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Jan Riezebos

Department of Operations, Faculty of Economics and Business
University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands
Tel.: +31 50 363 4853; Fax: +31 50 363 2032; E-mail: j.riezebos@rug.nl

Abstract

POLCA is a material control system designed for Make-To-Order or Engineer-To-Order companies. These firms have to cope with a high variety of customized products, and strong pressure to provide short throughput times. POLCA constrains the amount of work in progress on the shop floor in order to achieve a short average shop floor throughput time. Earlier work has shown that the POLCA system has the capability to reduce both the average shop floor throughput time and the average total throughput time, but it is only effective if the POLCA system has appropriately been designed. The design of the POLCA system is therefore being investigated and discussed in this paper. We give an extensive literature review and give attention to the authorization mechanisms of POLCA, the design of control loops, the route-specific capacity signals (POLCA cards), and specific facilities needed to use the POLCA system in practice. Finally, we report on the design of a POLCA system in practice, the first complete implementation of POLCA in The Netherlands, and present the quick scan that was used in the design of the POLCA system for this SME.

Keywords: POLCA, MTO, Pull, Material control system

1. Introduction

Firms that offer customized products cannot produce these items in advance. They often face huge problems with throughput time control, as demand for capacity fluctuates over time. Some of these Make-To-Order (MTO) firms will be able to use large lead times for these products, but most need to excel in throughput time management and control in order to survive.

Material control is an important part of the chain of tools used in realizing short throughput times. It regulates the flow of goods on the shop floor. This includes the authorization to start a job, release of new material to the shop floor, setting priorities for jobs that are waiting to be processed, and initiating the start of succeeding activities, such as transport, quality control, et cetera. Pull systems are a special type of material control systems. They aim to control throughput times by constraining the release of jobs to the shop floor. Well known pull systems such as KANBAN are designed for Make-To-Stock (MTS) situations, as they use small intermediate stocks. In these pull systems, cards or containers (bins) are directly related to a specific product type. E.g., an empty bin should be filled with exactly the same product type as before. For MTO companies, such a direct relation between signal and product type is not useful. MTO companies face a much higher product variety, which would lead to a very large number of different bins or intermediate stocks. Next, the repetition of identical jobs is not that frequent, which would lead to low cycle times of a bin once it has been filled. The combination of both effects would result in large work-in-process inventories (WIP).

Some pull systems seem to be applicable in MTO companies (Stevenson et al., 2005). POLCA is one of them. It has been introduced in Suri (1998) in his book on Quick Response Manufacturing, and is based on principles that can also be found in the KANBAN system (Sugimori et al., 1977) and the CONWIP system (Spearman et al., 1989). However, POLCA aims to improve these systems in order to make the principles better applicable in MTO situations as well. Literature has given attention to the design of pull systems such as POLCA, but mainly in MTS companies. Design issues resulting from comparison studies of pull systems in MTO situations are not well addressed in literature. Fernandes et al. (2006) did compare the performance of POLCA, MRP and Generic POLCA (GPOLCA), but for an MTS system. Germs and Riezebos (2008) compared POLCA with CONWIP and m-CONWIP in an MTO system. Krishnamurthy et al. (2004) compared several push and pull systems, but did not give explicit attention to design issues of these systems. The only paper that gives a more elaborate overview of design issues is the recent paper of Vandaele et al. (2008), who discuss the design of a load-based POLCA system for an MTO case study. However, they focus on rather specific planning-level design issues for this case and develop a computerized version of POLCA. We aim to provide a more general overview of design issues in a POLCA system and give attention to the tools that have been developed and can be applied in POLCA implementations in MTO companies. This results in a proposal for a quick scan that can be applied to design a POLCA system.

The structure of the paper is as follows. Section 2 provides a literature review. Based on this review, Section 3 will identify the main design issues of a POLCA system and proposes tools that are needed for supporting these decisions. Section 4 discusses the effectiveness of POLCA in MTO systems, based on a case study at the first firm in the Netherlands that has implemented POLCA. Finally, Section 5 concludes.

2. Literature review on characteristics of the POLCA system

POLCA is an acronym for **Paired-cell Overlapping Loops of Cards with Authorization** (Suri, 1998). It is a material control system that regulates the authorization of order progress on the shop floor in a cellular manufacturing system. POLCA controls the flow of work between cells. The main problem of planning in such cellular systems is related to insufficient synchronization of the processes between these cells, resulting in waiting times between the completion of a job in one cell and its start in the next cell (Riezebos, 2001). At the same time, another cell might face a lack of work to be done, which we denote as unbalance. POLCA not only aims to increase the speed of job transfer between cells, but also to reduce these unbalances in the system. In order to achieve this, it uses overlapping control loops that cover subsequent segments of the job routing. POLCA uses a visual signal (cards) to authorize the progress of an order. These visual signals are often denoted as *Polca's* (in order to avoid ambiguity of terms, we use italics if we refer to the visual signals and capitals if we refer to the system).

POLCA not only operates at the shop floor itself, but does also decide on the release of orders to the shop floor. It can affect the timing of release through the regular authorization mechanism (*Polca's*) as well as through an additional authorization mechanism, so called release lists. The decisions when and what to release to the shop floor have both a high impact on shop floor throughput time and delivery performance (Land and Gaalman, 1998; Germs and Riezebos, 2008). If jobs are released too early, they often wait a long time on the shop floor before being completed. This enables the shop floor employees to allow low-priority orders to be produced before high-priority orders. This behavior will lead to a higher standard deviation of lateness, with possibly negative effects on due date performance. By limiting the amount of work on the shop floor and regulating the inflow of work, POLCA aims to achieve short and stable throughput times.

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Most information on the POLCA material control system stems from the book of Suri (1998) and papers that have been published by Suri in QRM conference proceedings on POLCA (e.g. Suri 2003, Suri and Krishnamurthy, 2003). Other important sources of information are the proceedings of the tri-annual Group Technology / Cellular Manufacturing world conferences (Hernández and Süer 2000; Sormaz and Süer, 2003; Riezebos and Slomp, 2006). Journal and conference papers on POLCA or variants of the POLCA system are e.g. Krishnamurthy et al. (2000), Tien et al. (2004), Krishnamurthy et al. (2005), Suri (2005), Fernandes et al. (2006), Vandaele et al. (2008), Germs and Riezebos (2008). Other papers give attention to POLCA in a comparison of various suitable approaches for production planning, e.g. Zhou et al. (2000), Lödding et al. (2003), Ryan and Choobineh (2003), Krishnamurthy et al. (2004), Stevenson et al. (2005). We know from discussions with researchers that several case studies have been performed, but the number of published case studies is very small. Finally, many websites of research centers, consultancy agents, and MTO firms that apply POLCA nowadays provide descriptions of POLCA.

