being of an integrative nature (Neuman, 2003).

After these articles were identified and analysed, a classification method was developed. Some previous SCO classification frameworks are:

a) WIP-oriented × throughput-oriented production control system: Hopp and Spearman (2008) define a WIP-oriented system as one that defines/controls the WIP level and observes throughput, whereas, a throughput-oriented system defines/controls throughput and observes WIP.
b) Centralised × decentralised systems: Lodding et al. (2003) define a SCO as centralised if the WIP level (and thereby lead times and work utilisation) are determined on a centralised control level, whereas a decentralised system sets these parameters by means of control loops between manufacturing work centres.
c) Classification according to the field of application: considerable research attempts to classify SCO according to variables that favourably influence the practical application of SCO. Some variables used include product variety and complexity of material flow (Sipper and Bulfin, 1997; Lodding et al., 2003) and products repetitiveness level (MacCarthy and Fernandes, 2000), among others.
d) Push × pull systems: according to Bonney et al. (1999), in a push system, the materials and information flow go in the same direction, whereas in a pull system, the materials and information flow go in the opposite direction. Germes and Riezebos (2010) extend the pull system classification, denominating as unit-based pull systems those that limit the number of orders on the shop floor, whereas load-based pull systems limit the work content (processing time) of orders.

The classification framework developed in this paper arose from Burbidge (1968), who divided SCO into three classes: (i) make-to-order systems; (ii) stock-controlled systems; and (iii) programme-controlled systems. The classification framework proposed is presented further, and is divided into four categories:

a) Order-controlled systems: There is no stock of final items, once production is carried out according to customers' specifications.
b) Stock level-controlled systems (SLC): The decision about the release of an order is based only on the stock level, which pulls the production.
c) Flow-scheduled systems (FS): The release of an order is based on a centralised scheduling drawn up by the PC department. This centralised schedule pushes the production.
d) Hybrid systems (H): These have characteristics of groups B and C.

SCO CLASSIFICATION

The functioning logic as well as insights regarding the practical application of each of the twenty SCO found in the literature review are presented. The insights serve basically to show production environment characteristics that the SCO literature has demonstrated as being favorable.

Order-controlled system

Contract-scheduling system: This system, based on Burbidge (1968), is used to control orders in the event of complicated products made to special designs. The system basically breaks down single contracts for large complicated projects into a large number of small orders for individual items. The system also sets due dates for the delivery or completion of each item. This work must be done in such a way that the contract is completed within the required finishing date. Therefore, contract-scheduling systems are useful to manage large project systems, which produce high-complexity products.

Contract scheduling, unlike most of the other types of SCO, is generally concerned with controlling the production from the stage of initial design through all the stages of production. A number of techniques are used to help schedule the contract; examples are PERT (programme evaluation and review technique) and CPM (critical path method).

Stock level-controlled systems (SLC)

***Continuous-review system*:** The functioning logic of this system – always known as minimal stock system or reorder point system or continuous (Q,R) policy) – is to monitor the stock level continuously and to order a fixed quantity when the inventory level reaches a reorder point R.

With regard to practical application, according to Burbidge (1975), a periodic review system can be used to control independent demand items C (result from ABC analysis). Hautaniemi and Pirttilä (1999) agree, adding that the continuous-review system can also be used to control A items when the supplier lead time is long and the demand is low and difficult to forecast (this is supported by Jacobs and Whybark (1992), who claim that if the demand is difficult to forecast, the continuous review system obtains better results than MRP and with less effort). According to Jonsson and Mattsson (2003), this system is useful to control standardised items. A variant of the continuous review system is the cover time planning system (CTP), which, according to Jonsson and Mattsson (2002), is used in Swedish companies.

Periodic-review system: In this system, at fixed intervals – called review period – the inventory level (I) is checked and an order is issued if (I) is below a certain predetermined level. The size of the order is the amount required to bring the inventory to a predetermined level S.

