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OPTIMIZATION OF PRODUCTION AND INVENTORY POLICIES FOR DISHWASHER WIRE RACK PRODUCTION THROUGH SIMULATION

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ABSTRACT

A simulation model was built to represent the dynamics of a General Electric (GE) dishwasher wire rack production system associated with multiple types of racks and changeovers at the various work centers. A periodic-review inventory policy was simulated for the wire rack production system using order-up-to safety stock SS_i and a heuristic trigger variable P^* as the control variables. A discrete optimization model was formulated and executed in order to find near optimal values for the control variables with respect to minimization of the total inventory levels while satisfying constraints on demand for the various types of racks. Three different scenarios involving optimization of the simulation model were conducted to help GE improve their production strategy.

1 INTRODUCTION

Production systems are becoming increasingly complex, as a result of the various types of systems (e.g., parallel, rework, and JIT structures) in existence and their dynamic variations involving operation machine breakdowns and changeovers. These complexities make such systems extremely difficult to design and operate.

Although researchers have attempted to formulate and analyze these complex production systems via analytical models, it is rather difficult to capture dynamics and uncertainty in these models and analyze the corresponding systems accurately. Discrete event simulation is capable of mimicking large and complex systems with uncertainties, and hence is useful in the design and analysis of complex productions systems. This paper shows how simulation was used to help General Electric efficiently redesign and analyze their wire rack production lines for dishwashers.

To design and analyze a production system, the primary aspect one must consider is the production control strategy. The most generally known categories of production control strategies are “push” (e.g., MRP, MRP-II, and ERP) and “pull” (e.g., Kanban and CONWIP). Compared to the “push” strategy, the "pull" strategy maintains lower work-in-process (WIP) inventory levels in the system, thus requiring less space for accommodating fluctuation and minimizing congestion. For this very reason, General Electric's managers wish to redesign their current wire rack production lines for dishwashers from "push" to "pull" in their Louisville production and assembly plant.

The wire rack production lines for GE dishwashers is a production system with multiple products, stages and work stations which involve multiple changeovers at each station. In this paper, an Arena (Kelton et al. 2010) simulation model was built to represent such a complex system, which is rather difficult to formulate as an analytical model. Then, an (SS_i, P^*) inventory policy was developed and tested on the simulation model. A good solution for the new policy was found by OptQuest (Kleijnen and Wan 2007) through an optimization model. Even though the results from the search by OptQuest might not necessarily be optimal, it does provide valuable information to the GE managers for potential actions about how to operate the wire rack production system by following a "pull" strategy in the future.

2 LITERATURE REVIEW

2.1 Techniques for Design and Analysis of Production Systems

2.1.1 Analytical Models

To estimate key performance measures of a production system approximately, one could use analytical models with appropriate assumptions to ignore some complexities in the system. For a multi-product and multi-stage production system with changeovers (which is similar to the dishwasher wire rack production system at GE), one possible tool is dynamic programming. Ceryan et al. (2012) have applied this technique to find an optimal control decision for an assembly system with known demands for the end-product and intermediate components.

2.1.2 Queuing Network Models

Many production systems can be viewed as networks of suppliers, manufacturing sites, distribution centers, and customer locations, through which components and products flow. A node in a network can be a physical location, a sub-network, or just a process, while links represent material (components or products) flow. Hence, queuing networks and queuing theory are also widely used for modeling and analyzing the complex production systems. Wu and Dong (2008) have studied a multi-stage, multi-product production system using a queuing network model.

2.1.3 Simulation Models

Many researchers have demonstrated the benefits of simulation for modeling and analyzing complex production systems (Souza et al. 1996, Lin et al. 1998, Benedettini and Tjahjono 2009). Benedettini and Tjahjono (2009) have also pointed out that the complexities of dynamics in production systems can be explicitly reproduced by simulation models. These complex inventory policies for operating the production systems, such as CONWIP (Huang et al. 2007), AWIP (Masin and Prabhu 2009) and (s, S) inventory policy (Hu et al. 1993), are evaluated through simulation models. Also, optimization via simulation is an excellent tool to improve the production systems or obtain optimal control variable values (Nyen et al. 2006; Kumar and Sridharan 2007; Han and Zhou 2010).