Table 1 provides an overview of the above listed sources on POLCA research, The first column categorizes the type of contribution that is made. It appears that most contributions describe or analyze the POLCA system from a theoretical perspective instead of an empirical perspective. Two types of theoretical perspectives for analyzing the POLCA system have been used. Some contributions extend the initial description of Suri (1998) on POLCA, using theory from the related fields that have been listed above. For example, Vandaele et al. (2008) use a queuing theoretic perspective on determining the required cell throughput times given the (expected) demand during the next three months. Based on this internal lead-time setting method, they determine the number of *Polca's* in the system. Other contributions compare several material control systems and try to assess the area of applicability or the effectiveness of POLCA amongst other available material control systems. The main conclusion from these studies is that POLCA has to be considered as a promising approach for MTO-firms, due to its ability to control the material flows in shop configurations that tend more towards the job shop type with many different routings between the cells or work stations. For this type of configuration, known pull systems such as CONWIP and Generic KANBAN are not well equipped (Krishnamurthy et al., 2004; Fernandes et al., 2006), while at the same time use of detailed scheduling techniques may not be appropriate due to its complexity and reliance on the accuracy of the information systems (Stevenson, 2005).

There is clearly a lack of literature on well-elaborated case studies that describe and analyze POLCA system implementation. In the proceedings of the QRM workshops, several successful implementations of POLCA are discussed, but to our knowledge these implementations have not been company wide, but limited to some segments of the production system. Vandaele et al. (2008) describe a case of a Belgium firm for which they designed a POLCA system. This case is very instructive, but no details are provided on the actual implementation. Hence, there is still a lack of insight in the implementation problems and barriers that are encountered in design and implementation. Note that the same problem holds for research on CONWIP. Framinan et al. (2003:260) reports on CONWIP application studies and lists 19 papers that have analyzed the applicability of CONWIP, but only 4 of them did actually report on a real application!

Research on POLCA brings together various fields of interest. First of all, research on throughput time control and the relation with higher level planning systems. Next, research on cellular manufacturing and, more specifically, planning problems in cellular manufacturing. Finally, research on shop floor improvement. Table 1 does also categorize the point of view from which the various contributions to POLCA system design originate. We denote the first perspective as PPC (production planning and control), the second as CM (Cellular manufacturing) and the third as Improve (at the shop floor). The table shows that most contributions are provided from the perspective of PPC design. Hence, there is stronger focus

on understanding the basics of throughput time control and planning system design than on the design of POLCA loops, cells, and the way actual improvements can be realized at the shop floor. However, the latter two perspectives are not obvious at all if the POLCA system has to be designed. Many choices have to be made that have a high impact on shop floor operation and its effectiveness. For example, how to deal with cells that operate in different shifts, bottleneck cells, et cetera. In section 4 we will elaborate on these aspects when discussing the case study that has been performed, but first section 3 will discuss the last columns of Table 1, the methods and tools that have been developed for POLCA.

<<INSERT Table 1 ABOUT HERE>>

3. Methods and tools for POLCA system design

POLCA uses various tools and methods to facilitate managers, planners and shop floor employees with the task of improving throughput time control. We categorize the various methods and tools according to the next three categories:

- **Routing:** Route-specific cards that have to be attached to jobs on the shop floor to authorize order progress;
- **Release:** Release lists that show the earliest starting times of orders in parts of the cellular system.
- **Facilities:** Facilities to enable operating the system in various circumstances.

The last column of Table 1 lists the classification of papers on POLCA based on these categories. From this it becomes clear that the category Routing has received relatively more attention than the other categories Release and Facilities. However, even if two publications both address the same category, the extent to which it is being addressed may strongly differ. This section will describe the main methods and tools for POLCA system design that are described in literature. Where appropriate we will point to differences or similarities with CONWIP design.

3.1 Routing

The POLCA material control system does not provide product-specific, but route-specific control of the material flow. Product-specific control is, for example, provided by KANBAN and two-bin pull systems. Such systems signal the requirement for a refill of a stock position for a specific component or SKU. Krishnamurthy et al. (2004) has shown that such systems are not effective in case of MTO companies. The main reason is that the number of products in the assortment of these firms is generally much higher than in MTS firms, while at the same time the frequency of demand of these items is much lower. Together, these effects lead to a strong inefficiency of such pull systems in case of MTO companies.

An alternative for product-specific control is product-anonymous control. Several systems have been developed that provide product-anonymous control, such as CONWIP (Spearman, 1989) and Generic KANBAN (Chang & Yih, 1994). The idea of product-anonymous control is that the material control system only signals the need for releasing a new order to the shop floor irrespective of the actual product type.

POLCA further elaborates on this type of signal by introducing route-specific control of the material flow. Route-specific control is a special kind of product-anonymous control. However, there is an important difference, as the control system takes into account the availability of capacity in the next parts of the routings of the orders that are available for release. Hence, essential information on the remaining routing of the order is taken into account when deciding on the release or progress of an order at the shop floor.

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Literature is not uniform on the way this route-specific control should be implemented in POLCA. Two main issues have to be addressed:

- 1. Design of the visual signal
- 2. Design of the control loops

The visual signal (*Polca*) should provide information to the shop floor employees on route-specific characteristics of the order to which it is or should be attached. Suri (1998) suggested to provide the following information:

- (a) Originating cell (From);
- (b) Destination cell (To);
- (c) Card identifiers (Company name, serial number of card, et cetera).

The signal is provided through a card similar to a *Kanban*, where at the left side the information on the from-cell and at the right side the to-cell is listed (Suri, 1998:249).

Pieffers and Riezebos (2006) have suggested to increase the visual contents of these cards by using color-coding to identify the cells. If every cell has a unique color, each card consists of two colors: one for the from-cell and one for the to-cell. Employees of a cell can easily identify the direction of the card-flow. If their color is listed in the to-column, the card should be returned to the originating cell after completing the operations in the current cell. If their color is listed in the from-column, the card should remain attached to the order and be send to the to-cell after completing the operations in the current cell.

Vandaele et al. (2008) list several different types of cards / visual signals that are available for providing this type of information. They choose to use an electronic signal, mainly because of the shop floor layout in their case study. Electronic signals are shown on screens at the work stations and the operator can attach and detach these signals to orders in his system. The main advantage of electronic signals is that there is no information delay caused by the transportation of the visual signal if it is detached from an order. Other advantages are the avoidance of card damage and loss, mistakes when attaching or detaching cards, search time in order to localize cards, and easiness of changing the number of cards in the system by the shop floor manager or planner. The main disadvantage is the loss of connection between the flow of material and information, which might lead to less confidence in the system by the employees. Insights from lean manufacturing indicate that the strength of that connection often determines the success of a control policy.

Another important element in this discussion seems to be the possibility for employees to interpret the visual signal. This might be rather trivial, but nevertheless it is often overseen when designing systems for shop floor management. For example, color-coding does not work for color-blind people. The percentage of men that cannot distinguish red from green is for blank men 8%. Women suffer less from red-green color vision problems (< 0.4%) (Hunt, 1987). Written information is only accessible if employees understand the icons or letters used. As the number of analphabetic people in industry is still rather high, especially in some countries, a mixture of information types seems to be more appropriate when designing a visual signal. The same holds true for people that are “digibetic” (i.e. cannot easily use a computer to interpret, attach or detach signals). Finally, the way information is interpreted depends on the place where the information is provided on the visual signal. If information on the from-cell is provided at the left hand side of a card and on the to-cell at the right—hand side of the card, people that are used to read from right to left might become confused.