Regarding practical application, according to Burbidge (1975), the periodic-review system can be used to control independent demand items C, especially if items are common and have a low risk of obsolescence. Sipper and Bulfin (1997) recommend combining the periodic-review system (with a review period of typically one or two weeks) with the lot-for-lot strategy for independent demand A items. Examples of papers discussing this system in the literature are Maddah et al. (2004) and Lee and Schwarz (2009).

CONWIP-SLC system: The Conwip system was proposed by Spearman et al. (1990). The total work in process is limited by the number of cards. The functioning logic of this system is the following: an available card has to be present to authorise a job entering the production line. The card is attached to the job that is being routed through workstations. When the processing of the job in the line is completed, the card is removed and made available to authorise another job to enter the line. This characterises the system as being controlled by the stock level (SLC).

Regarding CONWIP-SLC practical application, abundant research suggests this system as being adequate to a flow shop repetitive environment (Huang et al., 1998; Yang, 2000; Krishnamurthy, 2002; Jodlbauer and Huber, 2008). According to Sipper and Bulfin (1997), this system is useful to control stable and uniform product lines. According to Spearman et al. (1990) and Li (2010), this system allows higher product variety than kanban systems. A recent study showing a practical application of CONWIP-SLC is found in Slomp et al. (2009). A variation of the Conwip system that, according to Stevenson et al. (2005) and Germes and Riezebos (2010), can be used for an environment with higher product variety is denominated ‘m-CONWIP’. In this system, there are m (multiple) CONWIP loops for every possible routing on the shop floor.

Kanban- SLC system: In this paper, Kanban- SLC was denoted as kanban variations that follow the logic of pull production from stock without centralised scheduling given by the PPC department. There are different types of kanban, but the two most common are production (P-kanbans) and transportation (T-kanbans). When both are used, the system is called dual-card kanban; when just one type is used, the system is called single-card kanban.

Regarding the field of application, Gelders and Wassenhöve (1985) claim that if the ideal conditions for kanban use are present, it is the ideal system. These conditions are well known in the literature: low set up time, low product variety, and stable demand (White and Prybutok, 2001; Pettersen and Segerstedt, 2009; Lage and Filho, 2010). Therefore, ‘Kanban system is not for everybody’ (Sipper and Bulfin, 1997). According to MacCarthy and Fernandes (2000), and Gupta and Snyder (2009), the Kanban system is adequate to repetitive, flow shop systems. A literature review dealing with kanban systems is found in Price et al. (1994) and Kumar and Panneerselvam (2007). Many variations of kanban systems are found in the literature: for example, the generalized kanban control system (GKCS) and the extended kanban control system (EKCS). However, Lage and Filho (2010) did a review concerning kanban variations.

TBC (two-boundary control) SLC system: Proposed by Bonvik (1997), the two-boundary control system, TBC (they call it hybrid kanban-CONWIP), combines kanban and CONWIP. The functioning logic of this system is thus: inventory at each of the stages is controlled by kanban cards. The last stage has no kanban control. The first production stage requires two authorisation cards: a kanban card from the second stage and a CONWIP card from the last stage. The CONWIP card has to do with the upper limit of total WIP allowed in the system. By means of this functioning logic, it can be seen that this system can be classified into two categories: it can be considered a system controlled by the stock level (SLC) if the authorisations from both kanban and CONWIP cards are based just on the stock level, or it can be considered a hybrid system if at least one of the card authorisations is based on scheduling from the PPC department. The TBC system showed good results when compared to other systems (for example, Kanban and CONWIP) in repetitive, flow shop environments (Geraghty et al., 2004; Gaury et al., 2000; Bonvik et al., 1997).

BBC (behaviour-based control) SLC system: The BBC system was proposed by Paternina-Arboleda and Das (2001). In this system, there are three types of authorisation: CONWIP, Kanban, and emergency. The WIP level is controlled as in the CONWIP system. In addition, BBC works with a one-time emergency alert if either the demand is not satisfied or a machine breakdown occurs. Moreover, the intermediate buffers are constrained by means of kanban-type authorisations. According to the way this system is proposed by Paternina-Arboleda and Das (2001), it can be concluded that it is controlled by the stock level (SLC system), once the release of orders (beginning and intermediate points within the production line) is based on stock level and not on a centralised schedule. Paternina-Arboleda and Das (2001) analyse the performance of this system in a flow shop, repetitive environment, obtaining positive results comparing the BBC system with TBC, CONWIP, kanban, and EKCS (extended kanban control system).

