Aligning Manufacturing Flow Control Techniques with the product-process matrix: A review for research

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Abstract

Many Manufacturing Flow Control Techniques (MFCTs) have been proposed, and selecting an appropriate one to implement can be challenging. Comparing their performances could also be tricky because, by design, many are not likely to perform similarly under different conditions. This work aggregates and maps the MFCTs to a standard planning and control artefact to provide guidance on selection and implementation of the techniques. It builds on a previously published work. The hermeneutics double loop review procedure with snowballing approach was the overarching method, initiated using partial umbrella review. The product-process matrix was used as the basis for alignment of the MFCTs to the manufacturing processes.

MFCTs were summarised into a few groups using the characteristics of the production system, products and demand pattern. Mapping the groups to the product-process matrix enhances the selection of appropriate control techniques for manufacturing environments. It also helps in anticipating the performance of the techniques under specified manufacturing conditions. Leading MFCTs and their notable variations considered to be representative of others were selected based on literature. All variants were grouped using characteristics considered important from literature. There may be some other ways of creating the groups.

The only work known to have linked the MFCTs to processes was published in 1989, and there has been many new techniques and variants of existing ones since then. This work expands on this foundation to provide a more comprehensive mapping, thereby helping researchers and practitioners to achieve a more structured implementation of the techniques and compare their performances.

Keywords
Manufacturing Flow Control, product-process matrix, card-based control, Kanban, volume-variety reconciliation.

1. Background
Manufacturing Flow Control (MFC), also called production control, is an important function of the production system. It is different from priority scheduling, and its main goal is the control of job release based on the shop floor situation (Graves et al., 1995). It significantly affects the throughput rate, production lead time and the level of the Work-In Process (WIP) inventory in the system. Many MFCTs have been proposed in literature, but some of are more widely applied. For instance, Graves et al. discussed Material Requirement Planning (MRP), Kanban, CONstant Work In Process (CONWIP), Work Load Control (WLC), Starvation Avoidance, Workload Regulating, BORA (a German abbreviation) and Base Stock (BS). Bagni et al (2021) stated that MRP, Kanban, CONWIP, Drum-Buffer-Rope (DBR), Periodic Batch Control, WLC, and Pared-cells Overlapping Loops of Cards with Authorisation (POLCA) were the classics at the turn of the millennium, while COntrol of BAlance by CArd BAsed NAvigation (COBACABANA) and Demand Driven MRP (DDMRP) are the newer but accepted post-millennium techniques.

MFCTs have different views about how decisions should be made. Such decisions may be system related, like the level of centralisation of control, important parameter(s) to monitor (WIP, throughput, etc), or the main system objective(s) (cost, service level, etc). Their adaptability also differs under different scenarios involving demand behaviour (relatively predictable or variable; dependent or independent; individual or aggregate), and the product nature (functional or innovative), amongst others. How each MFC technique (MFCT) makes decisions, considering all these, affects the overall performance of the system involved, hence the question of alignment of the MFCT to the product-process parameters.

Researchers have been studying the performance of the various MFCTs under different scenarios with mixed results, probably because some performance objectives may be more suited to some systems than others. Thürer et al (2016) noted that performance comparisons between the Kanban system and CONWIP is somewhat unfair since any evaluation would take place in the context of an order control problem, otherwise CONWIP simply would not work. It may, therefore, be appropriate to understand the possible alignment between the MFCTs considered, the manufacturing processes involved, and the choice of performance objective selected, as these may have ramifications for the results obtained.

In addition, many MFCTs have been proposed for managing production systems over the past decades, and there have been diverse modifications of these. Thürer et al (2016) stated that there are three main Kanban variants: WIP, production and withdrawal types. Junior and Filho (2010) identified 32 variants of Kanban implementations, while Prakash and Chin (2015) discussed 15 modifications of the CONWIP. Thürer et al (2016) wrote all of the following: CONWIP is essentially some form of the Reorder point system; CONWIP can be understood as a work-in-process or production Kanban loop used for coordinating the confluence of different product flows, the main difference being that CONWIP cards are job-anonymous; POLCA loop system is equivalent to a Kanban system, which is often hidden since the workings of a Kanban system are typically described from the end of the line, while the POLCA literature describes its workings from the beginning of the line, so POLCA is equivalent to a Kanban system with job-anonymous cards; COBACABANA was derived from the more mature Workload Control literature. Hopp and Spearman (2008) noted that Kanban can be viewed as a tandem CONWIP loop carried to the extreme of having only a single machine. If the main techniques here are argued to be instances of one another, their variants are probably more similar since each modification causes each technique to trade off some of its unique characteristics. In fact, Bagni et al. (2021) stated that most of the thirteen new MFCTs that have been proposed between 1999 and 2018 have been referenced only by their authors, and 7 of them are only adaptations of the Kanban system. Of these thirteen, DDMRP and COBACABANA seem to have been the popular ones. This leads to the questions:

- Can the diverse MFCTs be consolidated into a representative few to help with their selection for application and understanding their characteristics?
- Can the MFCTs be aligned with some extant production control artefacts for better performance prediction and comparison?

This research's objective is to answer these questions by:

- aggregating these MFCTs and their variants found in literature into a few groups based on some identified characteristics;
- mapping these groups to the product-process matrix;
- proposing some likely qualitative behavioural implications of the mapping;
- suggesting how to use this mapping to guide the selection of an MFCT for production control.

This research was not intended to provide a review of every article that has been written on MFCTs over the past years, but to cover the relevant variants of existing techniques considered fairly popular, show their interrelationship, and indicate how they may map to the product-process matrix of Hayes and Wheelright (1979). In essence, once one variant reasonably represents some others, those represented are assumed not to provide new information. Thereafter, using the general characteristics of the product-process matrix, the features of the MFCTs' group is used to predict the group's behaviour and guide the selection of a group member for manufacturing control purposes.