<<INSERT Figure 1 ABOUT HERE>>

The second issue that has to be addressed is the design of the control loops. POLCA uses overlapping loops. <<INSERT **Figure 1** provides a scheme for the operation of a POLCA system with such loops. The system shows three cells, *A*, *B* and *C*. Each cell has an internal queue where jobs that are allowed to start processing wait until capacity is available. The average cell throughput time is $\frac{1}{\mu_i}$ with index *i* indicating the cell. Jobs that have to visit these cells arrive with an arrival rate (= demand rate) λ . However, the POLCA system introduces an assembly waiting time before a job can enter a cell. First a suitable *Polca* needs to be attached to the job in order to signal the authorization to start processing in the next cell. What *Polca* should be attached depends on the routing of the job. The job in <<INSERT **Figure 1** needs to be processed subsequently in cells *A*, *B*, *C* and *D*. The first *Polca* that should be attached is therefore the *Polca* that circulates between the first two cells in this routing *A* and *B*. If no such *Polca* is available in the queue $Polca_{AB}$, the job will wait in queue Q_{AB} . As soon as an item is available in both these queues, the *Polca* will be attached to the job and continue to the internal queue of cell *A*. After completing processing in cell *A*, both the job and the attached $Polca_{AB}$ will move to cell *B*. But before they are allowed to enter the internal queue of cell *B*, first an additional *Polca* has to be attached. That *Polca* circulates in a new control loop between cell *B* and the next cell in the routing of this job. In the example this is cell *C*, so a $Polca_{BC}$ need to be attached. The job with $Polca_{AB}$ still attached therefore enters queue Q_{BC} if no such *Polca* is available in queue $Polca_{BC}$. Only if an item is available in that queue can the job proceed with now two *Polca*'s attached: one $Polca_{AB}$ and a $Polca_{BC}$. After completing the operation in cell *B*, the $Polca_{AB}$ is detached and returned to its originating cell *A*. The job proceeds to cell *C*, where the story of waiting on a suitable *Polca* before it can enter the cell starts over again.

The rationale of this procedure is that a job will only be allowed to ask for capacity in a cell upstream (e.g. cell *A*) if it is expected that the required downstream cell (Cell *B*) will be able to continue processing afterwards. If cell *B* would face a breakdown, no $Polca_{AB}$'s will be returned to cell *A* and no authorization is given to start new jobs that need to be processed on *B* after completing cell *A*. If cell *B* is a bottleneck, probably a lot of $Polca_{AB}$'s are waiting in Q_{BC} , as the internal queue of a bottleneck cell will often be lengthy. Hence, no new jobs will be released that have *B* in their routing until another job on *B* has finished and the $Polca_{AB}$ detached and returned to its originating station. As cell *A* cannot proceed with the jobs that have to visit *B* afterwards, but have not already a *Polca* attached, it will stay idle and –in accordance to the lean manufacturing paradigm- help the next stage in solving their problem. Alternatively, it might select another job that have a different cell than cell *B* as immediate follower in their routing. Orders selected will therefore for the moment bypass cell *B*, which has important benefits for shortening average throughput times. We denote this control behavior workload balancing.

Note that <<INSERT **Figure 1** does not indicate the number of *Polca*'s that circulate in a single control loop. However, it is obvious that if this number is zero, no jobs will ever be authorized to start production. Similar, if this number approximates infinity, the probability that a job will have to wait because there is no *Polca* available approximates zero. Suri (1998:256) provides a simple formula based on Little's law (Little, 1961). Little's law states that the average throughput rate of a system equals the quotient of the average number of elements in the system and the average time an element is in the system. The formula that Suri provides uses *Polca*'s as elements in the system. Following the notation that we introduced, the number of $Polca_{AB}$'s is denoted as n_{AB} with:

$$n_{AB} = (L_A + L_B)g\lambda \quad (1)$$

where λ equals the throughput rate of jobs that have to visit cells A and B subsequently, and $L_i = \frac{1}{\mu_i}$ is the average (job) lead time in cell i . If n_{AB} is a fractional number, it should be rounded up to the next integer value $\lceil n_{AB} \rceil$.

Formula (1) is not a correct application of Little's law. The main problem is that the elements of the left hand side ($Polca_{AB}$'s) are not identical to the elements at the right hand side (jobs). This problem mainly affects the first term of the right hand side, the estimate of the average time an element is in the system. $Polca$'s circulate in the system, so they should be returned to the originating cell before they can start a new cycle. So instead of using the average lead time of jobs, we should use an estimate of the average cycle time of a $Polca$. This average cycle time will also include the waiting time of a $Polca_{AB}$ in the queues $Polca_{AB}$ ($W_{Polca_{AB}}$) and Q_{BC} ($W_{Q_{BC}}$), and the average time that is needed to transport the card in the system (T_{AB} between cells A and B and T_{BA} back from cell B to cell A). As a $Polca$ will only start a new cycle if it is attached to a single job, and if we assume that only one $Polca_{AB}$ will be attached to a job that has to visit cells A and B subsequently, the throughput rate parameter of $Polca_{AB}$'s equals the throughput rate of these jobs. Hence, we propose to use:

$$n_{AB} = \left(L_A + L_B + W_{Polca_{AB}} + W_{Q_{BC}} + T_{AB} + T_{BA} \right) g \lambda \tag{2}$$

Note that formula (2) is only valid if there is no limitation on the release date of jobs to the various cells. Suri (1998:253) does describe the possibility to control the earliest release dates of jobs in the various cells in order to provide the planner increased control. How this information is presented to the cells will be discussed in the next subsection, but here we would like to stress the consequence it has for the determination of the required number of $Polca$'s. The increased flexibility of the planner comes at a cost in terms of longer average throughput times of jobs, as it introduces additional waiting times in **<<INSERT Figure 1**. Hence in case of authorization signals that specify the earliest release dates of a job in a cell, **<<INSERT Figure 1** transfers to **<< INSERT Figure 2** and formula (2) transfers to formula (3).

<< INSERT Figure 2 ABOUT HERE>>

$$n_{AB} = \left(L_A + L_B + W_{Polca_{AB}} + W_{Q_B} + W_{Q_{BC}} + T_{AB} + T_{BA} \right) g \lambda \tag{3}$$

The only change compared to formula (2) is the inclusion of the term W_{Q_B} between the brackets, i.e. the average waiting time of the job with a $Polca_{AB}$ attached on its earliest release date in cell B . Note that we do not need to include the time a job waits in cell A , as in that case the $Polca_{AB}$ will not have been attached to the job.

In practice, we often see that the latter five terms between brackets are replaced by a term $\alpha (L_A + L_B)$, with safety allowance $\alpha > 0$, which leads to the expressions:

$$n_{AB} = (L_A + L_B) g (1 + \alpha) \lambda \tag{4}$$

$$\alpha = \frac{W_{Polca_{AB}} + W_{Q_B} + W_{Q_{BC}} + T_{AB} + T_{BA}}{L_A + L_B} \tag{5}$$

However, we should note that there is no reason to assume that the ratio between the upper and lower side of this quotient is always similar for different combinations of cells. Hence we prefer to estimate the components of formula (3).

