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POLCA Control in Two-Stage Production Systems

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Abstract

POLCA (Paired-cell Overlapping Loops of Cards with Authorization) is a decision support system for material flow control under Quick Response Manufacturing. It operates in the context of low-volume, high-mix, and cellular manufacturing. While there is an increasing literature on POLCA performance, current studies usually assume full availability of components (or parts) at assembly stations, neglecting parts manufacturing and feeding. Therefore, this study uses simulation to assess POLCA performance in a two-stage production system, where at the first stage parts are manufactured and at the second, they are assembled into end-products. The study demonstrates that using POLCA to control both production stages, manufacturing and assembly, significantly outperforms the use of POLCA at the assembly stage only, leading to important reductions of the total throughput time of orders and on the percentage of tardy orders. Statistical analysis of our results was conducted using ANOVA.

Keywords: Two-stage production system; POLCA; Simulation;

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1. Introduction

POLCA stands for Paired-cell Overlapping Loops of Cards with Authorization. It is a decision support system for material flow control suitable for companies that produce many different and/or customer-specific products. It was developed by Rajan Suri as part of a broader management philosophy known as Quick Response Manufacturing [1, 2]. Lead time reduction is the main aim and focus of this philosophy.

POLCA is a card-based visual tool that manages material flow by controlling which orders (or products) should come next into production to meet delivery targets, e.g. short and stable throughput times. For that, POLCA cards link successive work cells (or stations) in the routing of the product and ensures that upstream cells only work on production orders that are needed downstream. In this way, POLCA cards act as pulling production capacity signals, being the key reason why POLCA is suitable for low-volume, high-mix and customized production [2].

The number of cards circulating in a POLCA loop restricts work-in-process (WIP). This WIP cap is complemented with orders' selection, at each cell in the routing of orders, based on authorization dates. Sorting the orders based on authorization dates leads to an authorization list that will restrict the number of orders allowed to be produced, preventing in this way 'traffic jams' on the shop floor [2].

While there is an increasing literature on POLCA performance, e.g. [3], [4], [5], [6], and [7], these studies usually assume full availability of components (or parts) at assembly stations. This therefore neglects the potential impact of capacity

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shortages at manufacturing, that may result in stock-outs at assembly stations. This paper attempts to fill this research gap using simulation to assess POLCA performance in a two-stage production system, with the first stage manufacturing the parts required at the second, the assembly stage, for assembly them into end-products. New insights into the behavior of the POLCA system are expected to be gained to support researchers in the design of more effective and efficient material flow control systems and practitioners in their implementation.

The remainder of this paper is organized as follows: a concise view of the POLCA system is provided in Section 2; the simulation model used is then described in Section 3, before results are presented and discussed in Section 4. Finally, conclusions, manufacturing implications and future research work are discussed in section 5.

2. POLCA decision support system

A number of studies in the extant literature report on implementations of POLCA in practice (e.g. [3],[4] and [8]). Quick Response Manufacturing [1] and POLCA are robust systems that can aid in situations where product manufacturing variety is high. For that POLCA makes use of overlapping loops of cards between pairs of successive stations (or work cells) in the routing of an order. Since loops overlap, every station, except the first and the last, belongs to two POLCA loops. POLCA cards are allocated to control loops, imposing a WIP cap on the loop and providing capacity signals between each pair of successive stations in the routing of the order. This ensures that upstream stations use their capacity effectively by only working on order that are needed downstream [1, 2].

Cards are not part-number specific, i.e., they can be seized by any order entering the loop. Cards are attached to the order when it enters the first (or upstream) station and detached after the order has finished processing at the second (or downstream) station of the loop. The number of POLCA cards attached to the order depends on the workload of the order and on the quantum of the cards. The quantum refers to the maximum amount of material that should accompany a single card. Detached cards are then sent back to the first station, where they can be attached to new arriving orders.

Regardless whether POLCA is implemented as unit-based (i.e., a card represents an order) or load-based system (i.e., a card represents the full workload contribution of the order), it assumes that only orders that have been authorized by a high-level MRP system can start processing at a station whenever POLCA cards becomes available. Authorization dates are calculated by backward scheduling from the orders' due dates using the planned cell lead times. The use of authorization lists prevents 'traffic jam' on the shop floor, ensuring that stations only work at the most urgent orders.

For a detailed description of the POLCA system we refer interested readers to, e.g., [1], [2] and [3].