2.2 Inventory Control Policies

Inventory which includes raw materials, work-in-process components and finished goods, is often used in the production strategy for production systems as a primary control variable. Numerous inventory production control policies are available. For a multi-product manufacturing system, the control policy must be able to determine and inform the work stations when to stop producing the current product and switch to another product to produce. Zipkin (1986) introduces a well-known (Q, r) policy for a multi-item batch production system. Altiok and Shiue (2000) propose a continuous-review (R, r) policy for controlling a pull-type production system with multiple product types. The production of a particular product stops when its inventory level reaches its target value R, and a request to initiate the production of a product is made as soon as its inventory level drops to or below its reorder point r. The (R, r) policy is very similar to the (S, s) policy developed by Scarf (1959) which is very widely used. However, Herer and Rashit (1999) have pointed out that the (S, s) policy might not always be appropriate, especially when there are multiple components. Nyen et al. (2006) have generated a periodic review (R, S) policy based on a queuing network model, where R is the review period for each product while S is the variable representing the order-up-to level.

A review of the literature indicates that many inventory control policies for multiple items were generated from analytical or queuing models and require a deterministic reorder point for each item. In this paper, a periodic-review inventory policy using order-up-to safety stock SS_i and a heuristic trigger variable P^* is proposed and integrated into the simulation model.

3 PROBLEM STATEMENT

General Electric's Appliance Park, located in Louisville, Kentucky, produces various appliances, including dishwashers. The dishwasher wire rack production system has three fabrication centers: 1) a center (denoted as FL) to produce three types of lower dishwasher racks (denoted as types A, B, and BXL), 2) a center (denoted as FU1) to produce four types of upper dishwasher racks (denoted as A1, B1, B2, B3), and 3) a center (denoted as FU2) to produce two additional types of upper racks (denoted as C2 and C4); the system also contains two coating centers: one for nylon coating (denoted as Nylon) which has three colors (Color A, Color B and Color C), and one for PVC coating (denoted as PVC) which only has one color (Color D). The five work centers (FL, FU1, FU2, Nylon and PVC) constitute the production system to produce the wire racks which supply dishwasher assembly lines. The facilities layout and production process are illustrated in Figure 1. GE has 9 types of WIP racks fabricated separately at the three fabrication centers (see Table 1). These WIP racks are stored in the WIP buffer area and #18 OH conveyor which can be treated as a buffer between two coating centers. Thirteen types of coated racks (see appendix A) are stored in the storage area and #25 OH conveyor serves as a buffer in front of the the assembly lines as well.

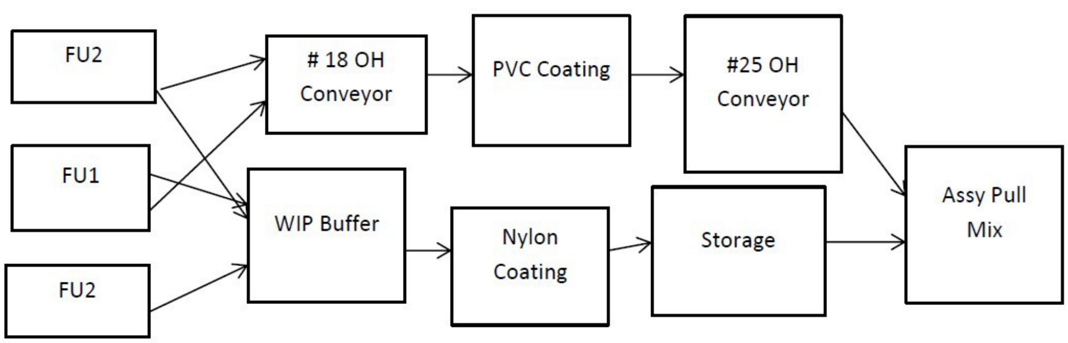

Figure 1: Production Process and Facilities Layout.

The different models of fabricated racks and the coating colors associated with the five work centers are summarized in Table 1. The estimated time intervals for making changeovers from one model or color to another at each work center were provided by GE.

The current dishwasher wire rack production policy in use at GE is a "push" strategy. The multiple types of racks are produced and a changeover is performed according to a production plan developed daily by the production manager. The fabricated and coated racks are stacked in the WIP buffer, storage areas

Table 1: Rack Model or Color at each Work Center.

Work Center	FL	FU1	FU2	PVC	Nylon
	A	A1	C2	Color D	Color A
Rack Model or	B	B1	C4		Color B
Color Types	BXL	B2			Color C
		B3			

and the two conveyors. GE wishes to redesign its production control policy via a "pull" strategy to react to and fill the assembly line demand, in order to minimize the number of changeovers and reduce the inventory levels significantly. GE contracted researchers at the University of Louisville to develop a suitable policy and to determine the size of the buffer and storage areas under the new policy.