Suri (1998:256) also introduced the notion of a *quantum*, i.e. the maximum amount of material that should accompany a single card. Jobs that exceed this limit need more than one *Polca* in order to be authorized to start processing in a cell. Vandaele et al. (2008) propose a load-based POLCA system that does not use cards, but electronic signals based on the actual workload released in a loop. This avoids the type of rounding effects that occur when using quantum cards. However, using quantum cards is still much better than using a limit on the number of jobs in a loop, as can be concluded from workload control theory (e.g. Bergamaschi et al., 1997; Land and Gaalman, 1998). In MTO job shop configurations, the correlation between work content and throughput time is much stronger than the correlation between number of orders and throughput time. Still there may be valid reasons to not use a quantum. For example, easiness of use and transparency of the system might lead to the use of a POLCA system with no quantum at all. Germs and Riezebos (2008) show that the POLCA system can have effective work load balancing capability even in this situation.

From this discussion we see that the POLCA system enables control of work order progress based on information of routings between cells in a loop and a measure of WIP that already has been released in that loop. The design of a POLCA loop does have to give attention to the cells that are included in a single loop, as this affects the information content on routings in the POLCA system. Moreover, it should give attention to the number of *Polca*'s that will circulate in that loop and the work load associated with a single *Polca*. When discussing the case study results, we will further explore this issue.

Note that these design issues are similar for CONWIP systems. In CONWIP, a card also signals the release opportunity of a new order. As long as total processing times of orders at operations are similar, there is no need to convert orders to workload in hours. The basic CONWIP system (Hopp and Spearman, 2008:489) is therefore as indifferent as POLCA with respect to the decision how much of each item will be in the WIP inventory. Variants of the CONWIP system that allow for the introduction of quanta have been developed as well (see e.g., Hopp and Spearman, 2008:490-500; Framinan et al., 2003). The important difference between POLCA and CONWIP is in the way routing-variety is being handled and the loops overlap. CONWIP designs longer non-overlapping loops for every different routing that can be encountered. If loops become too long, segmented or tandem CONWIP loops can be used (see e.g., Bonvik et al., 1997; Gaury, 2000). POLCA uses very short loops between two cells and includes the cell details on the visual signal. By chaining the various POLCA loops, each possible job routing can be controlled. The POLCA loops overlap, as one job generally has two cards attached when being processed. This results in improved signaling capability of capacity problems in subsequent parts of the routing (Suri, 1989).

Concluding, a POLCA system uses both visual signals and control loops to implement an effective routing mechanism that enables a firm to reduce average shop floor throughput time.

3.2 Release

The second category of tools and methods in the POLCA system supports the release of jobs to the shop floor. Although the authorization mechanism of the cards receives generally most attention in a POLCA system, the release list provides an equally important authorization mechanism. However, this mechanism is an instrument of the planner, i.e. it allows the planner to directly influence the release of jobs to the shop floor and the progress of jobs that already have been released to the shop floor. In the POLCA system, this is accomplished by enabling a planner to specify an earliest release date of a job in each cell. Therefore, the influence of the planner is not complete, but only partial. He or she cannot affect the actual starting moment of a job, as this is regulated by the *Polca*'s and the shop floor employees.

<< INSERT Table 2 ABOUT HERE>>

Other pull systems, such as CONWIP and KANBAN, do not have such an authorization mechanism at all (Framinan et al., 2003). They only have a release list in order to prioritize the release of jobs to the shop floor. Hopp and Spearman (2008:470) conclude that a simple sequencing mechanism to support CONWIP in case of a highly complex job shop is not useful. They suggest using instead a type of capacitated material requirements planning.

POLCA uses cell-specific release lists. It lists all jobs that according to their routing will have to visit the cell and specifies an earliest release date of this order in this cell. An example is presented in << **INSERT Table 2**. All jobs that are authorized to be released according to the specified earliest release date are listed above the red line, the others below. Note that some of the jobs above the red line cannot be started because the material has not yet been received from an earlier cell in its routing or from the warehouse.

In order to determine the earliest release dates of a job in a cell, the planner might apply backward calculation from the due date of the job. For each cell that is included in the routing and each stock point between two cells both the average throughput time and the standard deviation of throughput time can be calculated. By summing the average throughput time of the remaining part of the routing and including a buffer time to compensate for the variation, the planner can estimate the earliest release time in a cell. The problems that are faced when applying this procedure in practice are due to the unavailability of reliable data. Most firms do have an ERP system with information on the setup times of machines and (estimated) processing times of jobs at these machines. However, this information is not sufficient to determine the main component of cell throughput time, i.e., the waiting times within the cell. The reasons for these waiting times are unavailability of materials and/or capacity at the moment the job arrives. The probability of waiting on capacity increases if the utilization of the machine has to be higher. ERP systems normally neglect the sensitivity of throughput times for changes in utilization levels. They simply use standard lead times and use large buffer times to accommodate for variation and errors. The POLCA system copes with this problem in two different ways. First, it takes into account that the utilization of cell might fluctuate over time. POLCA determines the expected cell throughput times based on the expected work load that a cell has to process within a certain time fence. Next, it determines the buffer time at cell level instead of at operation level. In that way buffer times are smaller. Although POLCA proposes some improvements on standard ERP procedures with respect to lead time offsetting, Lambrecht et al. (1998) have described how to apply a capacity based lead time offsetting procedure. Vandaele et al (2008) use this ARP (Advanced Resource Planning) module to determine expected cell throughput times, buffer times, and the number of *Polca's* that have to circulate in a loop between two cells.

The use of an additional authorization mechanism, such as cell-specific release lists, will increase the shop floor throughput time of some jobs. It is unclear how this affects the average shop floor throughput time. The main reasons for introducing this mechanism are therefore focusing on achieving other performance indicators. For example, a planner might aim to prohibit cannibalization of components inventory, which might occur if cells start too early with orders that have enough time before they are due. The same holds true for using scarce capacity. In both cases, the planner may prefer some jobs to wait in order to prioritize the progress of other jobs. This might improve due-date related performance measures (e.g., tardiness or lateness), but it does not need to have a positive influence on average shop floor throughput time.

3.3 Facilities

One of the essential elements of pull systems that contribute to their success is the strong connection of the production planning & control system and the actual situation at the shop floor. The system quickly reacts if circumstances at the shop floor change, i.e. if a cell completes processing of a job or a machine breaks down. However, in some situations extraordinary circumstances occur that cannot easily be handled through the pull system. We denote such circumstances as calamities. A card-based system should include some measures that enable the users of the system to continue with the necessary operations in these circumstances without counterproductive behavior of the PPC system.

3.3.1 Safety cards

POLCA introduces safety cards in order to enable the system to cope with unforeseen events. An effect of these unforeseen events might be the decision to stop further processing of a job that is already at the shop floor. Reasons for this decision can be unavailability of components needed for this product (strikes), lack of solvability of the customer, et cetera. If the decision is made to (temporarily) stop progress of a job that already has some *Polca's* attached, these *Polca's* may be detached and send back to their originating cells, but this complicates the process of authorizing a future restart of the job. POLCA introduces safety cards in such cases. These cards look similar to the original *Polca's*, but they clearly identify the fact that they are special cards for emergency situations. The planner releases such a card whenever he/she thinks that the number of cards in a loop that still circulate is too low due to these unforeseen events. A safety card best replaces the original *Polca* that was attached to the problematic job. In that case, the regular *Polca* starts circulating again, while the safety card accompanies the problematic job. Whenever the progress of that job will be allowed, the safety card provides the required authorization to complete the job. However, instead of returning the safety card to its originating cell, the card is send back to the planner.