Flow-Scheduled Systems (FS)

Base-stock system: The classical reference on base stock is Clark and Scarf (1960). The base-stock system limits the amount of inventory between each production stage and the demand stage.

Each machine tries to keep a certain amount of material in its output buffer, subtracting the backlogged finished goods demand, if any (Bonvik et al., 1997). As it is necessary to transmit information from the PPC department to all production stages in order to authorise production, this system can be characterized as a flow scheduled one.

Regarding applicability, according to Burbidge (1968), the base-stock system is adequate to control repetitive items in a flow shop environment with a stable and non-seasonal demand.

Takahashi and Myreshka (2005), Karaesman and Dallery (2000), and Duenyas et al. (1998) claim this as well. Some of these authors also highlight specific situations where the base-stock system is appropriate: namely, when a higher due date is allowed and when the production rate for all workstations is the same.

PBC (period batch control) system: The PBC system was devised by Mr. R. J. Gigli in approximately 1926. PBC is a cyclical system, operating with a fixed cycle or periods during which the parts are produced that are required in a subsequent period in the next stage (Benders and Riezebos, 2002). Therefore, all the components required to build the products in one period are scheduled to be built beforehand in the previous stage of production.

Regarding the PBC area of application, according to MacCarthy and Fernandes (2000), this system is appropriate for repetitive and semi-repetitive production systems. Moreover, for PBC implementation, some conditions are required (Burbidge, 1994): product processing time should be less than one period; set-up times should be low, once it is required to work with small lot sizes; and purchasing lead times should be low. One attempt to try to deal with the first and second condition was to use flow shop, cellular manufacturing (Burbidge, 1975). More details regarding this system are found in Burbidge (1975, 1994, 1996) and Steele and Malhotra (1997). It is worth noting that Benders and Riezebos (2002) considered the PBC system to be a classic system, not an outdated one.

MRP system: MRP (material requirements planning) and MRP-II (manufacturing resources planning) are sophisticated SCO that have been used extensively in large companies worldwide since the 1970s. MRP, based on the definition of final products production, enables companies to define when, how many, and what items to produce and purchase (semi-finished products, components, and raw materials). MRP's successor, MRP-II, is a more developed system that takes into account decisions about capacity: namely, it puts into practice the decisions defined by the MRP. MRP-II uses a structured logistics planning that can predict hierarchical calculations, verification procedures, and decisions aimed at reaching viable production planning in terms of material availability and production capacity.

According to a large number of authors (Sipper and Bulfin, 1997), MRP systems can deal with complex situations, such as having a large number of products or products with a Bill of Materials (BOM). Hence, MRP is appropriate for non-repetitive production systems (MacCarthy and Fernandes, 2000). According to Gupta and Snyder (2009), MRP advocates suggest that the flexibility of the system allows it to adapt and to be used together with other SCO. However, MRP users must first overcome a number of problems for the system to work satisfactorily.

These include failure to determine parameters, the MRP infinite capacity approach, and MRP instability, known in the literature as MRP system nervousness (Filho and Fernandes, 2009 gives a more precise definition of system nervousness).

MRP literature is extensive. Examples of topics covered in the literature are: (i) system parameterisation (Hautaniemi and Pirttiä, 1999); (ii) lot sizing procedures (Ho, 2008); (iii) safety stock (Dellaert and Jeunet, 2005); (iv) comparison with other systems (Gupta and Snyder, 2009); (v) uncertainty and risks in the system (Inderfurth, 2009; Barba-Gutiérrez and Adenso-Diáz, 2009); and (vi) finite capacitated MRP (Lee et al., 2009; Kanet and

Stoßlein (2010).