This study background, research questions and objectives are presented in section 1. Section 2 presents the methodology adopted to review the pertinent literature. Section 3 contains the actual review, presenting the main properties used for classification of the techniques, followed by their grouping. Section 4 presents a brief overview of the product-process matrix, its volume-variety considerations, and the implications of this on the various sections of the matrix. Section 5 is a discussion of the mapping of the MFCT groups to the product-process matrix for what may be considered a proper alignment. In section 6, the expected qualitative properties of the mapping are discussed as corollaries of this mapping and the implications on the choice of measures used for the comparison of the performance of variants of the MFCTs when benchmarked against one another. Section 7 contains the conclusions and recommendations for future research.

2. Methodology

Three methodologies were adopted for this study, howbeit in part. The overarching approach was the hermeneutics loops of iterative reading and understanding cycles (Figure 1), through which the scholar engages the text to understand the literature within the context of its writing, and continually expands the scope of the literature until sufficient information is obtained (Boell and Cecez-Kecmanovic, 2014). This was preferred because the review is focused on answering particular questions and not summarising every published work. Moreover, expectation about the extant variants to be studied was unknown ab initio, hence, leads from intermediate findings were followed to identify more relevant articles.

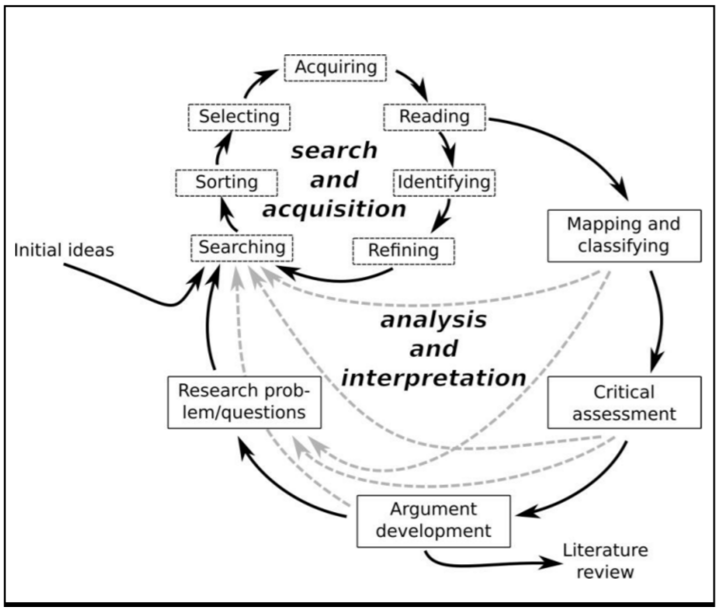

Figure 1. Hermeneutics Loops, source: Boell and Cecez-Kecmanovic (2014)

Two other approaches were used to kickstart the loop. A review of existing literature reviews on each of the WFCTs was done, not as an umbrella review, per se, because not all the review articles of the MFCTs were included, but only those addressing the modifications to the techniques, with motivations for such modifications. To find these reviews, a systematic search was done on google scholar and web of science databases using the main keywords comprising of review, study, and any or combinations of the MFCTs.

All the literature review articles downloaded were then reviewed, and only those meeting the stated requirements were retained. From this set, two snowballing processes were done to identify more relevant articles. First is the bibliographic snowballing, whereby all articles cited by the selected review papers were downloaded. Next was citation snowballing, whereby citations of these articles were tracked and all relevant articles were also downloaded. All these were read to identify all variants of the MFCTs that could be included, and the characteristics of the variants were documented. These variants were reduced into groups, and the main characteristics of each group was summarised. Next is a discussion of how this was applied in the review and analysis of the literature.

3. Review process and analysis

In broad terms, job release by MFCTs may be controlled by computers as in MRP, may be card-based as in Kanban, CONWIP, POLCA and COBACABANA, or utilise other signalling techniques as in DBR. This classification basis gradually erodes as variants of each technique is created; for instance, the e-Kanban variant of the classic Kanban utilises electronic signals. However, this review would start with the general card-based authorisation techniques, in particular, the Kanban technique. Thürer et al (2016) discussed the principles of the withdrawal, WIP and production Kanban systems. This is not really discussed in this section, but will be placed in context afterwards.

3.1. Card-based techniques

Most review articles on Kanban focused on its applications and performance. Thürer et al (2016) and Junior and Filho (2010) were considered most suitable because they focussed mainly on the variants. Between them, 35 variations of Kanban implementation were identified, hence, the fulcrum for the research's iterative loop. It seems pertinent to first discuss the main limitations of Kanban that necessitate the various modifications. Pure Kanban works well in a highly repetitive manufacturing environment with high volume, low variety, smooth and stable demand level, low setup times, adequately cross-trained workers, and smooth relationship with vendors. Rees et al. (1987) noted that it is not certain if JIT is cost effective when these conditions cannot be met. It is also important that the production rates and mix be known ahead of time so that the flow rates are synchronised (Takeda, Tsuge and Matsuyama, 2000). It is due to the operating environments in which one or more of these requirements may not be met that the variations become necessary.

The first group of Kanban variants discussed were mainly in response to variations in the general level of demand, e.g. trend and seasonal variations, hence inherent in single- and multi-product environments. The most common modifications for addressing this problem are: changing the number of Kanban cards in the system; allowing some safety/base stock to absorb the variation; or some combinations of these. Actually, these approaches may be doing the same thing indirectly because they ultimately change the stock level in the system. Blackstone and Cox (2002) pointed out that the entire WIP in any system can be classified into productive, protective, and excess stocks. The purpose of protective stock is to manage uncertainties. The aggregate level of stock in a typical Kanban system can, therefore, be assumed to, at least, be inclusive of the protective and productive stocks, hence, when the number of cards is changed, it might be affecting both portions of the stock. Hence, providing base stock and increasing the number of cards circulating within the production system might be similar interventions.