A POLCA system with such safety cards can only function if the occurrence of safety cards is limited. We expect that the number of safety *Polca's* should be less than 10% of the regular number of *Polca's*. The planner will generally not only release a safety card, but also start an investigation of the reason for the event to occur. This will provide useful information that might enable the system to respond differently in future.

3.3.2 Convergent routings

Another type of facility is needed in case of complex routings. We distinguish two types of complex routings: convergent and divergent routings. In practice, combinations of both occur as well. First, we give attention to the way a POLCA system copes with convergent routings.

Convergent routings occur in case of assembly. Various components and parts are required in the assembly stage and continue afterwards in a single product routing, but these components might need to have different routings in the preceding stages. An illustration is provided in <<INSERT Figure 3. Cell *A1* is an assembly cell. It uses non-standard components from both *M1* and *M2*. After completing the assembly, the product flows to *P1* for further processing. How does the POLCA system ensure that the assembly cell receives the required components from the preceding cells? And how will they signal the completion of a job to these preceding cells?

<<INSERT Figure 3 ABOUT HERE>>

This problem would not be difficult in case the components were standard and could be made to stock. However, we investigate the case of Make-To-Order companies, where

components can be product specific. Both components have to be in $A1$ in order to continue processing in $A1$. This can be formalized in the POLCA system by requiring that input cards from both cells (i.e., a $Polca_{M1A1}$ and a $Polca_{M2A1}$) have to be attached to the order as well as a $Polca_{A1P1}$ in order to start processing this job in cell $A1$, assuming that the current date is not before the earliest starting date in cell $A1$. In case of convergent structures, a job will therefore be accompanied by more than two $Polca$'s. After completing the job in cell $A1$, the two input cards return to cells $M1$ and $M2$ respectively, while the job together with $Polca_{A1P1}$ continues to cell $P1$.

As the POLCA system uses cards as capacity signals instead of product-specific demand signals, the information flow of the cards does not signal what items should be made. In case of assembly, it is necessary to co-ordinate what items to produce in the parallel cells (e.g., $M1$ and $M2$) in order to avoid the situation that one cell produces parts for job X and the next cell selects parts for job Y . This type of co-ordination cannot be done through the card system and should therefore be accomplished through the job release system of POLCA, i.e. the release list per cell and, if necessary, additional information or priority mechanisms. Hence, a release list per cell is a prerequisite in case of convergent structures.

3.3.3 Divergent routings

The question now arises whether or not additional measures are required in case of divergent routings. Such routings occur frequently in practice, e.g., in case of different packaging cells. <<INSERT Figure 4 provides an example.

<<INSERT Figure 4 ABOUT HERE>>

For cell $A1$ and $A2$ it is important to receive a relatively constant flow of work over time. High peak loads and lumpy periods are rather costly, especially in case of inflexible capacity. If the utilization of these cells is high, a fluctuating flow rate of work to the cell causes long throughput times, as the average waiting time between cell M and $A1$ or $A2$ will be longer than necessary. POLCA is designed to avoid this problem through its card system. Germs and Riezebos (2008) have shown that POLCA effectively balances workload between cells if the number of cards is determined appropriately and in this way reduces the average throughput times of jobs. This workload balancing capability is mainly apparent in these divergent structures.

However, in order to be able to select jobs in cell M for succeeding cells that have returned a card, cell M needs to receive a mixture of jobs from its preceding cell Z . It is there where a problem might occur if the regular POLCA system is being used. Cell Z is autonomous in its choice of jobs, as long as a $Polca_{ZM}$ is available and the release lists authorizes to proceed with this job. This allows cell Z to subsequently select jobs that all have to visit cell $A1$ afterwards. This mix of jobs that flows to cell M will cause negative effects on the total throughput time, as it will lead to an increase in the average waiting time of jobs between cell M and $A1$. Divergent structures therefore may be extended with a mechanism that avoids such a mix. From the literature on mixed model lines (e.g. Becker and Scholl, 2006) and level schedules in lean systems (Aigbedo, 2000), methods and tools are available that can be used here as well. Basically, it comes down to applying a look-ahead priority rule at cell Z . See e.g. Van der Zee (2004) for further details.

This completes our discussion of the specific facilities needed to use the POLCA system in practice. CONWIP system design has given attention to similar issues, such as card deficits and the use of CONWIP in assembly lines (Hopp and Spearman, 2008). However, in case of MTO production, additional measures are required. The POLCA system has addressed several of these issues. They enable a strong connection of the production planning & control system

and the actual situation at the shop floor of the make-to-order firm, which is very important for an effective pull system.

4. Quick scan for POLCA system design

This section will describe the approach we propose to perform a quick scan in an organization that is interested in applying POLCA. First we will describe the scanning tool. The next subsection will describe a case study where this tool has been applied in order to investigate the applicability of POLCA in that organization and implement POLCA. Note that the scanning tool investigates applicability, but does not indicate whether POLCA is the most appropriate planning mechanism for the firm. Applicability studies focus on the required conditions for a specific planning concept (see e.g., Henrich et al., 2004 for a Workload Control applicability study). Comparison studies (e.g., Stevenson, 2005) give attention to the appropriateness of a planning concept compared to some alternatives.

4.1 Scanning tool

The POLCA scanning tool is designed to investigate through a quick scan whether POLCA is a suitable system for a firm and whether the firm is ready for implementing POLCA. The tool can be considered as a practical guideline for checking the basic conditions for applying POLCA as well as identifying the company specific factors that have to be addressed when implementing POLCA. An extended version is online available (in Dutch: Riezebos, 2008).

<<INSERT Figure 5 ABOUT HERE>>

The scan consists of five stages (see <<INSERT Figure 5>) that need to be performed in the specified sequence.

The first stage focuses on the objectives of POLCA and identifies whether POLCA may add to solving the problems of the firm. This requires an analysis of the causes of these problems. We have encountered several situations in firms where the causes of the planning problems were related to delivery or quality problems of suppliers. Applying a card-based material control system such as POLCA will not solve these problems. The POLCA scan will identify the necessity to address these problems first before other design choices are being made. If the analysis reveals that POLCA may add to solving some specific problems, a performance gap analysis is made and objectives for the POLCA implementation are being set. Targets for dependability, inventory levels and throughput times are required, as these targets affect the design of the POLCA system. They also help to communicate the usefulness of a POLCA system and assess the effectiveness of POLCA in stage 5 of the POLCA scan.

In order to gather data in this stage, we suggest to interview executives as well as material planners, team leaders, and employees. Our experience has learned that the various viewpoints provide new insights on the causes of the performance problems and the contribution of a material control system.

