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Research Article

Reducing Lead Times in a Two-process Cell Using Lean and Simulation

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Abstract: An existing power system production process includes two operations and produces twelve different part types. The first operation fills WIP carts used by the second operation. A combined lean and discrete event simulation study supported by the analysis of order history information stored in a corporate information system is presented. The goal was to identify operations alternatives that could be used to reduce customer lead time from the current 3 to 3 days to 1 to 3 days. The application of lean methods included the examination of the order history data that showed that 80% of parts ship to a single primary customer and 20% to many secondary customers. The lean part of the study further concluded that the number of WIP carts should equal the number of different products, that each WIP cart should be associated with one and only one product and that each WIP cart should be should refilled daily after orders are processed. Using a discrete event simulation model, four order processing sequencing alternatives for improving on-time delivery were evaluated. The percent of orders delivered in 1 day was maximized, with the lowest variance, by sorting all orders for the primary customer first from smallest in size to largest. The orders for the same product from the remaining customers are processed immediately after the order for the same product from the primary customer. The value of the synergistic effect of combining lean tools with simulation supported by order data extracted from the corporate information system is demonstrated.

Keywords: Discrete event simulation, lead time, lean, order data, scheduling

INTRODUCTION

It is desirable to reduce the order lead time of an existing power system production operation from the current three to five days to one to three days. To achieve this goal, an integrated lean and Discrete Event Simulation (DES) approach is used supported by historical order data from the corporate information system to develop, validate and compare new operational strategies, including alternative order processing sequences. The paucity of literature concerning the integrated use of lean and DES is surprising given that both are applicable to the improvement of process and the delivery of services. This case study provides additional evidence of the value of using lean and DES in as integrated fashion.

The need for such as integrated approach is further discussed by Standridge and Marvel (2006). Lean includes proven tools for waste identification and elimination. However, these tools cannot be used to quantify performance measure improvements before implementation. To address this issue, Marvel and Standridge (2009) suggest a modification of the lean process that includes future state validation using DES. In the same fashion, Robinson *et al*. (2012) developed an integrated lean-DES process called SimLean. Additional applications of the integrated use of lean and DES are presented in Miller *et al*. (2010). This topic is further discussed by Jeong and Phillips (2011). Standridge (2013) provides a summary of the benefits of the integrated lean-DES approach.

The production system consists of two major work cells. The first cell uses a wire cutting machine to cut wires to a specified length. The second cell uses two injection molding machines that mold the cut wires in to a plastic connector. A WIP cart is replenished in the wire cutting cell only when it is completely emptied in the injection molding cell.

The wire cutting cell cuts reels of wire into predetermined sizes. This copper wire is insulated with eight different colored plastic coatings and is delivered in reels of 15,000 feet. Six different lengths of wire are used. Each of the six lengths has two types, one without a Center strip (NC) and one with a Center Strip (CS). Thus there are twelve unique part numbers. The wire cutting machine cuts the wire to the predetermined size, strips the end of the wire, places a terminal on the strip and places a center strip on the wire if required. Each WIP cart is filled with 500 pieces of wire and sent to the injection molding cell.

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The injection molding cell has two vertical injection molding machines operating in parallel. Each is used to mold a plastic connector around 8 wires of the same length. The operator removes one set of eight wires from the WIP cart and places them into the connector mold and shuttles the machine. The machine then molds the part around the wires. While the part is being molded, the operator loads the second side of the mold.

In the current state, the team leader of the wire cutting cell determines what sizes and how much wire needs to be cut. In the molding area, the assembly team leaders communicate to the molding operators which WIP cart to use and how many parts are needed.

The goal of the study is to reduce the current lead time. First, a P-Q analysis of order data concerning about 30 customers was conducted. A value stream map helped in developing strategies to reduce manufacturing lead time. DES was used to help validate the changes proposed by the lean part of the study as well as to assess impact of four order processing sequencing alternatives on lead time reduction.