OPT system: The OPT (optimized production technology) system was developed in Israel during the early 1970s by Eliyahu Goldratt. The OPT system is composed of two fundamental elements: a) a philosophy (expressed by means of the well-known 10 OPT rules (Goldratt and Cox 1986; among others); b) software. According to Sipper and Bulfin (1997), the OPT system is the bottleneck scheduler of the managerial concept known as the Theory of Constraints.

The basic functioning of OPT software is the following: input data are received by the BUILDNET module. After that, the SERVE module calculates a load profile and average utilisation for each resource. Based on this capacity calculation, the SPLIT module divides the network into two areas: critical and noncritical resources. It also allocates time buffers at the appropriate places. Finally, the OPT module, using a good heuristic, generates a realistic Master Production Schedule. OPT parameterization is found in Croci and Pozzetti (2000). As to applicability, according to MacCarthy and Fernandes (2000), the OPT system is useful to control semi-repetitive environments.

Hybrid systems

Hybrid CONWIP: This system is similar to CONWIP-SLC. The difference is that the orders that need to be processed in the production line come from a backlog list. This list is generated from a master production schedule (MPS) coming from a centralised PPC department. The backlog list dictates what goes to the line, and the card decides when, which characterises this system as a hybrid one.

CONWIP H is useful for flow shop, repetitive, and semi-repetitive environments, once –in the same way as m-CONWIP – CONWIP H allows higher product variety than Kanban SLC systems (Sipper and Bulfin, 1997).

According to Framinan et al. (2003), who present a literature review about the CONWIP system, some SCO are identical or similar to CONWIP, such as the C-WIP system (Glassey and Resende, 1988); the long-pull system (Lambrecht and Segaert, 1990); the global flexible-line system (So, 1990); and the single-stage kanban system (Spearman, 1992). Therefore, in this study, these systems were considered to be variations of the CONWIP system and thus, outside the scope of this paper.

Hybrid kanban system: In this paper, the hybrid kanban system was denoted to be those kanban variations that, despite pulling the production from stock level, have a master production schedule that drives the production of the last stage. Thus, the last stage is scheduled, and production at the rest of the work centres is pulled by the stock level. Lage and Filho (2010) give information about more kanban variations. The field of application of the hybrid kanban system is the same as Kanban SLC.

DBR (drum, buffer, rope) system: As well as OPT, the DBR system is based on the theory of constraints philosophy. According to Gonzalez et al. (2010), at the shop-floor level, TOC is usually implemented by means of the DBR production control system. DBR is composed of three elements: drum, buffer, and rope. The lower capacity station, which governs the throughput rate of the entire manufacturing line, is known as the ‘drum’ (also known as capacity constraint resource - CCR). This resource is scheduled based on the finite capacity of the constraint. The time ‘buffer’ protects the drum (and shipping) from variations. The input control mechanism is the ‘rope’, and it is based on the use of the bottleneck.

By means of this functioning logic, it can be seen that the system is hybrid, once the ‘buffer’ pulls the production using the ‘rope’, but the drum is scheduled by a PPC centralised department. The literature shows that DBR is appropriate for flow shop, repetitive environments (Miltenburg, 1997; Steele et al., 2005; Chakravorty and Atwater, 2005). Recent references to DBR include Gonzalez et al. (2010), Betterton and Cox III (2009), and Wu and Liu (2008).

A system similar to DBR according to Framinan et al. (2003) (also similar to CONWIP) is the starvation avoidance system. This system is described in Glassey and Resende (1988).

Hybrid TBC system: As shown earlier, the TBC system can also be classified as hybrid if at least one of the authorisation cards (kanban or CONWIP) is based on scheduling from the PPC department. We denominate this system Hybrid TBC. The application area of this system is basically the same as the TBC-SLC system.

Hybrid push/pull (HPP) system: The hybrid push/pull system, proposed by Hodgson and Wang (1991a, b), uses push systems to control some production stages, whereas others are controlled by a pull control strategy. A Markov Decision process is used to calculate the number of units that each stage is capable of producing in a given period. According to Gerathy and Heavey (2004), the optimal HPP policy involves pushing during the first stage and pulling in all subsequent stages. This characteristic of pushing some stages and pulling others gives the system a hybrid nature.