3. Simulation Study

To assess POLCA performance in a two-stage production system, discrete event simulation is used. Simulation is particular useful for modeling and analysis of complex system, for which no analytic tools are available. This section describes the simulation study carried out. Section 3.1 first details de simulation model, and then, control policies are detailed in Section 3.2. Finally, the experimental design and the key performance measures considered in the study are presented in Section 3.3.

3.1. Simulation model

A model of a two-stage production system (Fig. 1) was developed using Arena®. This kind of production systems can be found in practice in several industries, e.g. at assembly of products for cars feed from injection molded parts fabrication. Each production stage consists of three stations, where each station is modelled as a single and constant capacity resource, as in [9]. At the first stage, parts are manufactured, and at the second, they are assembled into end-products. Parts manufacturing requires visiting a single manufacturing station, while parts assembly requires visiting a variable number of assembly stations, between one and three, depending on the routing of the order (product). All assembly stations have an equal probability of being visited and a station is required at most once in the routing of an order. Moreover, a movement between any combination of two assembly stations may occur, but the materials will always flow in the same direction, i.e. in a logic identical to a general flow shop. Transportation or movement times are assumed to be negligible.

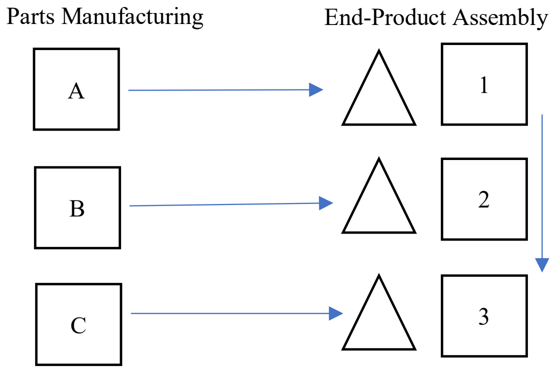

Fig. 1. Two-Stage Production System including manufacturing and assembly.

Customer orders arrive to the production system following an exponential process with a mean inter-arrival time that results in 90% average utilization at manufacturing and assembly stations. Whenever an order arrives, the exact number of parts is ordered at manufacturing, following one of two release policies, as defined in Section 3.2. Once manufactured, parts are then sent to the assembly stations where they are assembled into the end-product. Operation times at the stations of both stages follow a truncated 2-Erlang distribution with a maximum of 4 time-units and a mean of 1 time-unit (before truncation). Finally, set-up times are considered as part of the operation times whilst due dates are set exogenously by adding a random allowance factor, uniformly distributed between 35 and 50 time-units, to the order entry time. As in previous simulation studies on POLCA (e.g., [6], [7], [10] and [11]), it is assumed that necessary information regarding orders routings and operations times are known upon the arrival of the order to the production system.

3.2. Materials Flow Control Policies

Customer orders are released to the shop floor and the two consecutive production stages as follows:

Manufacturing Stage: Orders are released to this stage, for parts manufacturing, according to two alternative policies: (i) immediately release (IMR) - the order is immediately released whenever a new customer order arrives to the production system; (ii) POLCA controlled - the release of the order depends on the system status controlled by POLCA cards, i.e., the order is released only if the required POLCA card is available. The card stays with the part until the part is assembled into the end-product at an assembly station. Then, the card is detached and send back to the manufacturing station where it can be attached to a new order. This means that the POLCA card loop for the part encompasses the manufacturing station and the assembly station that uses it in the assembly of end-products.

Assembly Stage: Customer orders are released to the assembly stage whenever the required parts for the first operation are available at the corresponding assembly station and authorized by the POLCA system. POLCA is here used as a decision support system to control the material flow between assembly stations. Therefore, three conditions are required to process an order at an assembly station: (i) the required part must be available at the assembly station; (ii) a POLCA card must be attached to the order; and (iii) the order must be authorized by a high-level MRP. We assume that arriving orders have already been authorized.

Dispatching at all stations follows the first-come-first-served (FCFS) rule, which minimizes the variability between the orders' throughput times.

3.3. Experimental Plan and Performance Measures

The experimental factors considered in the study are: (i) the control policy of orders at the manufacturing stage (IMR and POLCA); (ii) the POLCA cards' quantum (a card represents an order, or a card represents the full workload of the order); and (iii) six levels for the WIP cap. This cap refers to the limit on the number of cards or on the workload at control loops, depending on the nature of the quantum, i.e. unit-based or load-based. A full factorial design was used with 24 (2x2x6) experimental scenarios, replicated 100 times each. All results were collected over 40,000 time-units following a warmup period of 4,000 time-units.