The second stage identifies the cellular system. POLCA controls the flow between cells, but not the flow within a cell. It is therefore required to identify a suitable cellular structure of the production system. This structure need not always be identical to the current structure of the firm. In earlier work (Riezebos, 2001) we discussed the design of cells from a planning point of view. It may be helpful to decompose a large department into several cells that are involved in separate loops. As the POLCA system controls the WIP in these loops, the flow of work to these cells can be controlled more effectively compared to the situation of one large department. This is especially important in case of bottlenecks or workstations that require

special conditions or handling equipment. Element of this analysis is therefore an inventarisation of the machines, stock locations, and other layout characteristics. The stage is completed with a proposal of a cellular structure of the production system, taking into account both the planning problems that POLCA should address (listed in stage 1) and the characteristics of the production system of stage 2. This proposal is not a detailed design, but detailed enough to determine the product routings between the cells (stage 4).

The third stage encompasses the input of the planning system. As POLCA uses lead time offsetting in order to determine the earliest release date at the shop floor, it depends on the information on cell throughput times in the planning system. The actual throughput times are highly affected by capacity utilization, variation in processing times, batch sizes / job work content, capacity control measures, et cetera. However, the information on cell lead times in the ERP system of the firm might not reflect the actual situation at all. Hence, stage three gives attention to the utilization levels, cell throughput time estimates, and the work content of jobs. It proposes necessary improvements in data accuracy and capacity control before implementing POLCA, and whether or not additional instruments are needed for release management, such as the release lists for cells in the POLCA system, or a simple priority mechanism.

The fourth stage designs the POLCA network in terms of control loops of the cards that will flow in the system. It identifies the product types that should be controlled using POLCA and produces a *from-to table* of the inter-cellular traffic that these product types will generate. Based on this analysis, the actual loops are set. This is an iterative process that requires involvement of many stakeholders. It is important to check whether the loops will provide the required control and solve the planning problems that POLCA should address (stage 1). Especially in case of convergent and divergent routing structures (see section 3.3), this decision requires careful attention.

Finally, stage five considers the product mix variety and available production flexibility. It determines the number of cards that will circulate in the POLCA loops and the need to introduce safety cards. We recommend using formula 3 of section 3.1 for setting the number of cards. Next, it assesses the effectiveness of the proposed POLCA system and recommends modifications of the various parts of the POLCA system. For example, it may be necessary to introduce additional information on the release lists because of some convergent routings. Finally, it investigates whether the objectives that were set in stage 1 are realistic and can be achieved with this design of the POLCA system. For example, the expected lead time of the various routings can be estimated and compared to the initial performance targets.

4.2 Case study on the applicability of POLCA

To our knowledge, the first implementation of a fully operational POLCA system in the Netherlands occurred in 2007 (Bosch Hinges, <http://www.boschhinges.com/>, Doetinchem, The Netherlands). Until then, several case studies had been performed in firms that were interested in applying the POLCA system. These firms have experimented with (elements of) the POLCA system, but did not yet implement it. The firm that has implemented POLCA is a small to medium sized enterprise that produces custom-made hinges (see <<INSERT Figure 6) for industrial applications, i.e. in the business-to-business market.

<<INSERT Figure 6 ABOUT HERE>>

Their customers are e.g., ship builders, furniture producers, train and machine builders. They need these hinges at the assembly line in their processes for their custom-made products. Batch sizes range from 10 to 5000, with an average of 500. The size of the hinges ranges from

smaller than a centimeter to more than 4 meter. The total number of orders per year is 1500 with an average repetition rate of 2.5 orders per year for similar products.

The first stage of the scan revealed that the main objectives of implementing POLCA were to improve the dependability (many orders were delivered two weeks over due) and reduce WIP and throughput time. Their lead times were 6-8 weeks, which needed to be reduced with more than 50% whenever the dependability had increased. The ultimate lead time target is 2 weeks. It appeared that the most important causes for the high throughput times and the bad due date performance were due to the large work in progress, lack of information when deciding on the acceptance and release of jobs, and the functional organization of the shop floor. It was decided that these issues could be addressed using a POLCA system.

The second stage investigated the possibility to apply a cellular structure. Until then, a pure functional structure had been applied, where machines were allocated without a clear plan and employees arrived at the start of their shift and asked the planner to assign them a job. It was up to the planner to select jobs that both could be produced (i.e., availability of materials, machine, tools and capabilities of employee matched) and needed to be produced (priority). The cellular structure that was proposed in stage 2 assigned employees to 6 cells. The tools and machines in the cells were color-coded. Each cell received an input-area, where products that need to be processed in that cell could be located and the accompanying order information could be left. In the new situation, buffers of inventory could only occur at these locations. A training program for the employees was developed to enable them to perform as many operations in the cell as possible.

The third stage focused on the ERP system, cell throughput times, and order information. The firm did have estimates of process and set-up times (the latter ranging from 2 minutes to one hour for a single order), but the information on expected throughput times of jobs in a cell could not be obtained from the ERP system. It was decided to buy some additional presses and milling machines in order to reduce the utilization rate and/or avoid too much intercellular traffic. This would change cell throughput times as well. Finally it was decided that the planner should make a realistic estimate of the cell throughput times, based on his experience. With respect to work content, it was decided to divide the large orders into several jobs in order to reduce the average work content of a job. This was preferred instead of adding complexity to the POLCA system by introducing a quantum (maximum of work content) per card.

The fourth stage identified the product routings of the jobs. Each job needs to visit 6-30 operations, including external operations such as heating, special cleaning, et cetera. The average number of operations required is 8. The use of cells has decreased the number of steps in the routing, but only slightly. Hence, each order information card uses color-coded routing information, showing the sequence of cells that need to be visited through colored stickers. The planner prepares these accompanying slides before the job is released to the shop floor. See <<INSERT Figure 7. It is interesting to note that between two cells flows can exist in both directions, i.e. a flow from the red cell to the black cell and a flow back from the black cell to the red cell. The cards that were designed for this POLCA system have both the color of the two cells as well as their names on it (see upper side of <<INSERT Figure 8), which makes identification of the correct card easy. There are 24 different control loops in this system with six cells, so on average each cell has relations with four other cells. The black cell is an externally located supplier and functions as a cell in the POLCA system.

<<INSERT Figure 7 ABOUT HERE>>

<<INSERT Figure 8 ABOUT HERE>>

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Finally, stage 5 identified the number of cards that should circulate in these control loops. As there was no information on the cell throughput times and waiting times between the cells, formula (3) of section 3.1 could not be applied, and therefore formula (4) was used, using the estimates of the planner. This firm did not encounter serious problems with convergent or divergent routing structures, so no special modifications of the POLCA system were needed. Due to the absence of convergent routing structures, special release lists per cell were not required. A simple priority system was used instead. The information slides of all orders awaiting a *Polca* in this cell are put in sequence of arrival in a file box (see lower part of <<INSERT Figure 8). The planner is authorized to re-sequence this list for planning reasons, and the employee is authorized to select a job that is not first in the list if he/she does not have the skills to complete the job. However, he should maintain the sequence as much as possible.

The firm has implemented both the cellular structure and the circulating *Polca*'s in October 2007. At the moment of writing, the firm is very enthusiastic about the change and performance improvements realized. Dependability issues have been solved and throughput times are much shorter. Lead times have been reduced with more than 70%, and the firm now even offers lead times of 2 to 3 weeks for special products to their customers. An important benefit is that productivity per employee has increased, due to the cellular organization and the focus on craftsmanship in that area. The material planner has a better view of the progress of orders in the system. There are less peaks and troughs, and the reaction speed in case of machine breakdowns is much better. Employee satisfaction has increased as well. The team concept and the improved control of workload in the system helps them to focus on their area. The skills training and increased autonomy works out well.