Regarding the field of application, Hodgson and Wang (1991a, b) and Gerathy and Heavey (2004) used HPP to control a flow shop, repetitive environment.

Minimal blocking system: The minimal blocking system, proposed by So and Pinault (1988), has a small difference with respect to the kanban system: if the machine upstream finishes its operation before the machine downstream, and the demand occurs at the downstream machine in the meantime, the upstream machine can start a new operation. Therefore, as a machine can start its operation as a result of either a requisition from the downstream machine or a schedule from the PPC department, this system presents a hybrid characteristic. The literature demonstrates that minimal blocking is adequate for flow shop, repetitive environments (Mitra and Mitrani, 1990). So and Pinault (1988) also stress that minimal blocking is adequate in situations where it is needed to facilitate machine recovery from failures, and to keep bottlenecks working even if there are failed machines upstream.

DEWIP (decentralised work in process) system: The DEWIP system was initially proposed by Lödding (2001). The basic function of DEWIP is to establish decentralised control loops between the manufacturing work centres. The logic of DEWIP functioning is as follows: before an employee starts to work, he or she requests the go-ahead from the work centre that will be performing that particular order's next operation. The last operation of an order can always be processed. The employee at the downstream work centre decides whether to give the go-ahead, on the basis of a defined WIP limit for that work centre. If the employee gets the go-ahead for an order, he or she begins to work on it. Otherwise, he or she asks for the go-ahead for orders destined for different downstream work centres. All known orders are scheduled by a central PPC department. This functioning logic characterises the system as a hybrid one.

According to Lodding et al. (2003), DEWIP is adequate to control job shop, non-repetitive environments.

LOOR (load-oriented order-release) system: According to Breithaupt et al. (2002), the LOOR system is part of a major concept denominated workload control (WLC). This concept recognises that job shop production inevitably shows queues of orders that compete for the capacity of each work centre. The WLC concept tries to create small and stable queues or, more precisely, low and stable levels of direct load. The direct load of a work centre is defined as the quantity of work resulting from waiting orders together with that of the order being processed. The WLC concept smoothes the flow between the work centres by trying to release the right order at the right time. The complexity of this kind of input control, results from the routing variety in job shops. After the release of an order, other operations may have to be completed before an order can be processed at a certain work centre. Thus, orders that constitute input to the direct load of a work centre may come either directly from release or indirectly from any other work centre. The LOOR system is an approach suggested by Bechte (1980) to smooth these combined inputs to the direct load. Other approaches are found in Hendry and Kingsman (1991) and Oosterman (2000).

LOOR has a centralised WIP control and a load balancing algorithm (Wiendahl, 1995) based on work centre load limits and on the conversion of order times. The load-balancing algorithm takes into consideration not only the actual load for each work station but also the orders scheduled for the given period. An order is released only if the work centre has load available to process the order. The functioning logic characterises this system as a hybrid one, once the load balancing algorithm, which directs the release of orders at the shop floor, is based on a centralised scheduling drawn up by the PPC department, despite the fact that the release of orders is based on the WIP level.

According to Graves et al. (1995) and Lödding et al. (2003), LOOR is adequate for job shop, non-repetitive environments. References to LOOR include those by Wiendahl et al. (1992) and Zapfel and Missbauer (1993). References to WLC include those by Stevenson and Hendry (2006) and Thurer et al. (2010).

POLCA (paired-cell overlapping loops of cards with authorisation) system: The POLCA system was proposed by Suri (1998). This SCO has been designed in line with quick response manufacturing (QRM) principles. Its objective is to guide the material flow through production systems with a cellular layout. In the POLCA system, the flow of orders through the different cells is controlled through a combination of release authorisations and production control cards known as POLCA cards. The release authorisations are generated using a high level centralised materials requirements planning system (HL/MRP). This functioning logic characterises POLCA as a hybrid system, once release of orders are based on WIP levels (POLCA card) and on scheduling from the PPC department (HL-MRP).

