Polca simulation of a unidirectional flow system

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ABSTRACT

Polca is a material control system that focuses on shop floor throughput time control in production situations with high variety and customization. It uses an authorization mechanism that consists of route-specific capacity signals (polca cards) and product-specific release signals (ERP system). The route-specific capacity signals level the maximum amount of work in progress within a loop. Each loop connects two route segments, e.g. two cells in the production system. The number of Polca cards in this loop is an important design parameter. If the number of cards is set too high, the system functions unconstrained and the Polca system does not regulate the control of shop floor throughput times at all. If the number is set too low, the system will not be able to cope with the amount of orders issued, and hence total throughput time (the sum of pool waiting time and shop floor throughput time) will steadily increase. Literature offers an approach to determine the number of Polca cards in a system, based on the expected utilization of the loops. This paper shows the effect of variation in several parameters of the arrival and service process while maintaining the expected utilization at the same level. Experiments with order arrival pattern, batch size, demand variation, product mix, priority rule, and occurrence of breakdowns have been performed.

1. INTRODUCTION

Polca is an acronym of the words “Paired-cell Overlapping Loops of Cards with Authorization”. It is a material control system that has been introduced by Suri (1998) in his book Quick Response Manufacturing (QRM). The QRM concept focuses on realizing short throughput times as a competitive edge in modern manufacturing. Many organizations need to reduce their throughput times in order to remain attractive for their customers. Competition is not based solely on price, but also on service, innovativeness, quality, and last but not least on lead time performance. This holds true especially for firms that offer customized products, as they cannot produce these items in advance. These firms 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 on the 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.

This paper discusses Polca, a material control system that has been developed specifically for segmented CM (cellular manufacturing) systems. A segmented CM system distinguishes itself from a regular CM system (see Hyer and Wemmerlöv 2002:18), as in a segmented CM system orders generally visit more than one cell.

2. PULL AND PUSH SYSTEMS

Literature often makes a distinction between push and pull material control systems. We follow Hopp and Spearman (2004:142) in defining a pull system as “one that explicitly limits the amount of work in progress that can be in the system”. Therefore, material control systems that are characterized as pull need to have an authorization mechanism that takes the amount of work in progress into account when deciding on a new release of work to the shop floor.

The pull authorization mechanism can be implemented physically, e.g., by introducing a limited number of cards that have to be attached to orders (“do not start production until one or more cards are available”) or assigning a limited number of locations for a product on a shelf (“do not start production until one or more locations have been emptied”).

The mechanism can also been implemented virtually, e.g. by formulating an aggregate load limit in the computer (“do not start production until the number of working hours released on the shop floor has been reduced below a load limit”).
Examples of pull systems are:
  - Kanban (Sugimori et al. 1977),
  - Conwip (Constant Work In Progress, Spearman et al., 1990),
  - WLC (Work Load Control, see Gaalman, Perona (2002) for a discussion),
  - DBR (Drum Buffer Rope, see Riezebos et al. (2003) for an integration of the latter two),
  - Cobacabana (Land, 2006), and
  - Polca (Suri, 1998).

Systems that not explicitly limit the amount of work in progress are denoted as push systems. Examples of push systems are
  - MRP (Orlicky 1975),
  - installation stock systems (e.g., using the economic ordering quantity),
  - base stock systems (also known as echelon stock systems), et cetera.

Pull systems have become popular as a result of the JIT crusade, i.e. the reinvention of the lean principle to eliminate all kinds of waste in production systems. Long throughput times and high work in progress are considered to be waste in this philosophy. According to the basic law of Little, both issues are interrelated. Hence, pull systems attempt to reduce throughput time by limiting the amount of work in progress on the shop floor. The dimension amount is an aggregate measure composed of what items and how much of each item. Pull systems differ with respect to these decisions. Some pull systems aim to have a very small stock of a large number of items, others prefer to have fewer numbers of items in their work in progress inventory, but the amount of each item might be larger.

If the total work in progress is below a critical level, the average throughput time will be very small, but the system will not be able to achieve the required output. Therefore, work in progress has an important function in smoothing production output. And it does matter where this work in progress is being located in the production system whether this smoothing function can be fulfilled adequately, i.e. whether the required output of the system can be achieved. If the work in progress in the production system is being located ineffectively, output might become too low. Therefore, an important further distinction between pull systems can be made as to where they locate work in progress in the production system.

To summarize, within the set of pull systems we have made the distinction between:
  - triggering mechanism (physical/virtual);
  - what items in work in progress;
  - how much of each item in work in progress;
  - location of work in progress.

The next section will discuss the characteristics of the Polca material control system with respect to these decisions.