4 SIMULATION MODEL AND VALIDATION

4.1 Simulation Model

Based on the information provided by GE, the daily demands (denoted as D_i) of the assembly lines for the 13 types of coated rack are distributed on half hourly basis over each day, the cycle times (denoted as CT_w) of the 5 work centers and the moving times (denote as MT_{kl}) from work center k to l are estimated to follow a triangular distribution, and the delay time (denoted as DCT_{ij}) for changeover from product i to j is assumed to follow a normal distribution. If the variability can be ignored, the system might be formulated as an analytical model instead of simulation model without too much difficulty. However, to better represent and analyze the system, a simulation model was built using the Arena simulation software package.

The changeover procedure for the 5 work centers are controlled by 5 sub-models in the simulation model. It follows five steps: 1) Stop entities from entering work centers undergoing changeover; 2) Finish processing only the entity currently in process at the work center; 3) Incur a delay of length DCT_{ij} for changeover; 4) Change the set up variables for appropriate work centers; 5) Start flow of entities into the work centers.

4.2 Inventory Policy Development

The above production system can be generalized with F types of intermediate components ($f = 1...9$ for the fabricated racks), C types of products ($c = 1...13$ for the coated racks) and W work centers ($w = 1...5$ for the five work centers). Since these work centers are operating separately, definition 1 is given below:

Definition 1 For a work center w, the set for the types of intermediate components or products associated with it can be denoted as S_w, where $S_w \in F$ or C.

To design an inventory policy for controlling a multi-product production system, one must define the variables to decide when to stop producing a certain product and which product is needed to be replenished. In this paper, an order-up-to safety stock variable (denoted as SS_i) is developed to help the work centers operating the stop criteria as Definition 2:

Definition 2 A work center w will stop producing product i (or intermediate component i) when the inventory level of product i (denoted as I_i) reaches its safety stock value SS_i, where $i \in F \cup C$.

As soon as the production of product i is stopped, the decision must be made for performing a changeover, and a replenishment product j must be picked up from S_w. The index of j is determined by a heuristic trigger variable P^*, which is given by (1):

$$P^* = \min\{j \in S_w | P_j = \frac{I_j - SS_j}{SS_j}\} \tag{1}$$

In (1), P_j actually represents the negative portion of the interval that product j's current inventory level differs from its safety stock variable SS_j, and P^* is the minimum value of P_j one can find among the set of S_w. The product index which needs to be replenished (denoted as j^*) is the index of j associated with P^* at work center w. Then j^* can be computed by (2):

$$j^* = \arg\min_{j \in S_w} P_j \tag{2}$$

Figure 2 illustrates how the (SS_i, P^*) inventory policy works. In this policy, the inventory level of the system is reviewed every 30 minutes, since the depletion period for the demand at the assembly lines is fixed to be 30 minutes, as decided by the GE manager.

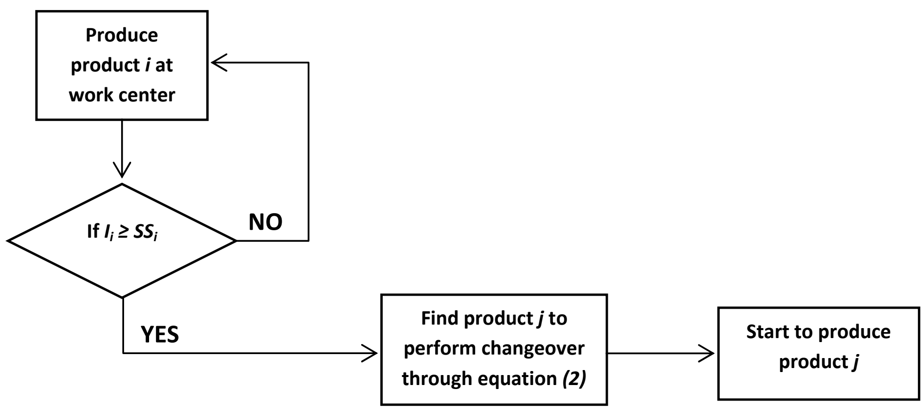

Figure 2: Dynamic Graph for Production Policy.