Regarding field of application, according to Suri (1998, 2010) and Krishnamurthy and Suri (2009), POLCA is adequate for high variety or custom-engineered products (non-repetitive). Lödding et al. (2003) suggest POLCA for environments with a high number of variants and complexity of materials flow. Variations of POLCA system are found in Fernandes and Carmo-Silva (2006) and Vandaele et al. (2008). Riezebos (2010) gives an overview of POLCA research, as well as a relevant case study.

Conclusion

This paper presents a literature review of production control systems, referred to in this paper as systems for coordination of orders (SCO). A classification method based on four categories is proposed and used to classify the twenty different systems found in the review. A brief summary of each system is presented, showing the functioning logic. This literature review provides managers with a finite set of SCO, which, according to Gonzalez and Framinan (2009), is the first step in choosing the

Table 1. Summary of insights regarding SCO application.

SCO	Application	References
Order-controlled system		
Contract-scheduling system	(i) Large project systems	Burbidge (1968).
Stock level-controlled system		
Continuous-review system	(i) Independent demand class C items; (ii) Class A items with long supplier lead time, low demand, and an erratic forecast; (iii) standardised items	Burbidge (1975), Hautaniemi and Pirttilä (1999), Jacobs and Whybark (1992), Jonsson and Mattsson (2003, 2002).
Periodic-review system	(i) Independent demand items C, especially if items are common parts and have a low risk of obsolescence; (ii) combination of periodic review system (with a review period of typically one or two weeks) with lot-for-lot strategy for independent demand A items	Burbidge (1975), Sipper and Bulfin (1997), Maddah et al. (2004), Lee and Schwarz (2009).
CONWIP-SLC system	(i) Flow shop, repetitive, and semi-repetitive environment; (ii) allows higher product variety than kanban systems	Spearman et al. (1990), Huang et al. (1998), Yang (2000), Krishnamurthy (2002), and Jodlbauer and Huber (2008), Sipper and Bulfin (1997), Li (2010), Slomp et al. (2009), Stevenson et al. (2005) and Germes and Riezebos (2010).
Kanban-SLC system	(i) Flow shop, repetitive environment; (ii) low set up; (iii) low product variety; (iv) stable demand	Gelders and Wassenhöve (1985), White and Prybutok (2001), Pettersen and Segerstedt (2009), and Lage Jr. and Godinho Filho (2010), Sipper and Bulfin (1997), MacCarthy and Fernandes (2000) and Gupta and Snyder (2009), Price et al. (1994) and Kumar and Panneerselvam (2007),
TBC-SLC system	(i) Flow shop, repetitive environment	Bonvik (1997), Geraghty et al. (2004); Gaury et al. (2000).
BBC-SCL system	(i) Flow shop, repetitive environment	Paternina-Arboleda and Das (2001).
Flow-scheduled system		
Base Stock system	(i) Flow shop, semi-repetitive environment; (ii) stable and non-seasonal demand; (ii) longer due date allowed; (iii) same production rate for all workstations	Clark and Scarf (1960), Bonvik et al. (1997), Burbidge (1968), Takahashi and Myreshka (2005), Karaesman and Dallery (2000), and Duenyas et al. (1998).
PBC system	(i) Flow shop, repetitive, or semi-repetitive environment; (ii) products processing time less than PBC cycle time; (iii) low set-up time; (iv) low purchasing lead times; (v) cellular manufacturing	Benders and Riezebos (2002), MacCarthy and Fernandes (2000), Burbidge (1975, 1994, 1996), Steele and Malhotra (1997)
MRP system	(i) non-repetitive environment	Sipper and Bulfin (1997), MacCarthy and Fernandes (2000), Gupta and Snyder (2009), Filho and Fernandes (2009), Hautaniemi and Pirttiä (1999), Ho (2008), Dellaert and Jeunet (2005), Gupta and Snyder (2009), Inderfurth (2009), Barba-Gutiérrez and Adenso-Diáz (2009), Lee et al. (2009), Kanet and Stoßlein (2010).
OPT system	(ii) semi-repetitive environment	Goldratt and Cox (1986), Sipper and Bulfin (1997), Croci and Pozzetti (2000), MacCarthy and Fernandes (2000)

Table 1 Contd.