Some Kanban variants that may be considered to be in this category include the flexible Kanban (Gupta and Al-Turki, 1997), dynamically adjusted Kanban (Rees et al., 1987; Chaudhury and Whinston, 1990), adaptive Kanban (Tardif and Maaseidvaag, 2001), reacting JIT ordering (Takahashi and Nakamura, 1999), decentralised reactive Kanban (Takahashi and Nakamura, 2002) and reconfigurable Kanban (Mohanty, Kumar, and Tiwari, 2003) systems. While some variants dynamically adjust the number of Kanban cards, others rely on human intervention. The common action is the changing of the number of cards, and hence the aggregate stock level, in response to general variation in the demand level. This class may, therefore, be represented by any member, and in this report, they would be referred to as the flexible Kanban group.

The second Kanban variants discussed were introduced in response to the problem of starvation that sometimes occur due to the pull process, usually consequent to latency of transmission of card signal. General fluctuation in demand level may further complicate this problem. Some of the modifications that have been made to manage this include pushing job within the manufacturing process between the release of the material and a particular station within the system, concurrently releasing the cards of all processing stations in response to a particular signal, providing stocks in selected stations where jobs are allowed to queue up while it flows through the other stations, or some combinations of these.

Examples of the variants in this category include periodic pull Kanban (Kim, 1985), push-pull approach (Spearman and Zazanis, 1992), minimal blocking Kanban (So and Pinault, 1988), generalised Kanban control system (Buzacott, 1989), and simultaneous and/or independent extended Kanban control systems (Dallery and Liberopoulos, 2000). Also included is concurrent ordering (Takahashi, Nakamura and Izumi, 1997), where cards of all the stations are released simultaneously in response to withdrawing materials from the final station, pushed jobs a step downstream for every withdrawal. The fake pull (Hendrick, 1988) variant pushes jobs in every station upstream till it gets to a designated station that ensures maintenance of the pull discipline of Kanban in response to resource failure downstream, hence also placed in this category. The Gated MaxWIP (Grosfeld-Nir and Magazine, 2002) variant also pushes jobs to the end of the line while the card goes back to the first station where job release is controlled by the gate. This group is called the push-pull group hereafter.

The third group of modifications is in response to high variety manufacturing. In such environments, there is the need to make an extensive number of products, usually in small batches, in a typical make-to-order environment, with the need to manage capacity more extensively. As mentioned by Thürer et al (2016), the main goal of the Kanban is synchronisation, which may sometime be more relevant to capacity than inventory, and in such instances, the cards are usually not tied to a particular inventory item, but allocated to different items based on the need to make capacity

available to produce such items in an integrated manner. Examples of modifications in this category includes the generic Kanban (Chang and Yih, 1994) and the job shop Kanban (Gravel and Price, 1988). This group is designated as the job shop group.
The last group discussed relates to technology induced adaptations and multi-technique integration. For instance, the e-kanban (Ansari and Modarress, 1995) was created to minimise the problem of latency of transfer of information and possible misplacement of physical cards. The Bar-code Kanban (Landry et al., 1997) is adapted to blend MRP with barcode cards acting as signals, thereby integrating the forward-looking capability of the MRP with the inventory capping capability of the Kanban system. Also benefiting from the hierarchical planning capability of the MRP with the tight shop floor control of Kanban are the hybrid push/pull approach (Geraghty and Heavey, 2004) and MRP/sfx-Shop (Nagendra and Das, 1999) variants. The virtual Kanban of Takeda et al. (2000) uses the production Kanban, but in a multi-item context, and limits the queue size of an upstream station by that of its downstream station. This group is called the integrated group hereafter.

CONWIP was proposed by Spearman, Woodruff and Hopp (1989) as an alternative to Kanban. It makes use of anonymous cards that link the end of the production line to the beginning. Job is pulled into the system from the first station only after one has been completed or removed from the last station, and the released job is pushed through to completion once released into the system, unlike the classic Kanban. From this description of the classic CONWIP, it can be seen that its properties would be similar to the variants in the push/pull Kanban group. In fact, González-R et al noted that G-MaxWIP of Kanban and the DBR can be considered as generalizations of the CONWIP. This means the classic CONWIP can be mapped into the push Kanban group, and consequently, almost all CONWIP variations would be in this group as well. The generic nature of CONWIP card makes it suitable for the job shop Kanban group, but it has been placed in the push-pull because jobs flow mainly through identical paths, unlike in typical job shop environment. Important variants of CONWIP is discussed next, mentioning their shared features with some other Kanban groups.

For the review of CONWIP modifications, Prakash and Chin (2015) and González-R, Framinan and Pierreval (2012) were the main texts. In particular, Prakash and Chin (2015) present fifteen variants of CONWIP. Segmented CONWIP has the main production line divided into series of smaller connected lines connected. These smaller lines are linked using cards as in Kanban, hence, it resembles the tandem Kanban (Tayur, 1992), and also resembles both the push Kanban and the DBR technique. The open loop CONWIP maintains a fixed sum of WIP and finished stock level such that job is released when the sum of the two drops below a level (Zazanis, 1994). This can make it comparable to the generalised and extended Kanban systems. The Capacitated CONWIP (CAPWIP) has dynamic card count, and can be seen to share the characteristics of the reactive Kanban which adapts the number of Kanban cards and also pushes jobs until a designated station is reached once released (Trietsch, 2005). The Constant Load CONWIP (CONLOAD) has the cards circulating between the input buffer and the bottleneck buffer, making it look like the DBR (Rose, 1999). The extended CONWIP kanban and closed loop MTS CONWIP are also quite similar to each other in that there are both local and global control parameters, and are similar to the tandem push Kanban (Boonlertvanich, 2005; Rubio and Wein, 1996). The hybrid CONWIP kanban is like a segmented CONWIP, but where local control utilises Kanban-style connection and global control is governed by CONWIP, reversing the logic of the segmented CONWIP that has local CONWIP control and each segment is linked by Kanban-style cards. The synchronised CONWIP is an adaptation for assembly systems and has been said to be identical to the GMaxWIP (Takahashi, Myreshka and Hirotani, 2005), hence, placed in the same group of the push-pull Kanban. Also, all cards for the tandem loops of synchro CONWIP are released simultaneously, making it similar to the concurrent Kanban. Since CONWIP generally pushes job through all stations, its variants can always be benchmarked against one push/pull Kanban group member.