METHODOLOGY

The study was conducted by integrating lean methods with DES. Effective improvement cannot always be achieved through the analysis of existing data and implementation of lean principles. Changes can have far-reaching effects, may be very complex and can involve multiple departments within the company as well as suppliers and customers. This complexity also suggests risk. To deal with this risk, proposed changes can be examined and tested via DES before implementation.

Two lean tools were used in the study as described in Tapping *et al*. (2002). Product Quantity (PQ) analysis is the process of identifying the mix of products produced by a production operation. This may include the customers who demand and receive the products. A Pareto chart of 3-6 months of production data is generally employed. Value stream mapping is used to document, manually analyze and propose improvements to the flow of information or materials required to produce a product or service for a customer. Current operations are documented in a current state map. An ideal state is also defined and a corresponding map created. A series of future states and corresponding maps provide a pathway from the current state to the ideal state.

However, a value stream map is a descriptive model and does not include variability. Thus, there is no mechanism for analyzing a future state map to see if the specifications that it contains will produce the desired system behavior or achieve performance targets. On the other hand, DES provides a method for including variation, validating the performance of proposed alternatives and identifying at least a very good solution to production system issues before implementation.

Furthermore, Kleinberg (2000a, b) states that simulation animation technology supports future state validation through the rigorous testing, analysis, validation and communication of business processes including assumptions and inter-dependencies. In summary, DES generates the information needed to demonstrate that changes will be effective before implementation including showing that the results from lean initiatives are sustainable.

RESULTS AND DISCUSSION

The PQ analysis, value stream mapping and DES model and experiment are discussed.

PQ analysis: With nearly thirty customers placing orders and twelve different parts, customer demand is highly variable. In order to gain a better understanding of the ordering patterns, a Product-Quantity (PQ) analysis was performed using 3 months of historical order data from the corporate information system. The data is shown in Table 1 and as a Pareto Chart in Fig. 1. Note that the first three product types account for 70% of the orders.

Another Pareto Chart, shown in Fig. 2, was created showing customer type and order quantity. This was done to gain a better understanding on which customer was ordering what quantity. Note that the vast majority of parts, about 80%, were ordered by customer “A”. Thus, it was decided for the purposes of analysis to aggregate the remaining 28 customers into one “B” customer.

Histograms of the order size for each customer type for each product were created. Twenty four histograms in all were created, twelve for the “A” customer and twelve for the “B” customers. An illustrative histogram is shown is Fig. 3. This represents “A” customer, Center Strip (CS), with length of 41.62 inches.

Table 1: PQ analysis July through September 2012

Molded part	Quantity	Cum. quantity	(%)	Cum. (%)
MA08057-3-CS-41.62	14000	14000	34	34
MA08057-3-CS-35.62	7303	21303	18	52
MA08057-3-CS-29.62	7244	28547	18	70
MA08057-3-NC-29.62	2742	31289	7	77
MA08057-3-NC-35.62	2716	34005	7	84
MA08057-3-CS-53.62	1663	35668	4	88
MA08057-3-NC-41.62	1041	36709	3	90
MA08057-3-NC-65.62	1004	37713	2	93
MA08057-3-CS-65.62	942	38655	2	95
MA08057-3-NC-47.62	836	39491	2	97
MA08057-3-NC-53.62	639	40130	2	99
MA08057-3-CS-47.62	560	40690	1	100