Since we focus on a make-to-order production system, three main performance measures are considered in this study, as follows: mean total throughput time of the order, i.e. the mean of the completion date minus the arrival date of the customer order; percentage tardy, i.e. the percentage of customer orders completed after the due date; and the mean tardiness of customer orders. In addition to these performance indicators, we also measure the mean assembly throughput time, i.e. the mean of the completion date of the customer order minus the release date to the assembly stage. While the total throughput time includes the time that an order waits before being released into assembly, the assembly throughput time only measures the throughput time after the order is released to assembly.

4. Results

This section presents and discusses the simulation results for the experimental plan defined in the previous section. Main results are assessed in Section 4.1 and statistical analysis using ANOVA is conducted in Section 4.2.

4.1. Assessment of Results

To better understand and assess performance differences between control polices concerning the release of orders to the parts manufacturing' stage, the results are presented in the form of performance curves. The left-hand starting point in each curve represents the tightest WIP cap per control loop. The WIP cap rises stepwise by moving from left to right in each graph, with each data point representing one card count (unit-based) or load limit (load-based). Raising the WIP cap increases the shop work-in-process and, as a result, the shop floor throughput time increases.

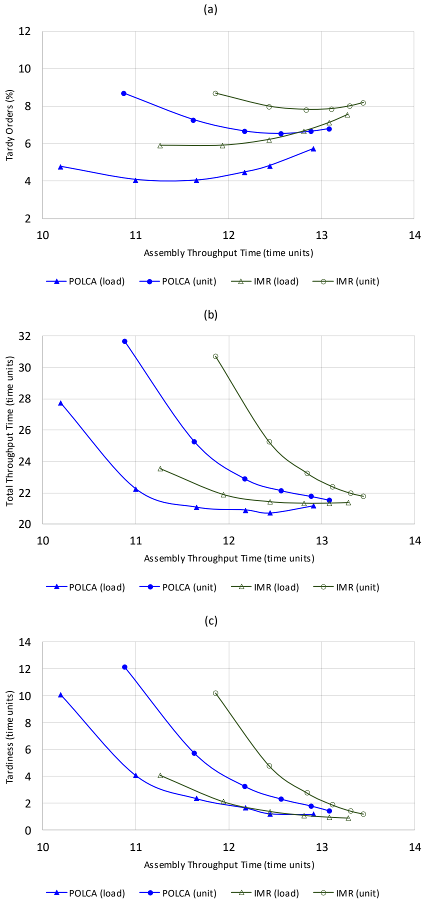

Fig. 2. Performance results for: (a) percentage tardy; (b) total throughput time; and (c) tardiness of orders.

Fig. 2 shows the percentage of tardy orders, total throughput time, and mean tardiness over the assembly shop floor throughput time, for the control policies resulting from the combination of the different levels of the experimental factors. The following can be observed:

Control Policy at the Manufacturing Stage: POLCA control outperforms IMR for all performance measures considered. POLCA links the manufacturing and assembly stages, controlling the release of orders for parts manufacturing and ensuring that manufacturing stations only work on parts that are needed downstream at assembly stations. This prevents 'traffic jam' at both manufacturing and assembly shops, leading to smaller mean assembly shop throughput time and, as a result, to smaller mean total throughput compared to IMR. We should realize that even when IMR of parts is applied, materials flow at their assembly into end-products is subject to POLCA control.

POLCA *quantum*: load-based card *quantum* clearly outperforms unit-based, as it allows for a better representation of the system workload. This leads to a better and finer load balancing than using unit-based, having as a result a substantial relative reduction of both, the mean assembly shop floor throughput time and mean total throughput time, as seen in Fig. 2. The percentage of tardy orders and mean tardiness is also substantially lower under a load-based card *quantum*.

We may conclude that, regardless whether POLCA is implemented as a unit-based or a load-based materials flow control system, it has the potential to perform well under two-stage production environments that combines manufacturing of parts with their assembly as the one studied here. Moreover, it is clear that in this environment where, not only assembly of end-products, but also manufacturing of parts to be assembly at these end-products are controlled by POLCA, important reductions of total throughput time, percentage of tardy orders and on the tardiness of the orders can be obtained over IMR, i.e. when controlled release is not applied.

4.2. Statistical Analysis

Statistical analysis of results was conducted using ANOVA (Analysis of Variance) [12, 13]. ANOVA is used to determine which factor (WIP cap, release policy and card *quantum*) has a significant effect on the performance measures (mean total throughput time, percentage of tardy and mean tardiness). The level of significance of the test is 0.01 (α = 0.01).