POLCA is a card-based control system design purposely for the job shop environment. It was invented by Rajan Suri as part of a philosophy termed Quick Response Manufacturing (QRM). Its main focus is the continuous reduction of lead time as a means of reducing cost and delivering organisational value (Suri, 1998). A card connects two work cells, which in the simplest case may be individual machines, and a job is not released (authorised) unless capacity for processing the job is available in the two cells stipulated on the card. This sequence of these cards having pairs of work cells map the path of every job through the manufacturing floor, and makes possible a large number of possible paths for manufacturing, while managing the WIP and processing station capacity simultaneously. These cards are not attached to jobs, but loaned to jobs needing capacity form the resources to which they are attached. It can be seen immediately that this concept has a number of similarities to the generic Kanban group, and for the purpose of this work, they would be placed together in a group. Riezebos (2010) noted that POLCA provides more flexibility than

Kanban, and the cards are essentially capacity signals. POLCA also makes use of release list which improves its flexibility.

A number of modifications have also been made to POLCA, and these are mentioned only for completeness since all POLCA variants are placed in the same group used for high variety situations like the job shop Kanban. The Generic POLCA (GPOLCA) is an adaptation of POLCA for a system manufacturing large varieties with variable demand where the job gets released only after the card for every pair of cells is available, unlike POLCA where job gets released after the first pair is available (Fernandes and do Carmo-Silva, 2006). The Load Based POLCA (LB-POLCA) uses advanced planning to incorporate the capacity implications of anticipated loads on the system due to the aggregate planning phase into the POLCA design. This indicates the need for some form of computer-based planning like the MRP system (Vandaele et al., 2008).

COBACABANA is also card-based and is designed for an environment of high variability and in need of high flexibility like the job shop, similar to POLCA. It was proposed by Land (2009) and is based on the Workload Balancing technique; but unlike POLCA, the load is centrally balanced by the planner. The capacity of each resource is broken into chunks that can be allocated to jobs and placed on a board where the load on each resource can be monitored and controlled by the planner. The cards of all the resources needed by a job are all simultaneously released when the job is launched, and as capacity becomes available on completion of an operation by a resource, the capacity card circulates back to the planner for reuse. The planner decides which jobs get released to maintain the work norms planned for the system using appropriate priority rules. The flow of cards between the planner and the production resources constitute loops, while another loop might be created between the planner and sales department to support order promising. Hence, COBACABANA readily fits in the job shop Kanban group, together with POLCA. COBACABANA is the most recent of these techniques and variations of it are not reported yet.

3.2. Non-card-based control

The next set of techniques do not make use of cards by design, but also make use of signalling mechanisms for job release. TOC, MRP, BS and basic RoP will be discussed briefly. The TOC technique has a massive review of its applications and on performance evaluation relative to other techniques, but does not seem to have had too many variations from the original form, and neither has there been a collective review of its modifications. The original TOC was proposed by Goldratt (1994), and it has at its heart the Drum-Buffer-Rope (DBR) technique, hence the interchangeability of the two terms in literature. This technique assumes there is a system constraint, which could be a resource within the production facility or the market, and constitutes the heartbeat of the system, hence called the drum, and dictates the job flow rate. This resource needs to be protected by an appropriately sized buffer, and there must be some means of communicating between the buffer and the source of material input into the system, called the rope. By design, it can be seen that the properties of TOC and most push/pull Kanban variants are similar, hence, it can be placed in the same category.

TOC works well in an environment where the demand level is fairly stable and the varieties of items made are not too much. Most research on TOC has been on deciding the optimal operational parameters like the buffer size, its applications and integration with other techniques, and performance evaluation, hence, no review was found on its modifications. Mabin and Balderstone (2003) reported that they couldn't find a report of the failure TOC while analysis on eighty applications. Two main variants have, however, been reported. The Dynamic DBR (Georgiadis and Politou, 2013) dynamically determines the level of the buffers supporting the critical resources. In essence, it provides means to dynamically adjust the buffer size within the system. This characteristic is shared with the flexible Kanban group in addition to the general DBR characteristics. Another variant of the DBR was the Simplified DBR (Schragenheim and Dettmer, 2000). This model assumes the market should always be a main consideration when applying TOC, irrespective of whether the constraint is within the production system or in the market. This essentially does not change the classification of the TOC in any significant manner, but always includes a market buffer in the pull.

MRP is a systematic technique following a hierarchical approach for planning the requirement for materials in an organisation. While the MRP engine is mainly concerned with planning the dependent demand for components needed to produce the end items that the customers actually demanded, the integrated plan usually starts with the Aggregate plan that reconciles the material and capacity requirement for product groups, followed by Master Scheduling which decomposes product groups aggregates to the constituent end items. It strives to preserve the general supply level proposed during the aggregate planning while paying attention to the end item mix and the cost of achieving both.

The resulting Master Schedule is a main input into the MRP engine that performs netting (using the inventory master data file record) and exploding (using the Bill of Material) to plan the component requirements, thereby scheduling the release dates for the end items and components through lead time offsetting (Jacobs et al., 2011).