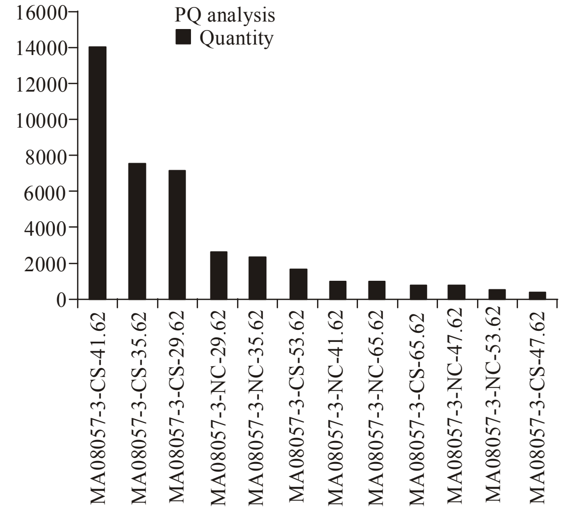

Fig. 1: Pareto chart July through September 2012

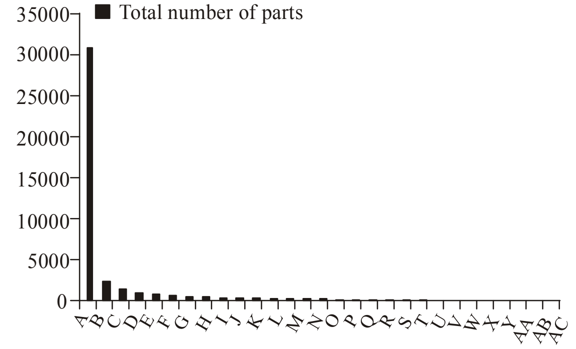

Fig. 2: Pareto chart customer and order quantity

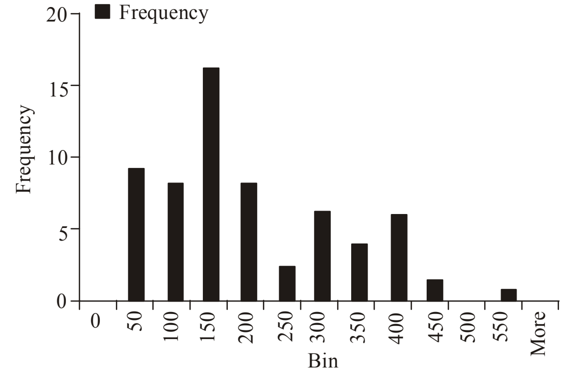

Fig. 3: Histogram for part number MA08057-3-CS-41.62 for "A" customer

Value stream mapping: To help visually identify waste, value steam mapping was used. The current state value stream map is shown in Fig. 4. Orders are received daily and sent to the production floor. Every day, the team leader in the wire cutting cell takes a manually count of inventory of all molded components and all WIP carts and compares this to the daily orders and then prioritizes the product to cut for the day. Also, the team leader in the assembly cell takes a manual count of inventory of molded components, compares that to daily orders and then communicates to the molding team leader the priority of what to run for the day.

In the wire cutting cell, there is one wire cutter that operates eight hours per day. There is a queue in the wire cutting cell that holds up to 6 empty WIP carts. The cycle time to produce one full WIP cart is 240 or 0.48 min/piece.

In the injection molding cell, there are two machines and two operators available for 10 h/day. The average cycle time per piece is 1.15 min. There is a queue in the molding cell that holds up to six WIP carts. For most cases, once a WIP cart is started, it is used until the WIP cart is empty. Once the WIP cart is empty, it is sent back to the wire cutting queue to be filled again. There are instances where the WIP cart cannot be emptied and another WIP cart is needed for orders for that day. In this instance, the WIP cart is changed out and the original WIP cart will run at another time.

There are 1.6 days of molded CS product and 1.8 days of molded NC product stored in the injection molding cell. There are 1.6 days of inventory of molded CS product and 0.8 days of NC molded product stored in the assembly cell. Daily demand averages 646 and 503 parts being CS and the remainder being NC. On average, 65 containers of product are shipped daily.

As seen in the current value stream map, there are areas of concern:

- There is a combined 5.8 days of molded inventory in two different work cells. There are times where the molding cell is molding product in order to empty a WIP cart. This product will be stored in inventory instead of being used to fulfill orders, the waste of overproduction.
- WIP carts sit idle in the molding queues for long periods of time. Once a WIP cart of a low demand product is filled, it can take up to a month to empty it. In this case, the lack of WIP carts bottlenecks the system and makes it hard to manage large orders for high volume products.
- There are currently 8 WIP carts in the system, with twelve part numbers. As wires for only one part number at a time can occupy a cart, the WIP carts have become a scheduling bottleneck.
- Scheduling is done by team leaders in different departments based on "tribal knowledge". There is a lot of unnecessary scrambling to make orders.