However, system design is still not finalized and it is too early to conclude that all objectives have been achieved. One of the things that has changed and works out very well is the change in behavior of the employees when starting their shift. They now know their responsibilities and tasks are less dependent on the decisions and authority of the planner, as they understand the basic mechanism of the POLCA system: only start working at a job when a signal is available that the next cell in the routing of this job has capacity available.

5. Conclusions and discussion

The design of a POLCA system involves important decisions with respect to routing, release, and special facilities that may be needed in order to let the system function appropriately. This paper has shown that literature gives mainly attention to the effect of routing decisions, i.e. the number of POLCA loops and the number of cards that should circulate in a loop. For the latter decision, some alternative formula's are presented. The design of both the release system and special facilities receive much less attention in literature. However, cell-specific release lists provide an important tool for planners to command on the progress of jobs that already have been released to the shop floor. Other pull systems, such as KANBAN and CONWIP, do not provide such an authorization mechanism. Special facilities may be needed in case of assembly operations (convergent routing structures), divergent routing structures with work load balancing opportunities, or special circumstances (material shortages, breakdowns, et cetera).

We propose to use a quick scan for POLCA system design that addresses the above mentioned issues. The scan consists of five stages. First, a gap analysis is performed that investigates whether the objectives of the firm match with the capabilities of a POLCA system. Next, POLCA cells, lead times and loops are identified. Finally, the effectiveness of applying POLCA in this situation is assessed.

There are still very few fully operational POLCA implementations described in literature. Since October 2007, a POLCA system is implemented in The Netherlands. We describe the POLCA system design in the case according to the five stages of the quick scan. The POLCA

system is able to control the complex processes with high routing, product mix, and processing time variety in this SME. Throughput times were reduced with more than 70%. Other benefits in terms of increased employee satisfaction, increased dependability, and improved control were substantial as well.

Concluding, companies in the Make-To-Order segment may benefit from applying a material control system that is suitable to manage the complex product flows in these firms. The design of a POLCA system can be supported using the quick scan approach that we propose and that has been applied in the case study of the first firm in The Netherlands that has implemented POLCA.

The literature review has shown that there is still a lack of case study descriptions. Future work should elaborate on these issues. Insights from these case studies should help to improve both the quick scan and enrich the description of relevant factors for designing routing, release and special facilities in POLCA systems.

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Source		Contribution			Point of view			Methods and Tools		
		Theory	Case	Compare	PPC	CM	Improve	Routing	Release	Facilities
Suri	1998	√				√	√	√	√	√
Krishnamurthy et al.	2000	√			√			√		
Zhou & Luh	2000	√		√	√			√		
Riezebos	2001	√				√				√
Lödding et al.	2003			√	√				√	
Ryan & Choobineh	2003			√	√			√		
Suri	2003	√				√	√			√
Suri & Krishnamurthy	2003	√	√		√			√		√
Krishnamurthy et al.	2004			√	√			√		
Tien et al.	2004	√		√	√			√		
Krishnamurthy & Claudio	2005	√			√		√	√	√	√
Stevenson et al.	2005			√	√			√	√	
Suri	2005	√					√			
Fernandes & do Carmo-Silva	2006	√		√	√			√		
Riezebos	2006	√		√	√			√		
Vandaele & Claerhout	2006	√	√		√			√	√	
Germes & Riezebos	2008	√		√	√			√		
Vandaele et al.	2008	√	√		√			√	√	