By design, MRP assumes deterministic demand and lead time, and that is one of the challenges with its use. The MRP list generated is static while the requirement list is dynamic. There is the problem of nervousness associated with the changes in requirement list influencing the stability of the schedule of job release generated by the MRP in both quantity and timing (Ptak and Smith, 2011). Unlike most token/card-based systems, MRP is forecast-driven, while orders progressively consume the forecast (Jacobs et al., 2011) as the demand is realised, hence, there is always the issue of the impact of forecast errors. Also, MRP is computationally intensive, so most systems cannot regenerate MRP schedules perpetually in response to changes in requirement, hence the need to manage customer responsiveness requirement of the front-end together with the computational intensity of schedule regeneration at the back-end. While technological advances like in-memory computing and columnar database design are beginning to address this issue, it has not fully resolved the problem. It, therefore, becomes necessary for MRP design and implementation to respond to these, and a number of other issues.

However, responding to these challenges has not resulted in creating many variants of the MRP system, but various tuning parameters have been created in the setup of the system to make it adaptable to diverse situations and needs (Yeung et al, 1998). Such parameters include MPS frozen interval, MPS and MRP replanning frequency and scope, MPS planning horizon, safety stock and safety lead time policy, Lot-sizing rules, time fencing policies, etc. For instance, MRP renewal logic could be regenerative or based on net-change; the material planning level can be end item or entire BOM, and scope mate be a single SBU or plant scope. Demand, planning and release times could be fenced and set at different values relative to one another, and the length of frozen, slushy and liquid zones could be adjusted to achieve the desired planning objectives. Lot sizing could be lot-for-lot, economic quantity, periodic or reorder point and many such combinations. All these settings make it possible for the MRP to be able to respond to a number of planning scenarios and to be closer to order based or forecast based planning when required. For instance, setting the planning, demand and release time fences equal to the lean pitch and all forecast values to zero in the MPS, keeping only the commitments, takes the execution closer to the typical Kanban environment.

Of course, the classic MRP system has also evolved into the MRP II to plan non-material (especially the capacity driven) resources and enhance closed loop supply chain, and this has further advanced into the Distribution Requirement Planning (DRP) that is particularly designed for stock replenishment, and the Enterprise Resource System (ERP) to integrate all the plans of the various functional areas of the organisation into a common platform. The extended ERP systems in the form of ERP II, ERP III and ERP IV, which included integrated supply chain planning, social media extension and the general industry 4.0 capabilities respectively have also emerged, adapting to the global evolution in fiscal, social and technological and realities (Wood, 2010; Ganly et al. 2019).

The DDMRP was proposed by Ptak and Smith and built around the three principles of Position, Protect and Pull. This means appropriate Positions for material buffer must be identified, which should help to Protect the flow of materials using appropriate buffer profiles and levels, and through which material is Pulled to enable flow using Demand Driven Planning. They proposed the use of the Decoupled Lead Time (DLT) as a compromise between component Lead Time (LT), which may be too short for stability of the system, and the aggregate LT, which may be too long for responsiveness to customer. The material explosion process utilises the DLTs for decoupled explosion based on a netting formula that is a modification of the traditional projected balance calculation of MRP. This formula uses concepts called the order spike horizon and qualifying spikes in the netting calculations to manage variability in demand, and hence, determine when order is placed and how much quantity it is. Demand, zone and LT adjustment factors were proposed to guide the timing and quantity of replenishment. To determine the buffer levels, they proposed the three-colour coding system like TOC, but chose the factors depending on the material type (Ptak and Smith, 2019). Variants of DDMRP have also not been published, but like MRP, many parameters have been proposed to tune its behaviour to be able to adapt to diverse manufacturing situations.

The Base Stock and Reorder Point (RoP) techniques are similar inventory-based control techniques, but differ in their echelon span of control, hence would be discussed together. They work by monitoring the stock level such that when it drops below a particular level, called the norm in BS, replenishment is triggered. Order quantity may be determined using diverse techniques, but that will not be discussed here. RoP's view is local, considering only stock level at the particular station, while base stock's view is global, considering stock in the echelons to which the station belongs as an aggregate before signalling a trigger (Timmer, Monhemius, and Bertrand, 1984).

4. Product-Process matrix overview

The product-process matrix (hereafter called matrix) was first introduced by Hayes and Wheelwright (1979) to link manufacturing processes to product life cycle. This model has been adapted to study the alignment of manufacturing processes and strategies in various industries. Of interest is how the volume-variety nature of the product manufactured may help to determine the natural line of alignment of products with the most likely matching process along the leading diagonal of the matrix, with the high varietal/low volume product being aligned with the top left corner of the matrix, and the high volume/low variety product at the bottom right. Four main process types were identified and different companies or industries may be mapped to a spot along the diagonal. The authors further explained that organisations might decide to strategically deviate from the line of natural alignment by being somehow above or below it, but concluded that a drastic deviation from this line without a deliberate strategic intent in mind will likely be to the disadvantage of the company. Auto-manufacturing, for instance, naturally fits in the connected flow-line segment in general, but within this segment, companies may choose strategies of further customisation, e.g. high-end cars manufactured in lower volumes. The appropriate MFCT that should also be adopted under the different scenarios may need to be different.

5. MFC and the matrix

It is important to first highlight at this point that there is no general consensus in literature about the precise segmentation of the matrix sections, but there is a general pattern. While Hayes and Wheelright indicated four sections, Silver, Pyke and Petterson (1998) and Pycraft et al (2014) each have five using different categorisations, and Heizer and Render (2010) has three main categories with mass customisation as the fourth. Furthermore, while most authors seem to agree on the lowest bottom section as being continuous process, some authors split the discrete production sections as flow shop and job shop sections, while both are further split into general and pure flow- and job shops (Stevenson, Hendry & Kingsman, 2005). Some also classified highly customized industry into Repeat Business Customisers (RBC) and Versatile Manufacturing Companies (VMC) (Amaro et al., 1999). For the purpose of this work, Silver et al will be the standard for classifying the MFCTs due to the relevance of their work to this review.