The assembly lines are scheduled to work for two 8-hour shifts from 6 am to 10 pm in a 24-hour day, and there are 10-minute breaks between each 4-hour period at each of the 5 work centers. A few unmet demands at the assembly lines are allowed in the production system. The unmet demands are considered as backorders in the simulation model, which will be filled as soon as the corresponding items are produced. In other words, the simulation model does not permit 'lost sales'.

4.3 Motivation of the (SS_i, P^*) inventory policy

In this project, an (SS_i, P^*) inventory policy was developed. This policy better addressed the problems which arise from other policies like an (s, S) policy. Since more than one type of product can be produced "simultaneously" at a work center, there may be difficulties associated with decisions to be made at the time of changeover. For example, with an (s, S) policy, after one 30 minute review period, work center FU1 may face a situation in which both racks of type A1 and B1 have reached their lower bounds, and the choice of which rack to switch to is problematic. An advantage of an (SS_i, P^*) inventory policy is that it could maximize the interval of the production volume from the most negative to SS_i; this approach can reduce the number of changeovers and reduce waste.

4.4 Model Validation

In this project, the GE manager wishes to determine the steady-state total inventory levels in the buffer area I_{WIP} and storage area $I_{Storage}$. He also wishes to minimize the number of changeovers at each work center. Since the system begins with zero inventory levels, three preliminary replications each of length 500 days were run in order to determine the warm-up period. By observing Figure 3 which plots I_{WIP} and $I_{Storage}$ (provided by the Output Analyzer in Arena), the best warm-up period was determined to be around 15 days.

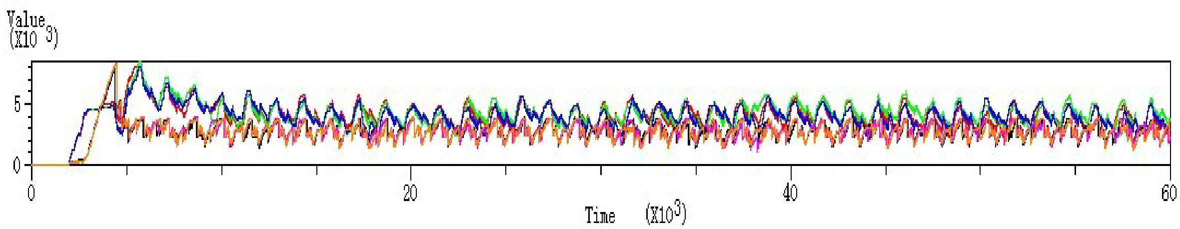

Figure 3: Plot of I_{WIP} and $I_{Storage}$ for preliminary replications.(X-axis: Thousands of Minutes; Y-axis: Inventory Level)

The actual daily production volumes at fabrication centers FL, FU1 and FU2 were used to validate the simulation model. Three initial replications with 15 days warm-up period and 280 days of simulation length were run to obtain the daily production volumes and compared with the data given by GE. Table 2 shows that the difference between the simulation results and the actual daily production volumes is very small, which indicates that the simulation models the actual system accurately.

Table 2: Comparison of Daily Production Volume.

Work Center	Simulation	Actual	Percentage of Difference
FL	3740	3797	1.05%
FU1	2883	2925	1.43%
FU2	865	872	0.86%

The three initial replications are also very helpful to determine the number of replications needed. The number of replications n^* needed can be calculated by the relative error γ' following equation (3):

$$n^*(\gamma) = \min\{i \geq n : \theta = \frac{t_{i-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}}{|\bar{X}(n)|} \leq \gamma'\}, \text{ where } \gamma' = \frac{\gamma}{1+\gamma} \tag{3}$$

To estimate I_{WIP} and $I_{Storage}$ with a relative error $\gamma' = 0.05$ and a confidence level of 95%, Table 3 was generated to find the θ. Since the values of θ for both I_{WIP} and $I_{Storage}$ are smaller than $\gamma' = 0.0476$, it is safe to say that three replications are adequate for this simulation model.

Table 3: Relative Precision for I_{WIP} and $I_{Storage}$.