For each of performance measure a separate statistical analysis is performed, and the results are summarized in tables 1, 2 and 3, respectively. After that, based on estimate marginal mean of performance we tried to find out which factor level results in the best performance. This is illustrated in figures 3, 4 and 5.

The analysis of variance for mean total throughput time (Table1) indicates that: (i) there are significant differences between the mean levels of WIP cap; (ii) there are no significant differences between the mean levels of the release policy and (iii) there are significant differences between the mean levels of quantum. Another important conclusion that can be drawn from Table 1 is that there are interactions between all the three factors. In other words, when the three factors are considered for analysis, their levels interact with each other and resulted in different performances. At this point it is possible to compare the levels of each factor to find out which level led to the lowest total throughput time for the production system. From Fig. 3 it is possible to conclude that the optimal (lowest) total throughput time will be achieve when WIP cap is at level 18, the release policy level is POLCA, and quantum is load-based.

Table 1. Analysis of variance table for mean total throughput time.

Source of variation	**Sum of Squares**	**Degree of Freedom**	**Mean Square**	**F_0**	***P*-Value**
Corrected Model	20369.256	23	885.62	58.74	0
Intercept	1285187.92	1	1285187.92	85241.47	0
WIP-cap	14759.116	5	2951.823	195.783	0.000*
Release Policy	33.002	1	33.002	2.189	0.139
Quantum	2791.003	1	2791.003	185.116	0.000*
WIP-cap * Policy	683.402	5	136.68	9.065	0.000*
WIP-cap * Quantum	1831.168	5	366.234	24.291	0.000*
Release Policy * Quantum	40.849	1	40.849	2.709	0.1
WIP-cap * Release Policy * Quantum	230.716	5	46.143	3.06	0.009*
Error	35823.015	2376	15.077		
Total	1341380.19	2400			
Corrected Total	56192.271	2399			

* Indicates significant difference between the levels of a factor or significant interactions.

Table 2. Analysis of variance table for the percentage of tardy.

Source of variation	**Sum of Squares**	**Degree of Freedom**	**Mean Square**	**F_0**	***P*-Value**
Corrected Model	4575.706	23	198.944	75.619	0.000
Intercept	104840.920	1	104840.920	39850.504	0.000
WIP-cap	276.969	5	55.394	21.055	0.000*
Release Policy	1273.354	1	1273.354	484.008	0.000*
Quantum	2370.201	1	2370.201	900.924	0.000*
WIP-cap * Policy	110.281	5	22.056	8.384	0.000*
WIP-cap * Quantum	412.640	5	82.528	31.369	0.000*
Release Policy * Quantum	123.959	1	123.959	47.117	0.000*
WIP-cap * Release Policy * Quantum	8.302	5	1.660	.631	0.676
Error	6250.913	2376	2.631		
Total	115667.539	2400			
Corrected Total	10826.619	2399			

* Indicates significant difference between the levels of a factor or significant interactions.

Table 3. Analysis of variance table for tardiness.

Source of variation	**Sum of Squares**	**Degree of Freedom**	**Mean Square**	**F_0**	***P*-Value**
Corrected Model	23193.380	23	1008.408	85.329	0.000
Intercept	26807.907	1	26807.907	2268.422	0.000
WIP-cap	18518.587	5	3703.717	313.400	0.000*
Release Policy	865.618	1	865.618	73.247	0.000*
Quantum	1321.256	1	1321.256	111.802	0.000*
WIP-cap * Policy	1036.827	5	207.365	17.547	0.000*
WIP-cap * Quantum	1019.353	5	203.871	17.251	0.000*
Release Policy * Quantum	129.943	1	129.943	10.996	0.001*
WIP-cap * Release Policy * Quantum	301.796	5	60.359	5.107	0.000*
Error	28079.255	2376	11.818		
Total	78080.541	2400			
Corrected Total	51272.635	2399			

* Indicates significant difference between the levels of a factor or significant interactions.

Based on Table 2 for the percentage of tardy orders, it is possible to conclude that there are significant differences between the mean levels of each factor and there are 2-way interactions between factors. Furthermore, it is possible to say that the lowest estimated marginal means for the percentage of the tardy orders will attain when the WIP cap is at level 14, the release policy is POLCA and quantum is load-based (see Fig. 4).

Finally, the analysis of variance for mean tardiness (Table 3) indicates that there are significant differences between the mean levels of each factor and there are interactions between all the factors. The comparison result which is based on estimated marginal means of tardiness indicates that the following combination of factor levels led to lower means of tardiness (see Fig. 5): level 20 for the WIP cap, IMR for the release policy and load-based for the *quantum*. Still, there are minor differences between the last three levels 16, 18, and 20 of WIP cap.