It has been argued that the MFCT adopted by a company should also be in alignment with the nature of product made and in particular, align with this matrix. Stevenson et al (2005) considers factors such as the importance of the customer enquiry stage, company size, degree of customization and shop floor configuration and play a large role in the applicability of planning and control choice. Silver et al (1998) actually presented a table showing how MFCTs align with the product process matrix. Their process categories are shown on the left-had side of Figure 2, while those of by Hayes and Wheelright are shown on the right-hand side. Silver et al. noted that while MRP vendors usually market it as a solution for the control of all types of manufacturing systems, it is unsuitable, or may even be detrimental, when applied to the bottom-right items on the matrix having simple BOM with tightly linked manufacturing stages, and the top-left corner items having shifting bottleneck, extremely variable lead time, and simple BOM. Both situations limit the benefit of BOM explosion, which is where the power of MRP really lies.

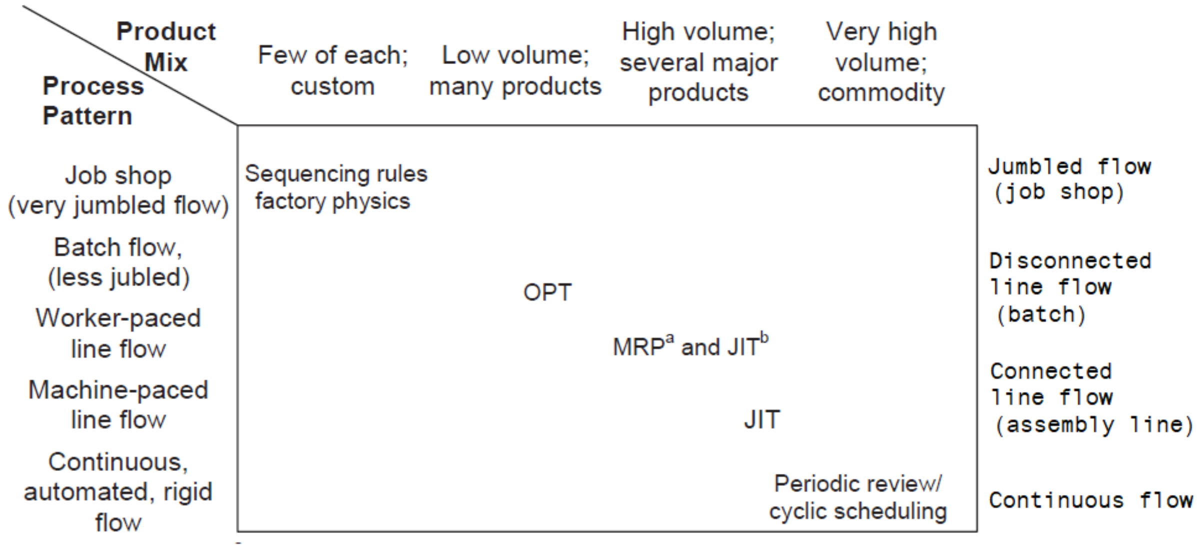

Figure 2. Alignment of MFCT with process types (Silver et al. 1998)

5.1. Expanding the MFCTs maps on the matrix

It is apparent that many more MFCTs and their variants have since been introduced, and this has provided opportunities to expand Figure 2. As it will be difficult to map all individual techniques discussed earlier into the matrix, mapping the groups seems more practicable. The practitioner needs to first select a general group, and then consider a more appropriate variant within the group. Therefore, a possible mapping is provided in Figure 3, and the motivation is then presented. It is important to point out, however, that while the figure shows the general placement of the MFCT groups, there may likely be some overlap between the applicability of some of the techniques placed within each group on the leading diagonal.

To enhance this discussion, a number of control parameters identified from MFCT literature as being important for discussing these techniques and their application would be referenced and linked to the suitability of the MFCT group suggested. Some of these parameters are system related while others are job related. For instance, some system related issues include the level of centralisation of control of job release; the important variable to monitor, e.g. throughput rate, WIP level or cycle time; and the appropriate system objective, e.g. to minimise cost, minimise lead time or maximise throughput rate. The jobs (or market) related issues include whether the demand is relatively predictable or variable; whether the demand is dependent or independent by nature, or individually or collectively planned and produced; whether the planning focus should be more on capacity synchronisation or stock availability; whether the items made are commoditised or customised; the general material flow (VATIX) structure (Finch and Cox, 1989; Umble, 1992); and whether the product is functional or innovative.

The bottom-right corner is left as is because the products placed in this category are continuously manufactured and are hardly differentiated from each other (e.g. fuel). The order penetration point is usually at the end since every customer buys about the same product. The similarity makes demand aggregation possible, leading to steadier pattern of demand. Since product is non-differentiated, they are produced in bulk and the MFCT does not need to account for items individually. Most products here have the typical I or V shaped flow. Process is usually fully automated and setup cost may be quite significant. Products are usually functional and highly substitutable, implying making to stock, hence the need for forecasting; but low demand variability also implies low forecast error. As noted by Zipkin (2000), this is the type of environment where lot sizing and some safety stock is typically applicable. Individual end items are usually centrally controlled using rate-based techniques, and their production levels are more predictable. While capacity planning is important, the main focus is usually on inventory since capacity utilisation does not vary wildly, the general capacity level is more important than capacity buffer, and safety stock is usually more useful than capacity buffer due to the extremely short customer response time relative to manufacturing lead time. Consequently, routine production using forecast information with some safety stock to absorb variability is good, hence, models of periodic inventory review would be good in this case. Base stock policy and general reorder point models may also be used in certain instances. Availability of material when needed is an important service performance measure of such system, and the cost of making it available is crucial for competitiveness, hence, high utilisation of manufacturing assets is important for aligning market and operational strategies.