To achieve the first future state, the following improvements were identified:

- Increase the number of WIP cart to twelve with each cart dedicated to one product.

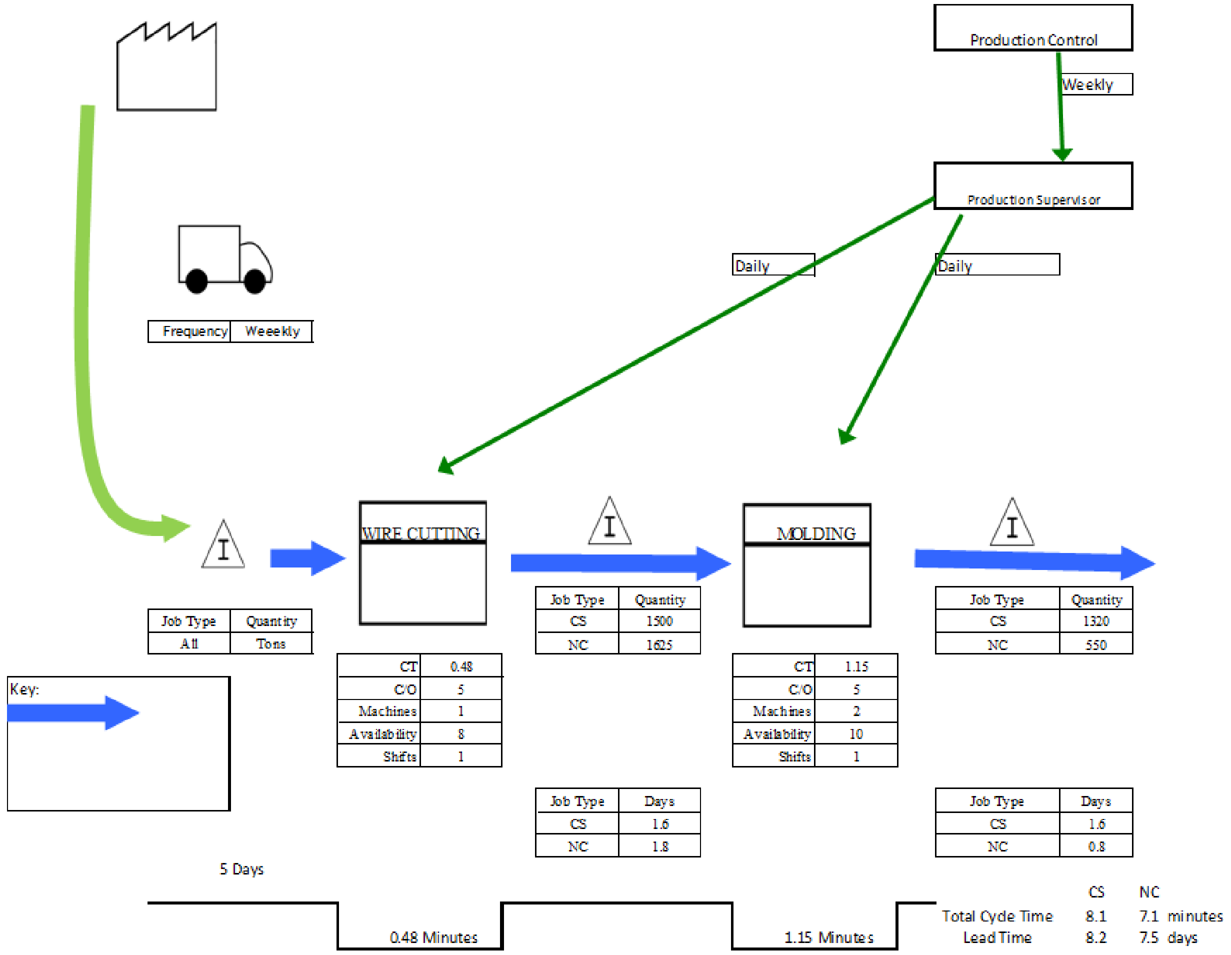

Fig. 4: Current state value stream map

- Replenish each WIP cart daily when corresponding orders are completed.
- Mold parts for orders only.
- Develop schedules based on the priority of daily orders.