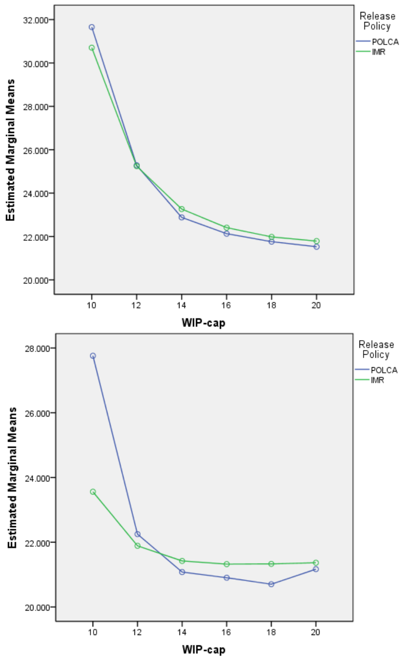

Fig. 3. Estimated marginal means of total throughput time: (Up) unit-based quantum; (Down) load-based quantum.

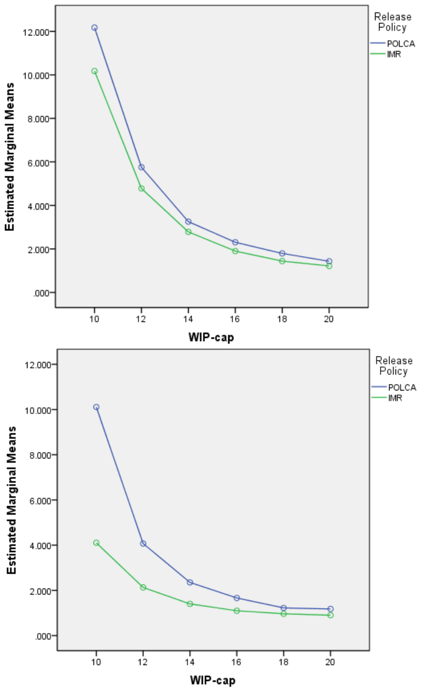

Fig. 5. Estimated marginal means of tardiness: (Up) unit-based quantum; (Down) load-based quantum.

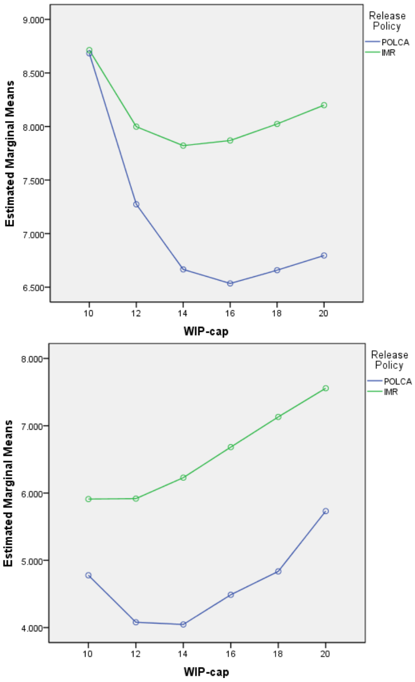

Fig. 4. Estimated marginal means of percentage tardy: (Up) unit-based quantum; (Down) load-based quantum.

4. Conclusions and Managerial Implications

POLCA is a decision support system for material flow control in low-volume, high-mix and cellular manufacturing environments. In this paper, we assess for the first time POLCA performance in a two-stage production system. The first stage manufactures parts that are then assembled into end-products at the second stage. This kind of production system can be found in practice in several industries, e.g. at injection molded parts for cars.

The study shows that using POLCA to control the material flow of parts between manufacturing and assembly stages, i.e. involving the two stages of production, outperforms the use of POLCA at a single stage, i.e. at the assembly. Controlling both stages allows for important performance improvements, namely decreasing the total throughput time of orders and the percentage of tardy orders.

The study has the following implications. It extends existing literature on POLCA, which typically focuses on the assembly stage, neglecting parts manufacturing and feeding, and reemphasizes the important role of controlled order release.

A major limitation of our study is that our findings are based on a theoretical manufacturing system, although based on practical experience of the authors. Other manufacturing environments, representative of the industrial practice where, for example, parts require several manufacturing operations before being assemble into the end product, should therefore be considered in future research work. Future research could also seek to identify POLCA implementations that further corroborate our findings.

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