3. Polca

A general introduction of the Polca system of material control can be found in Suri (1998). This section will provide a more analytical but limited introduction of some characteristics of Polca. Note that Polca is a pull system according to the definition of Hopp and Spearman (2004). It uses a combination of two authorization mechanisms: both a physical and virtual one. According to Suri (1998), the physical triggering mechanism limits the amount of work in progress. It is implemented as a card system. In order to start production, a cell needs to attach a card that specifies the next cell to visit after completing the order in this cell. However, the E-Polca system (Vandaele et al., 2004) implements Polca as a virtual card system instead of a physical card system, so it is not a prerequisite to have a physical triggering mechanism in a Polca system.

The virtual authorization mechanism of Polca does not use a fixed limit to the amount of work in progress, as it is based on the production plan. However, Polca enables the planner to control the progress of orders by stating planned release dates of each order in one or more cells. Even if a cell has a card available that enables them to start producing an order, it is not allowed to start this order until the current date is beyond the planned release date of the order.

The decision what items to produce depends in a Polca system on the virtual authorization mechanism, i.e. on the list of orders with their planned release dates. The contents of the work in progress inventory changes over time if new orders are being released, as these orders do not need to be similar to orders that had been released before. The physical authorization mechanism (the cards) is anonymous with respect to the order specification. The same card may be attached to totally different orders in the course of time, as long as these orders visit the same combination of cells subsequently.

Polca is indifferent with respect to the decision how much of each item will be in the work in progress inventory. The description of Polca in Suri (1998) notes that each order will have one new Polca card attached to indicate the cell to be visited after all operation of this order in the current cell have been completed. However, if the number of working hours per order differs too much, a Polca system may be designed that requires several identical cards to be attached to large orders. Pieffers and Riezebos (2006: 23) have described this issue more in detail, using an illustrative example.

Finally, Polca locates work in progress within and between cells. It limits the release of work in the system by requiring that a signal from the next cell in the routing should be available in order to start production in the current cell. The signal from the next cell in the routing is to be viewed as an expression that it is to be expected that in the short term capacity will become available in that cell. The material will have to await this signal before production will start, so work in progress will be located before the entrance of the cell. Within the cell, there will also be some work in progress, but here Polca cards are attached to the orders that are in progress.
4. RESEARCH DESIGN

The effectiveness of a Polca system depends on the characteristics of production system that has to be controlled and the market in which it operates as well as the design of the Polca system itself.

An important design parameter is the number of Polca cards that circulate in a loop between two cells. In order to determine this number, we apply Little’s law.

\[ n_{ab} = D_{ab} \cdot CT_{ab} \]  

(1)

where:

- \( n_{ab} \): number of Polca cards circulating between a and b
- \( D_{ab} \): average number of orders that flow from a to b during a period of time
- \( CT_{ab} \): average cycle time of a Polca in the loop a \( \rightarrow \) b

Note that the cycle time is defined as the time between the start of subsequent loops of the same card. This cycle time consists of the throughput time of this card in cell \( a \) as well as cell \( b \), but also of the time the card waits a new order, the transportation time of the card, the waiting time before the order to which the card is attached is being released to cell \( b \), etc. et cetera. Hence we have:

\[ CT_{ab} = LT_a + LT_b + \varepsilon \]  

(2)

with \( \varepsilon \gg 0 \). We will often encounter that the error term is approximated through a safety factor formula:

\[ \varepsilon = \alpha (LT_a + LT_b) \]  

(3)

and \( \alpha \) will be chosen such that the resulting cycle time is sufficiently large.

The problem with this approximation formula is that it does not take into account any variability in lead times within the cells. It also neglects the reason for waiting times in a looping of the card. The focus of this research project is therefore:

- to investigate whether this variability component will have effect on the effectiveness of Polca,
- and how significant it is for a unidirectional flow system.

We use discrete event simulation to evaluate the effectiveness of Polca. A discrete event simulation describes the behavior of a system over time according to events that occur at specific moments in time and that have effect on the system state. An example of an event is the arrival of an order. This event will initiate one or more processes (for example, order acceptance, purchasing, engineering, production, delivery, et cetera) and therefore lead to several actions of one or more actors. These actions belong to processes, and discrete event simulation describes the behavior of systems according to the sequence of activities or decisions within such processes. In general, the occurrence of such events depends on external factors that can not be influenced by the actors.

Such events are often modeled as if they originate from random processes, i.e. the probability or duration of their occurrence is described using probability distributions.

The Polca simulation model distinguishes several processes. The Order generation process describes the arrival of new orders. This process determines the number of orders that will arrive simultaneously, the arrival time of this new batch of orders, and the routing of the orders.