DES modeling and analysis: A simulation model was constructed using Automod (Banks, 2000) based on the value stream map in Fig. 4. Daily demand was created by sampling from the demand histograms. Once the daily orders were generated, they were sequenced based on the scheduling scheme being evaluated. Once an order was completed at the injection molding machine, the WIP cart was sent back to the wire cutting department to be refilled to the maximum level, set at five hundred as determined in the lean part of the study. At the same time, the molded product was sent to the assembly department where it would be assembled into a final product and then shipped.

The experimental design, shown in Table 2 as well as verification and validation strategies are based on Standridge (2013).

The four scheduling alternatives are as follows:

Table 2: Simulation experiment design

Element of the experiment	Values for a particular experiment
Model parameters and their values	Schedule alternatives: 4
Performance measures	Percentages of orders completed in 1, 2 and 3 days, respectively Utilization of molding machine
Random number streams	12; one for each part type including center strip/no strip combination
Initial conditions	No orders in system
Number of replicates	20
Simulation end time/event	7 days (168 h)

- Random schedule (baseline model, existing scheduling scenario). This refers to processing orders in the sequence received.
- For each product, Customer “A” (smallest order to largest order), then Customer “B” for the same product.
- All Customer “A” (smallest order to largest order), then all Customer “B” (smallest order to largest order).
- For each product, Customer “A” (largest order to smallest order), then Customer “B” for the same product.

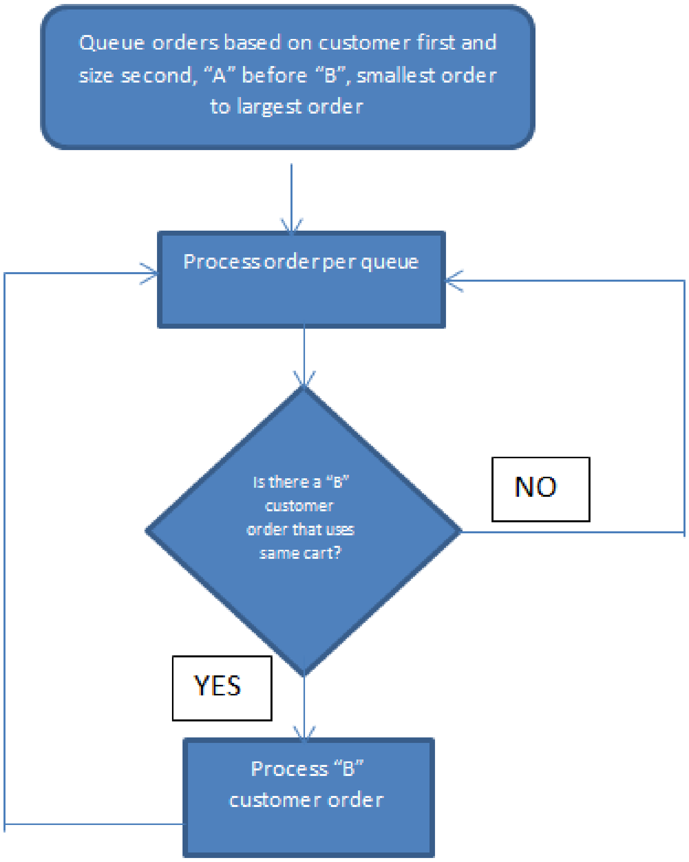

Fig. 5: Order sequencing flow chart

Hopp and Spearman (2007) suggest that for a single machine problem, the total time to complete the jobs depends on the sum of the processing times for the parts comprising the job. The average cycle time can be minimized by processing jobs in the order of their processing times, with the shortest job first and the longest job last. Using this Shortest Process Time (SPT) first sequencing rule, small jobs move through the plant more quickly than long jobs and which tends to reduce congestion as well as lead time. This is the basis for scheduling alternatives 2 and 3.