Parameters	$S^2(n)$	$\bar{X}$	θ
$I_{Storage}$	21.8	4035	0.01342
I_{WIP}	4.11	2745	0.00372

5 OPTIMIZATION AND ANALYSIS

5.1 Optimization Formulation

In this paper, an integer program was formulated to search for the optimal inventory policy which minimizes the total inventory level at the WIP buffer and storage areas via the simulation model:

$$\min f(SS_i) = E[I_{WIP}(SS_i)] + E[I_{Storage}(SS_i)] \tag{4}$$

$$\text{s.t. } \frac{\sum_i^C \sum_t^T UD_{it}}{\sum_i^C \sum_t^T D_{it}} \leq \beta \tag{5}$$

In equation (4), $E[I_{WIP}(SS_i)]$ and $E[I_{Storage}(SS_i)]$ are the expected values (averages obtained by simulation) of the inventory levels for the WIP buffer and storage areas associated to a certain series of order-up-to safety stock variables SS_i. In equation (5), UD_{it} and D_{it} are the unmet demand and demand for product i at period t, while β is the tolerance level for the percent of unmet demand.

5.2 Results and analysis

The OptQuest software in Arena (Kleijnen and Wan 2007) was used to search for a near optimal solution for the SS_i. Three scenarios were run in OptQuest for β=0.05, 0.08 and 0.11. The best value of SS_i obtained for each scenarios can be found in Appendix B.

Table 4: Number of daily changeovers and utilization at each work center.

Work	No. of Changeovers			Utilization		
Center	$\beta = 0.05$	$\beta = 0.08$	$\beta = 0.11$	$\beta = 0.05$	$\beta = 0.08$	$\beta = 0.11$
FL	2.99	2.98	2.98	87.07%	86.87%	86.82%
FU1	4.44	4.48	4.55	81.73%	81.67%	81.87%
FU2	2.89	3.55	3.85	26.57%	27.76%	28.49%
Nylon	2.85	2.83	2.83	89.02%	87.43%	90.45%
PVC	0.00	0.00	0.00	25.21%	24.82%	25.65%

At each work center, the time required to perform a changeover is typically around 30 minutes, during which time no product is produced. The GE manager wishes to know how frequently they must perform changeovers at each work center with the new inventory policy.

Table 4 shows the daily number of changeovers and utilizations at each work center. Because there is only one color used at the PVC coating center, there is no changeover there. The number of daily changeovers estimated by the simulation model for the new inventory policy was acceptable for the GE manager. By observing Table 4, the average number of respective changeovers performed each day at work centers FL, FU1 and Nylon are almost the same for the three scenarios. However, it is interesting to observe that the number of changeovers at work center FU2 increases with higher β values. By reviewing the daily demand of the 13 types of product (appendix A), one may notice that the daily demand of the products produced by FU2 is much lower compared to the other work centers. For this reason, the utilization of FU2 is also low as shown in Table 4. Hence, the increasing of β will allow the lower safety stock SS_i for the intermediate components associated with FU2, which can reduce the objective function value in (4). With lower SS_i, FU2 can be better utilized, thus permitting shorter, but more production cycles at that station. This is the reason that the number of changeovers at FU2 increases when β is higher.

If the GE manager wants to further reduce the frequency of changeovers at these work centers, he may adjust their production plan at the assembly lines to call for these products which have low daily demands with a longer production interval but larger volume, rather than producing them at the small volume each day.

Table 5: Inventory Levels at the WIP Buffer and Storage Areas.

				Portion of Inventory			Portion of Reduction	
β	0.05	0.08	0.11	0.05	0.08	0.11	5 to 8	8 to 11
$I_{Storage}+I_{WIP}$	7047.85	6382.95	5541.49				9.43%	13.18%
$I_{Storage}$	4472.95	3935.39	3292.27	63.47%	61.65%	59.41%	12.02%	16.34%
I_{WIP}	2574.90	2447.56	2249.22	36.53%	38.35%	40.59%	4.95%	8.10%

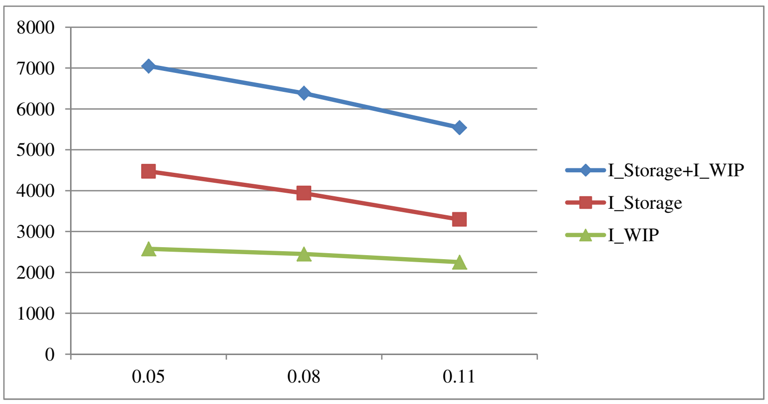

Figure 4: Trends of Inventory Levels as β Increasing.(X-axis: β; Y-axis: Inventory Level)