The order process describes the sequence of activities of an order in the system. After it has been generated and the specific routing has been determined, the order waits until it is allowed to start (release date authorization and a Polca card available), next it waits until processing is started, next it awaits until it is transported to the next cell in the routing and then this sub process will be repeated until the last cell in the routing has been visited.

Each cell is described using a cyclical process. A cell can either wait an order or be busy. It is busy if it is either processing or setting up for an order, or if it faces a breakdown.

Each polca card is also described as a cyclical process. A polca either waits an order in the first cell of its loop, or it is connected to an order. Transport times are zero in the simulated polca system, so other states of a polca card (i.e. awaiting transport or in transport to the originating cell) do not consume time. When a polca is connected to an order, it visits both the originating cell and the destination cell before it is released from the order.

A simulation tool can be used to experiment with different settings of parameters of a system. The effect of a specific set of parameters can be compared with another set of parameters. For this research project, we experimented with the following factors:

- Order generation process:
  - constant or exponential interarrival time
  - low or high number of orders arriving simultaneously (batch size)
  - constant or random number of orders arriving simultaneously (demand variation low or high)
  - constant or random number of cells to visit in a routing (product mix variation low or high)
- Cell process:
  - selection rule used (longest waiting time (default) or minimal set-up time)
  - occurrence of breakdowns (yes/no)

All \( 2^6 \) combinations of experimental factors were tested when simulating a segmented cellular manufacturing system with a unidirectional flow (see Figure 1) and six cells.

Every order has to visit the first cell A (orange). Next (a subset of) cells B, C, and D have to be visited. Finally, all orders visit cell E and F. Cell A is the only cell that might have to be set up for an order. At time zero, the cell is not set up for any order, so the first order that is selected (order 4) is located in a set up position. The border of this circle is yellow colored, which indicates that cell A is
Currently being set up for orders that will visit the yellow colored cell B after being processed in cell A. The processing time does not vary randomly, but may differ per cell. In cell A it is two time units, as each circle represents one time unit. Cell B has no set up, but each job faces an identical processing time of 4 units. The same holds true for cell C. Cell D even has a processing time of 5 units. Note however that cells B, C, and D are not visited by each order, as the routings of the orders differ with respect to the subset of cells B, C, and D that have to be visited.

A cell can only process one order at a time. So a cell needs to complete the whole sequence of processing steps before another job can be started in the same cell.

When applying the different experimental settings, the aim was to keep the utilization level of the system at the same level in order to make it possible to compare the outcomes. Hence, any changes in throughput times and waiting times that are encountered will not be due to changes in the overall utilization level, but can be assigned to the differences in experimental settings.

The simulations were performed using DESIMP, a discrete event simulation library within Delphi. DESIMP is very fast, flexible and suitable for this type of research. The model runs on any windows computer. Figure 1 is in fact a screenshot of the animation screen of the simulation system within DESIMP. DESIMP has been developed by E.J. Stokking, Faculty of Economics, University of Groningen, The Netherlands. The model and animation screen has been developed by the author of this paper.
5. RESULTS

At the moment of writing this paper, not all results have yet been analyzed. Therefore, we can only present some first results and impressions. Suggestions and ideas are highly appreciated!

5.1. STABLE AND UNSTABLE SYSTEMS

![Frequency of unstable replications](image)

Figure 2 Frequency table

The experiments have been performed for different numbers of Polca's in the loops. As a simplification, we use the same number of Polca’s for all loops in the system. Therefore, the analysis focuses on the performance of the Polca system in managing and controlling the (temporary) bottlenecks in the system, and realizing short throughput times on the shop floor.

The total throughput time of an order is defined as the time between order generation and order completion. The shop floor throughput time is defined as the time between the start of production in the first cell till order completion. We denote the location of orders waiting to be released and started in the first cell as the order pool.

Experiments with a too small number of Polca's in each loop might result in a non-stable system, i.e., a system with on average an infinite number of orders in the order pool. Measuring such a system is useless, as increasing the length of a simulation run will logically result in a larger total throughput time measure. At the same time we see that the required average utilization of the system will never be reached. Therefore we had to investigate during the simulation run whether the results of that replication would lead to useful results.

We have performed more than 1800 replications and evaluated the stability of each of them by hand. Figure 2 shows the frequency of unstable replications for the various experimental settings. An ANOVA analysis revealed that the mean frequencies of each couple of experimental settings differed significantly. Note that the number of replications for the two levels of each experimental factor did not need to be equal.