Table 1 Classification of POLCA literature

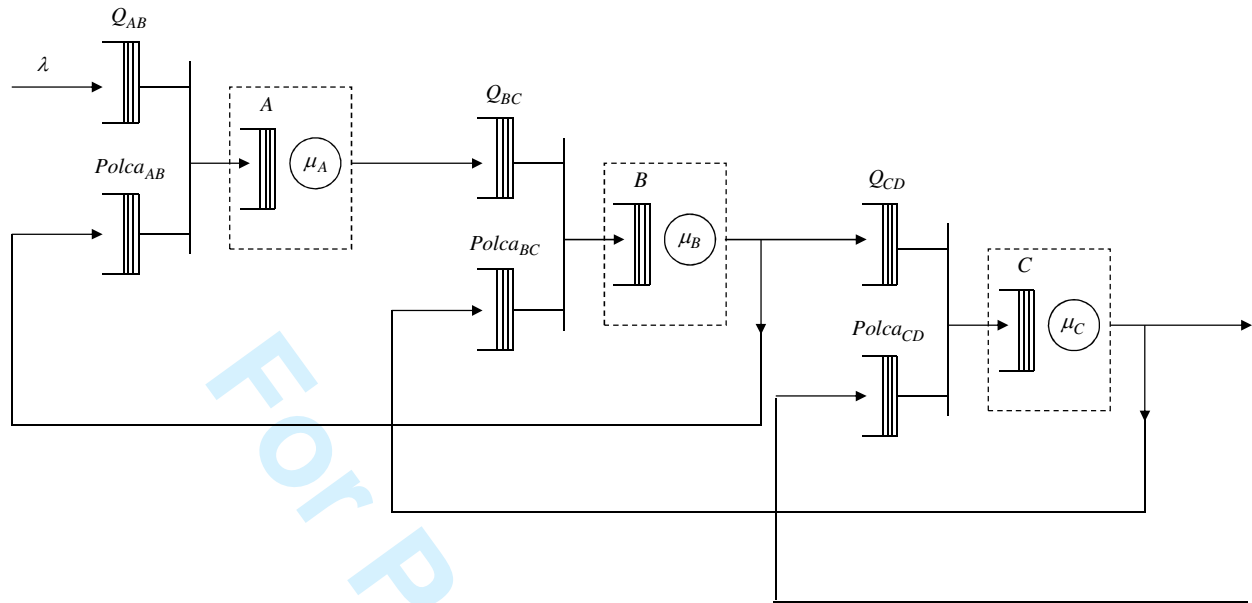


Figure 1 POLCA control loops

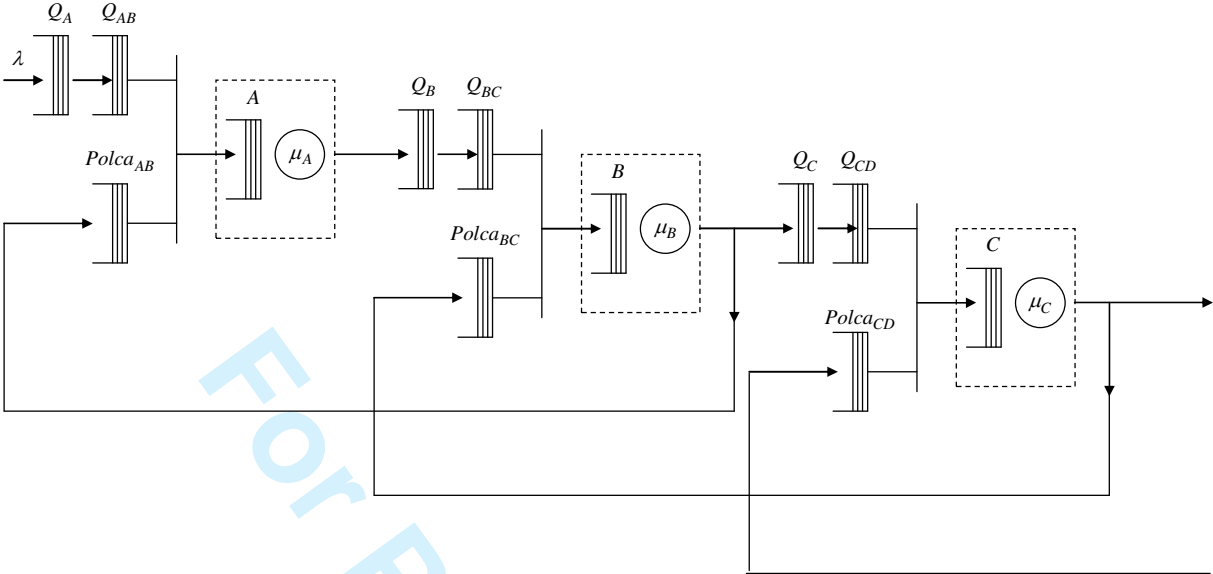


Figure 2 Earliest release dates causing additional waiting time before jobs enter a cell

Release list Cell A (released on 26-3-2008 (dd-m-yyyy))							
Order number	Material check	Earliest start date	Route in cell A (proc. time)			Next Cell	Required <i>Polca's</i>
			1	2	3		
CL002	not ok	21-3-2008	M1 (10)	M5 (20)	M8 (10)	B	1 A / B
CL003	ok	24-3-2008	M2 (30)	M1 (40)	M3 (50)	B	1 A / B
CK001	ok	25-3-2008	M3 (10)	M1 (60)		C	1 A / C
ST253	ok	26-3-2008	M1 (110)	M2 (140)		B	1 A / B
CK005	not ok	26-3-2008	M4 (20)	M1 (40)	M5 (70)	C	1 A / C
CL015	ok	26-3-2008	M2 (40)	M3 (60)	M5 (60)	B	1 A / B
HY563	ok	28-3-2008	M3 (100)	M8 (120)	M2 (10)	B	1 A / B
ST237	ok	29-3-2008	M1 (180)	M2 (120)	M5 (120)	B	1 A / B

Table 2 POLCA release list

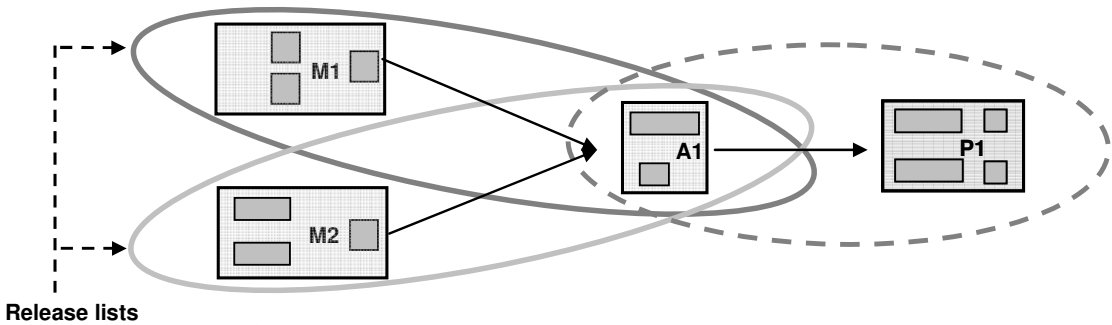


Figure 3 Convergent structure requiring multiple POLCA loops

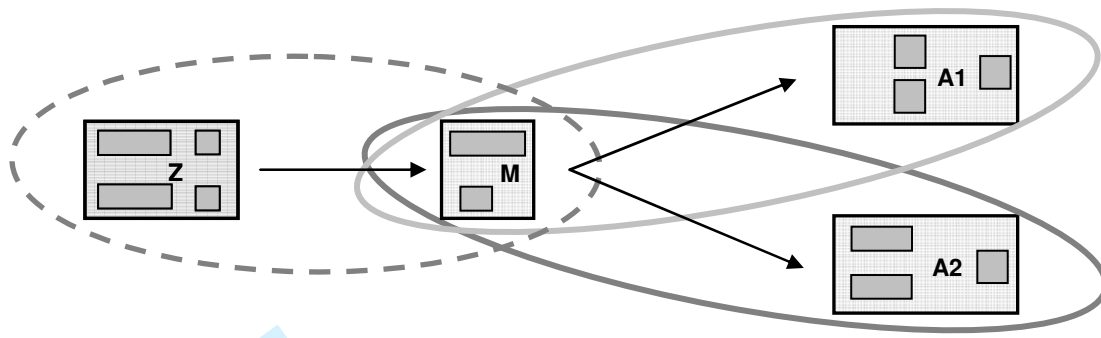


Figure 4 Divergent structure

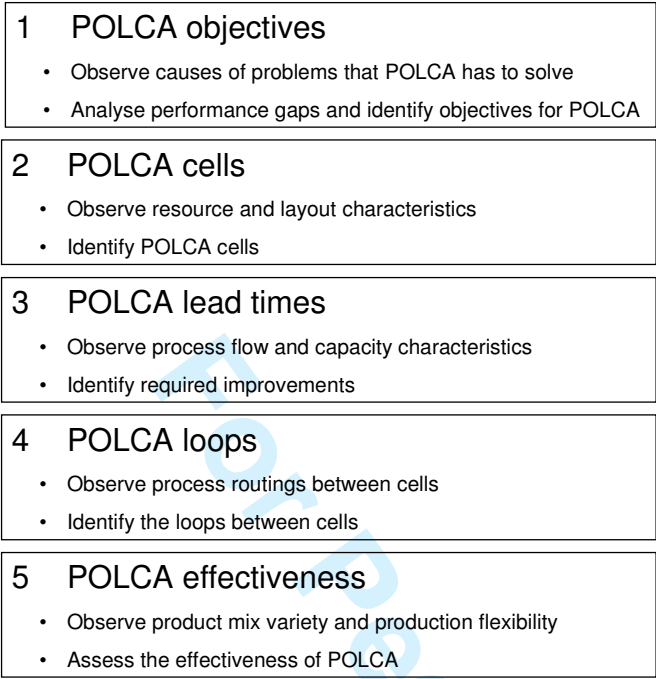


Figure 5 Stages in POLCA scan



Figure 6 Examples of custom-made hinges

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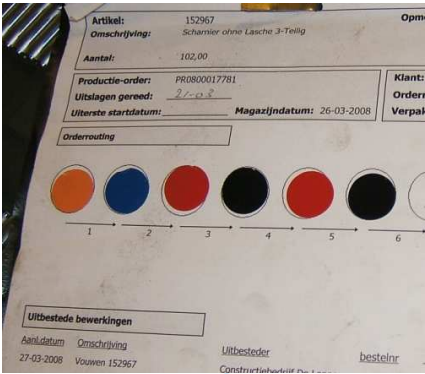


Figure 7 Example of order information slide



Figure 8 *Polca's* awaiting new orders (above) and orders awaiting *Polca's* (below)