The following assumptions are made:

- If there is an order of greater than WIP cart maximum of 500 parts, the order is divided into two orders.
- Set up time is negligible when WIP carts are changed out both in the injection molding cell and the wire cutting cell.
- Injection molding cycle time is a constant 75 sec.
- There are twelve WIP carts, one for type of product as determined in the lean part of the study.

Verification and validation are the next steps (Sargent, 2013). Verification of the model develops confidence that the computer model as implemented faithfully corresponds to the model specifications. One piece of verification evidence can be obtained by confirming that the number of entities entering the model equals the number of entities departing the model plus the number of entities that are still in the model at the end of simulation.

Consider the simulation of the scheduling strategy: process the smallest "A" customer order first followed by the "B" customer order that shared the same wire WIP cart, if any. For one replicate of this simulation, there were 5,050 total orders: 3,725 "A" customer orders and 1,325 "B" customer orders. At the conclusion of the simulation there were 10 "A" customer orders and 3 "B" customer orders still in process in the model. There were 5,037 orders that departed the simulation:

$$3{,}725 + 1{,}325 = 5{,}037 + 10 + 3$$

Another piece of verification evidence can be obtained by comparing the process steps of the computer model and model specification. The sequencing of orders will be evaluated.

Figure 5 is a flow chart that shows the decision making for order sequencing. Table 3 shows the first 3 days of orders and the sequencing used in the simulation.

Table 3: Order sequence for the first 3 days of orders

Day 1					Day 2				Day 3			
Processing order	Customer	Size	Strip	Order size	Customer	Size	Strip	Order size	Customer	Size	Strip	Order size
1	A	29	NC	1	A	47	CS	19	A	29	NC	20
2	B	29	NC	11	A	65	NC	21	B	29	NC	19
3	A	41	NC	2	A	29	NC	21	A	41	NC	25
4	A	53	NC	7	A	35	NC	23	B	41	NC	29
5	A	47	NC	13	A	35	CS	40	A	53	CS	31
6	A	65	NC	17	B	35	CS	26	A	53	NC	41
7	A	53	CS	34	A	41	NC	43	A	35	CS	42
8	A	35	NC	75	A	29	CS	77	B	35	CS	1
9	A	29	CS	119	B	29	CS	26	A	35	NC	45
10	A	35	CS	174	A	41	CS	79	B	35	NC	46
11	B	35	CS	2	B	65	CS	45	A	29	CS	54
12	A	41	CS	372					B	29	CS	18
13	B	41	CS	29					A	65	NC	61
14									A	41	CS	447
15									B	41	CS	25

Table 4: Percent of "A" customer orders completed in 1 day

	Scheduling alternative			
	Random	Small A then B same cart	Big A then B same cart	All A then all B
Average	92.0	92.8	83.1	93.4
Standard deviation	10.4	5.0	22.6	5.2
Minimum	58.2	82.4	12.9	77.9
Maximum	98.7	98.7	100.0	98.7
99% CI upper bound	98.7	95.9	97.6	96.8
99% CI lower bound	85.4	89.6	68.7	90.1

Validation of the model develops confidence that the computer model and the model specification each represent the actual system with sufficient accuracy to support the decision making process. Utilization of the injection molding machine was determined from sixty days of actual production data. The following formula was used to calculate machine utilization:

> Utilization = (Machine Time for one part) * (Average Production per day) / (Number of seconds available per day) = (75 sec/part) * (598 parts/day) / (67.560 sec/day) = 0.66

The injection molding machine utilization for the simulation of the scheduling strategy: process the smallest "A" customer order first followed by the "B" customer order that shared the same wire WIP cart, if any was, = 0.64 with 99% confidence interval for the true mean (0.60, 0.68). Since the actual utilization of the injection molding machines falls within this confidence interval, model is validation evidence is obtained.