Based on the set of replications and experiments that have been performed, we conclude that increasing variety leads to a higher frequency of unstable systems. Figure 2 shows on the vertical axis the two levels for all six experimental settings. For each set of two rows that represent the same experimental factor, the upper row is characterized as low variety, and the second row as high variety. However, the type of variety and the effects caused by the variety introduced by the different experimental factors differs strongly. Hence, it would be interesting to consider the differences in amplitudes between pairs of experimental factors. However, as the number of replications was not equally distributed over the two levels, and differs between the six factors as well, this analysis is not yet possible. Figure 2 and the corresponding ANOVA analysis can only be used to formulate some hypotheses with respect to the influence of these different types of variety.

One of the hypotheses is that large batch sizes have a higher impact on system stability than interarrival time variation. Variability of batch sizes has even less impact.

Second, the type of selection rule used in cell 1 has a large impact on system stability. If set-up time reduction is aimed for, systems less frequently become stable. Further research is needed to investigate this hypothesis.

As we started the experiments generally with one Polca card per loop and steadily increased the number of Polca’s until a stable system was reached, an increased variety in the experimental settings leads to a higher number of Polca’s required in order to obtain a stable system. This result was expected and confirms with general insights based on queuing theory.

5.2. THROUGHPUT TIME

The main performance measures used in the analysis of stable replications were Total Throughput Time (TTT) and Shop floor Throughput Time (STT). They have been defined in subsection 5.1. The following relation holds:

\[ TTT \geq STT \]  \hspace{1cm} (4)

We have performed an ANOVA analysis in order to test whether the main effects of the six experimental factors and the effect of the number of Polca’s are significant, i.e. result in significantly different means. The results of this analysis are shown in Table 1.

The indices a-l in Table 1 indicate the level of a main effect. The interpretation of these indices can be found in Figure 2.

The results show strong significant differences for all main effects and performance indicators except gh for the Shop floor Throughput Time measure (gh indicates Product mix variation). Moreover, the explanatory power is in both models high as we look to the r-squared. However, we urge to be careful with such a conclusion, as many more replications have to be performed. A full factorial analysis is necessary with about the same number of replications per cell.
Table 1 Tests of Between-Subjects Effects

<table>
<thead>
<tr>
<th>Source</th>
<th>Variable</th>
<th>Sum of Squares III</th>
<th>df</th>
<th>F</th>
<th>Sig.</th>
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<td>5739356.078</td>
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<tr>
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<td></td>
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<td>22.139</td>
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<tr>
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<td>.003</td>
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<td></td>
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<td>1</td>
<td>1.193</td>
<td>.275</td>
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<tr>
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</tbody>
</table>

\[a \] R Squared = .824 (Adjusted R Squared = .821)  
\[b \] R Squared = .938 (Adjusted R Squared = .937)

The analysis focuses on the effect of variability on the number of Polca cards that are necessary to perform optimally. Although we have analyzed several different combinations of factors, we will only present two figures with different variability settings.

The scenario that is characterized as “Low variety” is presented in Figure 3. It has the factors a-c-e-i and h-l. The scenario that is characterized as “High variety” in Figure 4 has the factors b-d-f-j and again h-l.

The two figures show similar patterns as well as important differences between both situations.

The pattern that is similar is the effect of a changing number of polca cards on Total throughput time and Shop floor throughput time. If we read the figures from the right to the left, we see that a reduction of the number of Polca’s causes at first a small increase of TTT, while STT starts to decrease in a somewhat higher pace, but if the number becomes too small, TTT increases rapidly.

We conclude that it might be possible to operate a production system with less work in progress and smaller Shop floor throughput times, without a strong increase in Total throughput time. This result is important, as many firms try to postpone the release decision to the shop floor in order to be able to be flexible, apply customer modifications, etcetera. The total throughput time is not much influenced by such an approach.

Important differences between the two figures can be identified as well. The impact of increasing variance leads to much higher average throughput times (almost twice as high). Moreover, the difference between the figures of TTT and STT increases as well. Finally, the number of Polca cards that seems to be the critical limit might also increase.
CONCLUSION

This paper has investigated the effect of various variability components on the effectiveness of Polca. We have used discrete event simulation to show the impact of the number of Polca cards on throughput time in a production system. Work in progress is directly related to Shop floor throughput time, and both decrease if the number of Polca cards is reduced. However, total throughput time includes the waiting time in the order pool (i.e., before release to the shop floor) as well. As long as this Total throughput time does not strongly increase, a firm that uses Polca becomes more flexible and will be able to provide better service to its customers.

The simulations have been performed for a unidirectional flow system. There are no backflows in such systems. Therefore, the variability in routing is still limited compared to the classical job shop system.

Future research should focus on the full factorial design of the experiments and investigate the effect of the six types of variety (interarrival time, batch size, demand variety, product mix variety, selection rule, and breakdowns) in depth.

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