Hybrid system		
Hybrid CONWIP system	(i) Flow shop, repetitive, or semi-repetitive environment; (ii) allows higher product variety than Kanban system	Sipper and Bulfin (1997), Framinan et al. (2003), Glassey and Resende (1988), Lambrecht and Segaert (1990), So (1990), Spearman (1992).
Hybrid Kanban system	(i) Flow shop, repetitive environment; (ii) low set up; (iii) low product variety; (iv) stable demand	Lage Jr. and Godinho Filho (2010)
DBR system	(i) Flow shop, repetitive environment	Gonzalez et al. (2010), Miltenburg (1997), Steele et al. (2005), Chakravorty and Atwater (2005)), Betterton and Cox III (2009), Wu and Liu (2008), Framinan et al. (2003), Glassey and Resende (1988).
Hybrid TBC system	(i) Flow shop, repetitive environment	
Hybrid push/pull system	(i) Flow shop, repetitive environment	Hodgson and Wang (1991a, b), Gerathy and Heavey (2004),
Minimal blocking system	(i) Flow shop, repetitive environment; (ii) high rate of machine failures	So and Pinault (1988), Mitra and Mitrani (1990).
DEWIP system	(i) Job shop, non-repetitive environment	Lödding (2001)
LOOR system	(i) Job shop, non-repetitive environment	Breithaupt et al. (2002), Bechte (1980), Hendry and Kingsman (1991), Oosterman (2000), Wiendahl (1995), Graves et al. (1995), Lödding et al. (2003), Wiendahl et al. (1992), Zapfel and Missbauer (1993), Stevenson and Hendry (2006), Thurer et al. (2010).
POLCA system	(i) Semi-repetitive or non-repetitive environment; (ii) cellular manufacturing	Suri (1998, 2010), Krishnamurthy and Suri (2009), Lödding et al. (2003), Fernandes and Carmo-Silva (2006), Vandaele et al. (2008), Riezebos (2010).

most adequate SCO for a manufacturing system. In addition, this paper also presents general insights regarding the practical application of such systems. Table 1 summarizes these insights.

As can be seen in this table, the present review identified one order-controlled system, six stock level-controlled systems, four flow-scheduled systems, and nine hybrid sy-stems. It can also be seen that the majority of systems are designed and appear to be adequate to more simple environments (flow shop, repetitive environment).

One conclusion that arises regarding the practical application of an SCO system is that the main field of application of all systems controlled by the stock levels (here named SLC systems) is the flow shop, repetitive environment. These systems are pulled by the stock level, and therefore, have difficulty in dealing with an environment characterized by high product variety and complexity of material flow. This claim is supported by Germes and Riezebos (2010). For these authors, pull sy-stems that are applicable in make-to-order environments (characterized by high product variety and complexity of material flow) are scarce. One explanation is that the pull system requires a minimum level of stock, and this is prohibitive in an environment with high product variety. The exception to this conclusion is the CONWIP-SLC system, which appears to be useful even in an environ-ment with a higher product variety. The possibility of establishing m-CONWIP loops makes this system even more flexible.

Another conclusion is that, on average, the flow-scheduled systems are more adequate to a non-repetitive environment than those controlled by the stock level. Examples of such systems are MRP and OPT. The base-stock and PBC system also appear to allow some flexibility in dealing with more product variety: less than MRP and OPT, but higher than the majority of the systems controlled by the stock level.

The literature review and classification presented in this paper also demonstrate that hybrid systems constitute a promising field of research regarding the practical application of SCO in job shop, non-repetitive environments. Examples of such systems are DEWIP, LOOR, and POLCA. This claim is supported by Krishnamurthy (2002), who states that systems with hybrid characteristics appear to be more useful in job shop environments than pure pull systems.

It is hoped that the review, the proposed classification method, and the resulting analysis will be a useful resource for anyone interested in SCO research, and will help to stimulate further research in this area. In addition, through a better understanding of SCO functioning and application – the core of production control activity – this paper intends to contribute to managers to better understand and choose from among these systems.

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