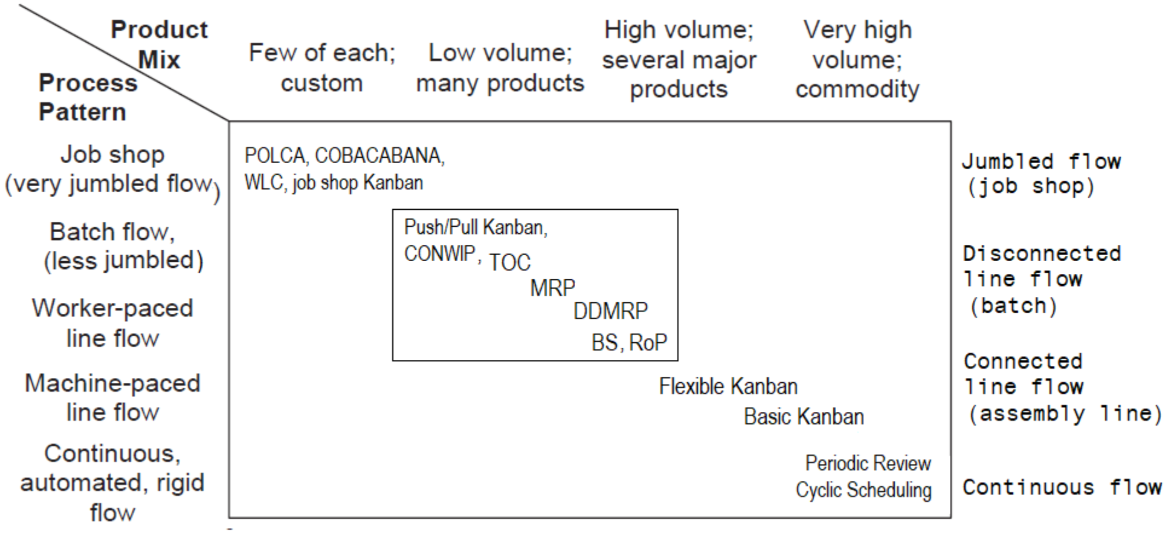

Figure 3. Expanded alignment of MFCT with process types

The next section machine paced line flow producing highly standardised discrete products of high volume relative to capacity, fairly stable demand with little variability, and very low variety. Such system may produce a number of simple end items assembled on the same line in a repetitive manner, or standard parts that are used assembling some finished products. The objective of the system is usually to ensure availability of item as at the time of request, hence, material buffers may be used to absorb the little variability that might be present. The items produced are controlled at individual level periodically using backflushing (rate-based control), and the control is decentralised, hence, cards are labelled for individual items, and material availability is more important than flexibility of production system. Most facilities used for this production are laid out in series (I-plant) for series of lines building towards the final assembly (T-plant) like in a typical car manufacturing. This is ideal for the classic JIT/Kanban environment. Here also, availability of material when needed and the cost of making it available is crucial for competitiveness, hence, high utilisation of manufacturing assets is important for tactical alignment. Pure Kanban may be quite suitable here.

Immediately above the repetitive section on the diagonal is the man paced line flow system, offering more varieties, lower general output level relative to the maximum capacity, still with the goal of high utilisation, usually achievable through process automation in a high-volume manufacturing, rather than an assembly system. Such systems share characteristics with both batch and repetitive production systems, (see Chaudhury and Whinston, 1990). Usually, there is the need to adjust to varying demand levels, a fairly high volume of production, and the need for more varieties than in pure repetitive systems unlike pure assembly systems. Kanban is still implementable, but needs to be supported by either flexibly managing the stock level of items, maintaining higher safety stock, or some combination of both, to absorb higher demand variation than observed in the steadier repetitive system. Control of stock may still be at individual item level in a decentralised manner with cards labelled for individual items, and the planning focuses more on inventory than capacity. The interaction between the number of varieties allowed in the system and variation in demand level tends to impact on the level of utilisation attainable in such systems. Availability of material when needed is also crucial for competitiveness, but cost becomes less important compared to the two previous systems. More emphasis needs to be placed on and job scheduling and its impact on capacity due to changeover. The flexible Kanban and some batch procedures may be suitable in this category. Silva et al (1989) stated that drug manufacturing and steel rolling with customisation may also be in this category.

Next up the diagonal on the matrix is the job shop environment with the need for a significant number of variety and lower volume. Many jobs share capacity frequently and it is sometime uncertain if some jobs will be produced or not. Techniques like CONWIP should be well suited to this category. A characteristic of CONWIP worth mentioning here is that the cards are item-neutral, hence, the cards are not attached to a particular item, but available for whatever item should be scheduled, else, there would have been the need to have so many cards, many of which would not be used frequently. In addition, stocks are not maintained for individual items at each station for a pull, but rather, any item scheduled is pushed through till the end of the line. This makes it possible to start treating inventory of items in aggregate terms. While control may still be decentralised, the number of control points is significantly reduced. Planning focus is getting balanced between inventory and capacity, receiving more attention than in the flow shop. Most of these properties of CONWIP are also shared by many push/pull Kanban and TOC systems, hence, they have been put together.

The top-left corner is the most flexible end of the matrix and contains the MFCTs most suitable for typical job shop, called few of each. There is the need to cater for a lot more varieties with very low volumes, and the possibility of flow combinations is almost infinite. This makes it almost impossible to dedicate cards to materials produced. The cards that are used are usually linked to processing resources or operations. This way, the cards are used to balance loads and time job release based on actual events on the shop floor. The control may be done centrally as in COBACABANA or locally as in POLCA. In this group is also placed the job shop and generic variants of Kanban as they work in similar manners. In this end of the matrix, the planning effort goes more towards capacity than inventory. The important measure of performance here is the job cycle time. WIP is also important, but its effect is usually reflected in the cycle time. There is usually multiple changeover in this system, hence, studying this system should consider this, and hence, the implication of the job priority rules on the system performance. The Kingman's equation is important here and utilisation needs to be monitored due to the high variability (Hopp and Spearman, 2008).