To predict how much space is required for the buffer and storage areas for making further decisions, the GE manager is interested in the values of I_{WIP} and $I_{Storage}$ obtained via the simulation model. Figure 4 shows the estimated average values of I_{WIP} and $I_{Storage}$ for different levels of β. Both of I_{WIP} and $I_{Storage}$ decrease when β increases. This is as expected. However, the results show that increasing β affects $I_{Storage}$ more significantly than I_{WIP}. When altering the plant layout, the GE manager must take into consideration the fact that more space is required for the finished storage area than the buffer area.

Because the run times for performing the optimization experiments on this simulation model are very high (because we may have to search for 100 possible solutions requiring approximately 4 hours), no other experiments besides the three scenarios were conducted on OptQuest. The manager can select a suitable tolerance level β from Table 4, and use the suggested inventory levels for the buffer and storage areas from our results. Because the work schedule for the fabrication and coating centers are three 8-hour shifts for a 24-hour day and this schedule does not correspond to the assembly line schedules, a potential improvement that might significantly reduce the inventory level is to adjust the work schedule of the assembly lines to match the production schedule at the fabrication and coating centers.

6 CONCLUSION AND FUTURE WORK

In this paper, simulation is shown to be a valuable tool to model and handle the complexities in a real-world production system. To control the inventory and operate a production system which has multiple products and changeovers at work centers, a periodic-review inventory policy using order-up-to safety stock SS_i and a heuristic trigger variable P^* was proposed and integrated in the simulation model. Compared to the other inventory policies available in the literature, the (SS_i, P^*) policy is very helpful for constructing the simulation model and avoiding operational conflicts. An integer program was formulated to search for the optimal policy to minimize the total inventory levels at the buffer and storage areas. Although the run times for simulation optimization are relatively high, three experiments were conducted with OptQuest to find a near optimal solution of SS_i^* at different tolerance levels β for unmet demand. Then the suggestions based on the simulation results were provided to the GE manager to take the necessary steps internally for improving the production system. The following changes can be implemented and tested on the simulation model to see if the performance of the system can be improved:

1. The distributions for the low demand products can be changed in such a way that higher volumes are demanded less frequently.
2. The work-shift plans at the assembly lines can be rescheduled so they match with the work schedule at the fabrication and coating centers.

The simulation model can be extended to the overall General Electric's dishwasher production system in the plant, rather than just focusing on the wire rack production. Also, we could experiment with other types of demand distributions. Weight parameters can be integrated to the variables of P_j to account for the priories of products. Moreover, a dynamic programming model might be formulated on the production system for generalization and further analysis of this kind of problem.

A 13 TYPES OF COATED RACK

Fab Center	Rack #	Model	Coating Type	Color	Daily Demand
FL	1	A	Nylon	Color A	1504
	2	B	PVC	Color D	587
	3	B	Nylon	Color A	652
	4	BXL	Nylon	Color B	939
	5	BXL	Nylon	Color C	65
FU1	6	A1	Nylon	Color A	1504
	7	B1	PVC	Color D	587
	8	B2	Nylon	Color A	652
	9	B3	Nylon	Color B	126
	10	B3	Nylon	Color C	17
FU2	11	C2	Nylon	Color B	196
	12	C4	Nylon	Color B	617
	13	C4	Nylon	Color C	48

B BEST SS_i^* OBTAINED BY OPTQUEST

Coated	SS_i^*			Fabricated	SS_i^*		
Rack	0.05	0.08	0.11	Rack	0.05	0.08	0.11
1	900	800	750	A	900	600	500
2	400	400	400	B	650	500	450
3	350	350	100	BXL	750	650	750
4	600	550	600	A1	750	1000	850
5	20	20	10	B1	250	350	300
6	750	650	500	B2	200	300	200
7	450	200	250	B3	80	60	40
8	600	500	400	C2	100	70	60
9	80	70	60	C4	250	250	200
10	15	15	20				
11	190	90	120				
12	400	350	300				
13	40	30	200				

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