There are two questions that are of interest with respect to the percentage of orders completed in 1, 2 or 3 days which will be addressed using the simulation experiment results:

- Is there a difference between sequencing orders from smallest to largest and sequencing orders from largest to smallest?
- Is there a better sequencing scenario than random scheduling?

The paired-t statistical method, whose application in DES is discussed in Standridge (2013), is used to compare alternatives. The paired-t method compares two samples in cases where each value in one sample has a natural partner in the other. In this case, two scheduling strategies are compared simulation replicate by replicate by taking the difference between values of the same performance measure. The performance for one replicate is better than the other if the average difference is not equal to zero.

Table 4 provides summary statistics over the 20 simulated replicates concerning each scheduling alternative for the percentage orders delivered to the single "A" customer in 1 day.

The average percent of orders completed in one day is about the same for all alternatives except processing the largest "A" orders first and the "B" orders from the same WIP cart, which is about 10% less. Using the paired-t method, the difference in the percent of orders delivered in one day between this alternative and the random alternative was statistically significant ($\alpha = 0.01$). There is no statistically significant different between the random alternative and each of the other two alternatives ($\alpha = 0.01$).

The standard deviation is about half of the random sequencing alternative for the smallest "A" orders first and the "B" orders from the same WIP cart as well as for processing all "A" orders first and then all "B" orders.

Table 5 provides summary statistics over the 20 simulated replicates concerning each scheduling alternative for the percentage orders delivered to the 28 "B" customers in 1 day.

Table 5: Percent of "B" customer orders completed in 1 day

	Scheduling alternative			
	Random	Small A then B same cart	Big A then B same cart	All A then all B
Average	81.8	77.1	68.9	72.0
Standard deviation	12.3	12.4	21.9	21.1
Minimum	54.5	50.0	4.8	25.0
Maximum	96.3	100.0	100.0	100.0
99% CI upper bound	89.7	85.1	82.8	85.5
99% CI lower bound	73.9	69.2	54.9	58.5

The average percent of orders completed in one day is less in all other three alternatives than for random scheduling. However, this difference is not statistically significant for the smallest "A" orders first and the "B" orders from the same WIP cart alternative ($\alpha = 0.01$).

The standard deviation is about the same for the smallest "A" orders first and the "B" orders from the same WIP cart as for the random scheduling case. The other two alternatives have a larger standard deviation.

CONCLUSION

The integrated lean-DES approach produced results that would not have been otherwise achieved. The PQ analysis of order data revealed the surprising result that 80% of parts orders were by one "A" customer while 20% were by the other 28 customers combined, the "B" customers. Thus, the DES model and experiment needed to consider only two customer types. Interpretation of the experiment results gave more weight to on-time delivery to customer "A" than to customer "B" based on the relative demand. Experiment results included both the percent of orders delivered in one day and the variation in this percent. This illustrates the importance of the DES capability to compute the variation in the performance of a future state, which lean does not do.

In addition, lean tools identified that improving flow can be accomplished by having as many WIP carts as part types, 12, as well as replenishing the WIP carts each day. DES was used to confirm the positive impact of these changes with respect to on-time delivery as well as to assess four scheduling alternatives. For the "A" customer, three of the four scheduling alternatives showed the equivalent percent of orders delivered in one day. However two of the alternatives: the smallest "A" orders first and the "B" orders from the same WIP cart as well as for processing all "A" orders first and then all "B" orders yielded a standard deviation that is about half of that of the random sequencing of orders. For the "B" customer, the random sequencing alternative and the smallest "A" orders first and the "B" orders from the same WIP cart yield statistically equivalent percent of orders delivered in 1 day with about the same standard deviation. The latter was about half of that of the other two alternatives.

Thus, the smallest "A" orders first and the "B" orders from the same WIP cart appears to be better than random sequencing of orders that is processing of orders in the sequence received as well as outperforming the other two sequencing alternatives.

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