We now discuss, particularly, the middle portion having the box. The first thing is to note is that as we progress from the two extremes, the demarcations get fuzzier, and applicable techniques overlap significantly towards the middle. Next, the base stock technique is placed towards the lower end of the box as it is a stock-based technique. It can be seen from literature that it is usually integrated with Kanban, CONWIP, TOC and MRP variants in diverse ways. RoP is also placed within this box because it is very suitable for intermediate-volume flow, suitable for batch production (Stevenson, 2014 pp 692). Also, MRP is placed in the same box because it is readily adaptable mainly to all types of flows within this area. This point was made by Silver et al (1998, pp 619) when they pointed out that MRP thrives where multiple items are planned simultaneously and where these have complex bills of materials. In typical job shops (top-left) dominated by small businesses and where there are no complex bills, or pure flow shops (bottom-right) where there are simple BOMs and the line behaves like a single station in unison, the power of BOM explosion of MRP is usually not needed. The DDMRP was also designed to be able to work under a large variety of situations, but is not ideally suited to either pure flow or job shop conditions, hence, placed within the box as well.

6. Potential consequences of the matrix

It is worth reiterating some patterns observable in the matrix and the implications on choices made for planning and control purposes.

- Firstly, volume driven items (typical of bottom-right) emphasise inventory control once sufficient long-term capacity level is established, hence, cards are tied to individual stock items. As we move up the diagonal, cards get tied to product groups or aggregates, gradually balancing need to control inventory and capacity, and as it gets to the top-left, the emphasis shifts more to capacity management. This is consistent with the view of Webster (2008) that inventory, capacity and time are three views of organisational resources that receive different emphasis depending on the market's competitiveness pressure and organisational strategy;
- Secondly, the relative importance of making-to-order (pull), a making-to-stock (push) or decoupling somewhere in between is context dependent. Moreover, most control strategies need to make use of both to different extents depending on the context and the strategy of the organisation, and this is part of the balance the planner needs to find;
- Thirdly, not every technique should be compared to the other because their performances would depend on the context. For instance, comparing pure Kanban system to POLCA can have varying results, depending on the manufacturing context and the performance measure selected. Kanban will likely perform better towards the bottom-right and CONWIP towards the top-left. It is more useful to compare techniques within a cluster to one another, for instance, POLCA versus COBACABANA, or CONWIP versus push/pull Kanban, will likely produce more consistent results in almost all scenarios than POLCA versus Kanban;
- Fourthly, it is more important to think of how to take advantage of the different techniques to create more powerful solutions, than modifying one to fit all scenarios for instance, blending the power of MRP push and BOM explosion with the close local control of the card-based techniques will likely produce better result

than trying to use only one technique under every condition. This is even more important as we consider the region within the rectangular box in the matrix where pure flow or job shop situations do not obtain;

- Next, it is possible to use any of the control techniques to manage job implemented in any of the matrix. The reason for seeking alignment is because of the likelihood of improved performance with better alignment;
- Finally, positioning the preferred control technique in a particular section of the matrix is an important issue related to proper alignment (global choice), but selecting a member of the group to use is more of organisational policies and strategy (local choice). For instance, considering either CONWIP, TOC, DDMRP or some variants of the Push/Pull Kanban group for a typical job shop environment (having many item varieties but fairly low volume for each item produced) will be related to alignment, but deciding on which variant to use (e.g. should base stock be allowed, where and in how many places should the base stock be positioned, should push be made to the end of the line or some places within the line, should flexibility be allowed in the number of cards etc) would be related more to strategy and policy, and more evaluation effort is better spent analysing the local than the global choice since the global choice is guided by alignment. An application is of this logic is discussed next.

6.1. Application

Consider a company manufacturing small batches of products for a number of repeat businesses. The company should select the group having CONWIP and others as this is an alignment decision. To select which of the techniques would likely perform well, they need to ask a number of other questions. For instance, how valuable are the product being made on the average?. If the product is highly valuable, it is probably more reasonable to avoid too much stocks (holding cost), and consequently, one should prefer a technique that keeps stock in strategic places rather than in many places. This probably means not favouring a technique like concurrent Kanban. Another question may be what drives sale in the market: quick availability of item or keeping to promised delivery date?. If very quick replenishment is very important, a technique that keeps inventory at the end of the line like CONWIP, periodic pull Kanban or simplified TOC might be more suitable. Another relevant question may be how many products would this system need to make simultaneously?. If there are many products, then, one may prefer CONWIP with generic cards, or simplified TOC. Asking further if card control is preferred over monitoring of buffer level? and answering yes suggests preference for CONWIP over simplified TOC. This is a small example, but this questioning approach has helped to narrow the number of options to be considered for subsequent rigorous testing for performance and extreme behaviours using appropriate models, e.g. intensive simulation modelling. A rigorous evaluation of a set of few techniques left after such reduction of techniques will likely lead to a like for like comparison, rather than testing everything against everything, which may likely make intensive comparison almost impossible.

7. Conclusion

This work proposes a framework for grouping the numerous MFCTs into a few groups and mapping the groups to the product-process matrix. This enables decision making about the choice of MFCT selection for controlling the manufacturing process under defined conditions. It also guides the decision on which metrics should be more suitable for comparison the performance of two or more MFCTs under a given condition. It builds upon the template model of 1998 to map the diverse manufacturing control techniques to appropriate processes. It uses a two-level decision-making process to first select an MFCT group that aligns the MFCTs and process types, and then answers relevant questions related to organisational preferences to narrow down on particular MFCTs of choice.

The study limitation includes the further review of the grouping and classification of the techniques. While effort has been made to appropriately place each technique in a group and map each group, there may be some other ways of grouping the techniques, and it is suggested that further research should be done in this regards.

Moreover, this study did not empirically test the comparative performance of the MFCTs in each group or between the groups based on their identified similarities or differences. It only proposed what may likely be. This area may be investigated further by creating appropriate scenarios and developing models (mathematical, simulation etc) using different parameter value ranges, and testing those considered more suitable or otherwise for each group.

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